Measuring the linewidth of a stabilized diode laser

Lal Muanzuala, Harish Ravi, Karthik Sylvan, and Vasant Natarajan
Department of Physics, Indian Institute of Science, Bangalore 560 012, India

∗vasant@physics.iisc.ernet.in; www.physics.iisc.ernet.in/˜vasant

We demonstrate a straightforward technique to measure the linewidth of a grating-stabilized diode laser system—known as an external cavity diode laser (ECDL)—by beating the output of two independent ECDLs in a Michelson interferometer, and then taking the Fourier transform of the beat signal. The measured linewidth is the sum of the linewidths of the two laser systems. Assuming that the two are equal, we find that the linewidth of each ECDL measured over a time period of 2 µs is about 0.3 MHz. This narrow linewidth shows the advantage of using such systems for high-resolution spectroscopy and other experiments in atomic physics.

Keywords: ECDL, Grating stabilization, Littrow configuration, Michelson interferometer.

I. INTRODUCTION

The advent of diode lasers in the last couple of decades has revolutionized laser spectroscopy in atoms, and made possible several experimental studies in fields such as precision measurements [1–3], laser cooling and trapping of atoms [4], atomic clocks [5], quantum optics [6–8], and so on. This is because most experiments are done using the D lines of alkali atoms, which are in the near infrared (IR) and hence accessible with diode lasers. In addition, alkali atoms have high vapor pressure at room temperature so that vapor cells with sufficiently high atomic density can be used.

However, in order to be useful for high-resolution atomic spectroscopy (where transitions have linewidths of a few MHz [9]) the laser linewidth should be below 1 MHz. Since the linewidth of a commercial diode laser (of the kind that is used in CD players for example) is of the order of a few GHz, it is necessary to reduce this linewidth. The required reduction is typically achieved using optical feedback from a diffraction grating, in what is called the Littrow configuration. This also serves the purpose of making the frequency of the laser tunable by changing the angle of the grating. The grating is usually mounted on a piezoelectric transducer so that the angle can be changed electronically.

The configuration, shown schematically in Fig. 1 is arranged so that the −1\textsuperscript{st} diffraction order is fed back to the laser, while the specular reflection is the output. From the grating equation, we have

\[ 2d \sin \theta = m \lambda \]

where \( d \) is the spacing between the successive lines of the grating, and \( \theta \) is the angle of the \( m \textsuperscript{th} \) order diffraction. Since the specular reflection is the output beam, it is convenient to have \( \theta \) close to 45°. This is achieved by choosing \( d \) appropriately—e.g. the grating for accessing the D lines of K, Rb, and Cs (770–900 nm) has 1800 lines/mm. The power available after optical feedback is usually about 70% of the open-loop power. Thus, although the linewidth reduction of the diode laser is by more than a factor of 1000, the loss in power is only 30%, showing that this is not wavelength selection (as for a grating used to disperse the light from a white-light source) but actual reduction in wavelength uncertainty. In effect, the grating along with the back facet of the diode forms a second lasing cavity—which is why this configuration is called an external cavity diode laser (ECDL)—with the longer cavity resulting in a smaller linewidth.

The linewidth of the laser can be measured in a Michelson interferometer, with the requirement that the phase difference between the two arms be larger than the phase coherence of the laser [10]. If the linewidth of the laser is about 1 MHz, the corresponding coherence length is 300 m. This means that the two arm-lengths of the interferometer have to differ by a kilometer or more. This is not easy to implement in the lab unless one uses a coiled optical fiber of that length. An alternate (and easier) way would be to use two identical laser systems and interfere/beat them in the interferometer. Since the
phase of the two lasers are independent, the two arm-
lengths can be nominally equal, with the understand-
ing that the beat signal will represent the convolution
of the two laser linewidths. If we assume that the two
ECDLs have Lorentzian distributions with center fre-
quencies $\omega_1$ and $\omega_2$, and linewidths (full-width-at-half-
maximum, FWHM) $\Gamma_1$ and $\Gamma_2$, respectively, then the
normalized distribution in frequency-space is

$$L_i(\omega) = \frac{\Gamma_i/2}{\pi (\omega - \omega_i)^2 + (\Gamma_i/2)^2}$$

(1)

where $i$ is 1 or 2 for the two laser systems.

In this study, we present the results of such a linewidth
measurement on two home-built ECDLs beat over a
time period of 2 $\mu$s. As expected, the linewidth of each
laser is below 0.5 MHz. To see if there is an effect of lock-
ing the frequency of a laser, we have done three studies—
(i) both lasers free running, (ii) one laser locked and the
other free running, and (iii) both lasers locked. The re-
results indicate that locking lasers has no effect on the
linewidth, at least over this time scale.

