Frequency locking of tunable diode lasers to a stabilized ring-cavity resonator

Ayan Banerjee, Dipankar Das, Umakant D. Rapol, and Vasant Natarajan

Department of Physics, Indian Institute of Science, Bangalore 560 012, INDIA

Abstract

We demonstrate a technique for locking the frequency of a tunable diode laser to a ring-cavity resonator. The resonator is stabilized to a diode laser which is in turn locked to an atomic transition, thus giving it absolute frequency calibration. The ring-cavity design has the principal advantage that there is no feedback destabilization of the laser. The cavity has a free-spectral range of 1.3 GHz and $Q$ of about 35, which gives robust locking of the laser. The locked laser is able to track large scans of the cavity.
The easy availability of diode lasers over most of the near-infrared spectrum has led to their widespread use in atomic and optical physics experiments \[1\]. The principal advantages of these lasers lie in their low cost, narrow spectral width, tunability over several nm, efficient power consumption, reliability, and ease of operation. In addition, by placing a single-mode diode in an external cavity and using optical feedback from an angle-tuned grating, it can be made to operate at single frequency (single longitudinal mode) with linewidth of order 1 MHz \[2,3\]. Such frequency-stabilized diode lasers find applications in several experiments as low-cost replacements for ring-cavity dye or Ti-sapphire lasers. In particular, experiments on laser cooling have become accessible to a large community of researchers because several alkali atoms and alkali-like ions have cooling transitions which are accessible with diode lasers \[4\]. However, to use lasers in such applications effectively it is necessary to set their absolute frequency with $\sim$MHz precision. In many cases, this is achieved by locking the laser to a known atomic or molecular transition using saturated-absorption spectroscopy in a vapor cell. But this may not always be possible, especially when working with short-lived radioactive species or trapped ions.

In this Letter, we solve this problem by locking a tunable diode laser to a stabilized ring-cavity resonator. Tunable lasers are traditionally locked to linear Fabry-Perot reference cavities. In fact, several commercial dye and Ti-sapphire lasers use a temperature-controlled linear cavity for locking. The main problem with such a design for the diode laser is that it can cause unwanted feedback into the laser and destabilize it. By contrast, our ring-cavity design has a traveling wave inside the cavity and there is no possibility of feedback into the laser. The ring cavity has several other advantages: i) The cavity provides at least three output beams that can be used to measure the signal from the cavity. ii) The angle of incidence on the cavity mirrors is not normal, therefore the mode structure inside the cavity is elliptical; diode laser outputs are also elliptical, and this makes it easier to mode-match the output of the diode laser into the cavity. iii) The design is compact and the cavity is easily temperature controlled to increase its passive stability.

The cavity is actively stabilized to a diode laser (called the “master laser”) that is
itself locked to an atomic transition. Using a diode laser locked to an atomic transition as the absolute frequency reference has several advantages over alternatives such as using a stabilized HeNe laser. The atomic transition typically has several hyperfine peaks and the laser can be locked to any of them. For example, we use the $D_2$ line in Rb for locking the master laser. Rb has two stable isotopes, and two ground-state hyperfine levels and four excited-state hyperfine levels in each isotope. Thus, there are potentially 24 lock points available in the saturated-absorption spectrum, with frequencies varying over a range of several 100 MHz. Now, when the arbitrary frequency of a tunable laser (called the “slave laser”) has to be set, its frequency will generally be offset from the cavity resonance, and the offset can be as large as the cavity free-spectral range. This offset is accounted for by shifting the laser frequency using an acousto-optic modulator (AOM) and then locking to the cavity. If the cavity is stabilized to a single frequency from a HeNe laser, the free-spectral range of the cavity has to be quite small so that the frequency offset lies within the range of the AOM, which is typically limited to 100–200 MHz. This implies the use of long cavities with their concomitant difficulty in maintaining temperature stability. By contrast, the wide range of lock frequencies available with the atomic transition means that the cavity free-spectral range can be of order GHz, and it is still possible to find one lock point for which the slave laser frequency lies within the range of the AOM. One other advantage of using a diode laser locked to an atomic transition is that it makes scanning of the slave laser quite simple. The master laser can be scanned over a large frequency range around the atomic transition by changing its grating angle, and the slave laser tracks this scan. This kind of scanning is quite important in spectroscopy experiments.

The schematic of our system is shown in Fig. 1. The master laser is tuned to the $D_2$ line of atomic Rb at 780 nm ($5S_{1/2} \leftrightarrow 5P_{3/2}$ transition). It is locked to one of the hyperfine peaks or crossover resonances in the saturated-absorption spectrum. The absolute frequency of the Rb $D_2$ line has been measured previously with kHz accuracy, therefore the frequency of this laser is known very precisely. The error signal for the locking is obtained by modulating the injection current into the diode. Next, the cavity is stabilized by locking it to the master
laser frequency. The error signal for this is obtained by modulating the cavity length using a piezo-mounted mirror. Finally, the slave laser is locked to a cavity resonance by dithering its injection current. All the modulation frequencies are in the range of 10–50 kHz and the lock-in amplifiers are home built around the Analog Devices AD630 mixer chip.

The two diode laser systems are built around commercial single-mode laser diodes. The output is first collimated using a 4.5 mm, 0.55 NA aspheric lens. The laser is then frequency stabilized in a standard external-cavity design (Littrow configuration) using optical feedback from an 1800 lines/mm diffraction grating mounted on a piezoelectric transducer. For the master laser, a part of the output beam is tapped for Doppler-free saturated-absorption spectroscopy in a Rb vapor cell. The laser is locked to one of the hyperfine transitions in the $D_2$ line by feeding the error signal to the piezoelectric transducer that controls the grating angle. The slave laser is tuned near the $D_1$ line of Rb at 795 nm.

The ring cavity consists of two plane mirrors and two concave mirrors in a bow-tie arrangement, as shown in Fig. 1. One of the plane mirrors is partially reflecting (97%) and is used to couple light into the cavity. The second plane mirror is mounted on a piezoelectric transducer and is used to adjust the cavity length electronically. The two concave mirrors have radius of curvature of 25 mm. The concave mirrors are placed 26.5 mm apart, while the optical path length between them through the plane mirrors is 200 mm. The angle of incidence on all mirrors is $15^\circ$. The mirrors are mounted on a 10-mm thick copper plate that is temperature controlled to $\pm 0.01^\circ$C using a thermoelectric cooler.

We have analyzed the cavity using standard $ABCD$ matrices for Gaussian beam propagation. Because of the non-zero angle of incidence on the curved mirrors, it is necessary to analyze the sagittal and tangential planes separately. The cavity modes are therefore elliptical. The cavity has two beam waists, a small one of diameter $13.8 \mu m \times 13.4 \mu m$ between the concave mirrors and a large one of diameter $224 \mu m \times 119 \mu m$ between the plane mirrors. The larger waist is used for efficient mode matching of the laser beams into the cavity. The output of the diode lasers is directly fed into the cavity through a lens of focal length 50 cm. About 15% of the light gets coupled into the cavity. Using an anamorphic
prism pair after the diode laser, it is possible to adjust the ellipticity of the input beam and improve the coupling efficiency to 50%, but we do not do this on a routine basis.

The cavity has been designed to have a $Q$ of about 30. The measured cavity modes are shown in Fig. 2 which is a plot of the power inside the cavity as a function of the cavity length. The measured $Q$ is 35, which is close to the designed value. The free spectral range is 1.3 GHz corresponding to a cavity length of 226.5 mm. This implies that the cavity modes have a linewidth of about 37 MHz. The low $Q$ of the cavity ensures that the locking of the slave laser is robust and is quite insensitive to sudden perturbations. The error signal obtained by modulating the cavity length is fed to the piezo-mounted mirror to lock the cavity to the master laser. The piezoelectric transducer has a full deflection of 6.1 $\mu$m for a voltage of 150 V. This gives a wide dynamic range for the cavity to track scans of the master laser.

There are two ways to produce the error signal for locking the slave laser to the stabilized cavity. The first technique, which is easier to implement, is to modulate the injection current into the slave laser. The second technique is to modulate the frequency of the AOM which is used to shift the frequency of the laser and match it to a cavity resonance. The second technique has the advantage that the laser frequency does not vary and there is no increase in its linewidth. However, the scheme is complicated because it requires double passing through the AOM in order to maintain directional stability. Therefore, we have used the first technique in these experiments.

In order to test the ability of the slave laser to track scans of the master laser, we have used the slave laser to measure transitions on the Rb $D_1$ line ($5S_{1/2} \leftrightarrow 5P_{1/2}$ transition) while it was locked to the cavity. The slave laser is first tuned near the $D_1$ line by measuring its frequency using a home-built wavemeter [8]. The wavemeter also uses the master laser locked to the atomic transition for absolute frequency calibration. This gives us the slave-laser frequency with an accuracy of about 20 MHz. The frequency shift in the AOM is then adjusted so that the slave laser is on a cavity resonance and the laser is then locked to the cavity. The master laser is now scanned over a frequency range of several 100 MHz. The
saturated-absorption spectrum of the $5S_{1/2}, F = 2 \rightarrow 5P_{1/2}, F'$ transitions in $^{85}\text{Rb}$ is shown in Fig. 3. We see that the slave laser is able to track scans of order GHz or more without losing lock.

In conclusion, we have shown that the frequency of a tunable diode laser can be locked using a stabilized ring-cavity resonator. The ring cavity has several advantages over a linear etalon, the main one being that there is no feedback destabilization of the laser. The cavity is stabilized using a diode laser which is in turn locked to an atomic transition. The atomic transition has several peaks in the spectrum, and thus provides several calibrated frequency markers for locking. The cavity we have used in the current experiments has a free spectral range of 1.3 GHz and a $Q$ of 35. The low $Q$ allows robust locking of the slave laser. The piezo-mounted mirror in the cavity has a wide dynamic range that allows large scans of the master laser to be tracked by the slave laser. We have verified that the slave laser stays locked while the master laser is scanned over a frequency range of 1 GHz or more. The cavity modes have a linewidth of about 37 MHz and this determines the tightness of the lock. In future, we plan to use a longer cavity with free spectral range of about 500 MHz and mode linewidth of 15 MHz. We expect to get much tighter locking with the new design.

This work was supported by research grants from the Board of Research in Nuclear Sciences (DAE), and the Department of Science and Technology, Government of India.
a) Electronic mail: vasant@physics.iisc.ernet.in

[1] C. E. Wieman and L. Hollberg, Rev. Sci. Instrum. 62, 1 (1991).

[2] K. B. MacAdam, A. Steinbach, and C. Wieman, Am. J. Phys. 60, 1098 (1992);

[3] L. Ricci et al., Opt. Comm. 117, 541 (1995).

[4] A good review of laser cooling experiments is contained in the Nobel Prize lectures: S. Chu, Rev. Mod. Phys. 70, 685 (1998); C. N. Cohen-Tannoudji, ibid. 70, 707 (1998); and W. D. Phillips, ibid. 70, 721 (1998).

[5] Each ground level can couple to three excited levels producing three peaks in the spectrum. Each pair of peaks has a corresponding crossover resonance, thus giving 6 peaks per ground level for each isotope.

[6] J. Ye, S. Swartz, P. Jungner, and J. L. Hall, Opt. Lett. 21, 1280 (1996).

[7] H. Kogelnik and T. Li, Appl. Opt. 5, 1550 (1966).

[8] A. Banerjee, U. D. Rapol, A. Wasan, and V. Natarajan, Appl. Phys. Lett. 79, 2139 (2001).
FIGURES

FIG. 1. Schematic of the system. The master laser is a frequency-stabilized diode laser locked to an atomic transition in Rb. The ring cavity has a bow-tie design with two plane and two curved mirrors. It is stabilized to the master laser by adjusting its length using the piezo-mounted mirror. The slave laser is a frequency-stabilized diode laser that is locked to the cavity. The acousto-optic modulator (AOM) is used to account for any difference between the cavity resonance and the slave-laser frequency. Figure key: LIA is Lock-in amplifier, PBS is polarizing beamsplitter, M is mirror, BS is beamsplitter, PD is photodiode.

FIG. 2. Cavity modes. The figure shows the power inside the cavity as the cavity length is scanned using the piezo-mounted mirror. The mean cavity length $L_0$ is about 226.5 mm. The dotted line is a Lorentzian fit to the two peaks which yields a $Q$ of 35.

FIG. 3. Scan of the slave laser. The plot is a saturated-absorption spectrum of the $5S_{1/2}, F = 2 \rightarrow 5P_{1/2}, F'$ transitions in $^{85}\text{Rb}$ obtained by scanning the master laser while the slave laser was locked to the cavity. The outer peaks are the hyperfine transitions corresponding to $F' = 2$ and $F' = 3$, while the middle peak is the crossover resonance. Probe detuning is measured from the $F = 2 \rightarrow F' = 2$ transition. The total scan width is 1.2 GHz.
F = 2 → F'

Probe transmission (a.u.)

Probe detuning (MHz)

2

(2,3)

3

-400 -200 0 200 400 600 800