II. EXPERIMENTAL DETAILS

The diode laser system consists of a Sharp laser diode
(GH0781JA2C) operating with a free-running wave-
length of 784 nm and power of 120 mW. The laser is
stabilized using feed back from an angle-tuned grating
with 1800 lines/mm, as shown in Fig. 1. The system
is mounted on a thermo-electric cooler for temperature
stabilization. Using a combination of operating temper-
ature and operating current, the laser system is brought
near the Rb D$_2$ line ($5S_{1/2} \rightarrow 5P_{3/2}$ transition) at 780
nm. Part of the laser output is fed into a saturated ab-
sorption spectrometer (SAS) [10], so that the laser can
be locked to a hyperfine transition, if necessary. The
locking is achieved by modulating the laser current at 20
kHz, and demodulating the SAS signal using a lock-in
amplifier.

The experimental setup for obtaining the beat signal is
shown in Fig. 2. The two lasers have a fixed frequency dif-
fERENCE of about 16 MHz. This is so that the beat signal
is centered around a non-negative value, and the varia-
tion around this value can be measured unambiguously.
By contrast, if the frequency difference were zero, the
lineshape would be a half-Lorentzian function, because
only positive frequencies would appear in the spectrum.
The output of the two ECDLs is mixed on a 50-50 non-
polarizing beam splitter, as shown in the figure. The beat
signal is measured on a fast photodiode, with response
time sufficiently fast in order to measure the 16 MHz sig-
nal. The signal is measured at a sampling rate of 1 GHz
for a total time of 2 $\mu$s, corresponding to 2000 points. A
fast Fourier transform (FFT) of the signal gives the fre-
quency spectrum, with sufficient zero padding to make
the spectrum smooth.

III. RESULTS AND DISCUSSION

Before turning to the experimental results, we see
what is the expected lineshape for the beat signal. A
Lorentzian centered at non-zero frequency can be simu-
lated using a function of the form

$$f(t) = e^{-2\pi\gamma t/\gamma} \cos(2\pi f_0 t)$$

(2)

where $\gamma$ is the linewidth, and $f_0$ is the center frequency.
We take typical values of $\gamma = 0.6$ MHz and $f_0 = 16
MHz$. Using experimental values of 2000 samples at a
sampling rate of 1 GHz and total time of 2 $\mu$s, the FFT
of this function (magnitude squared with zero padding
of 100000 points) is shown in Fig. 3. The lineshape is
dominantly the convolution of a Lorentzian with a sync
function (because of the finite time duration of the func-
tion) as evidenced by the zeros of the spectrum. The
lineshape near the peak is primarily Lorentzian as seen from
the near-perfect overlap with the Lorentzian fit, and the
linewidth obtained from the fit is 0.63 MHz—close to the
chosen value of 0.6 MHz. Therefore, in the following, the
experimentally measured spectrum is fit to a Lorentzian,
and the linewidth determined from the fit.

A typical experimental FFT spectrum obtained with
two free running lasers is shown in Fig. 4. The data are
taken at a sampling rate of 1 GHz and for a total time of 2
$\mu$s—exactly the conditions used for the theoretical results
presented in Fig. 3. It has a similar lineshape with zero
points due to the finite signal duration. A Lorentzian
fit to the central peak yields a linewidth of 0.61 MHz.
If we assume that the two lasers are identical, then Eq.
(1) shows that the linewidth of each laser is 0.3 MHz.
Since this is the linewidth obtained after 2 $\mu$s, it can be
regarded as an average linewidth over this period. The
instantaneous linewidth is expected to be lower.

In order to study the effect of locking the laser to a
hyperfine transition, we have repeated the above exper-
iment with one of the lasers locked, and with both the
FIG. 3. (Color online) Calculated power spectrum for a function given by Eq. (2) with center frequency 16 MHz, linewidth 0.6 MHz, and lasting for a time of 2 µs (shown with a dotted line). The solid line is a Lorentzian fit to the central peak, which matches the spectrum almost perfectly and yields a linewidth of 0.63 MHz.

FIG. 4. (Color online) Experimental power spectrum obtained by beating two ECDLs. A Lorentzian fit (not shown) yields a linewidth of 0.64 MHz.

IV. CONCLUSIONS

In conclusion, we have presented a technique where the linewidth of a grating-stabilized diode laser can be measured using a Michelson interferometer. Instead of the usual technique of having a km long fiber in one of the arms of the interferometer to create the required phase delay, we use the simpler technique of having two independent diode lasers with nominally equal path lengths in the two arms. If we assume that the linewidths of the two laser systems are equal, we find that the linewidth averaged over 2 µs is about 0.3 MHz. This shows the advantage of using such stabilized diode laser systems (ECDLs) for high-resolution spectroscopy and other experiments in atomic physics.

ACKNOWLEDGMENTS

This work was supported by the Department of Science and Technology, India.

TABLE I. Measured linewidths of the beat signal under different conditions of locking of the two ECDLs. Listed is the average value from 3 measurements.

| Condition of ECDLs           | Average linewidth (MHz) |
|------------------------------|-------------------------|
| Both free running            | 0.57                    |
| One locked and one free running | 0.60                |
| Both locked                  | 0.58                    |

[1] A. Banerjee, D. Das, and V. Natarajan, “Precise frequency measurements of atomic transitions by use of a Rb-stabilized resonator,” Opt. Lett. 28, 1579–1589 (2003).
[2] D. Das and V. Natarajan, “Hyperfine spectroscopy on the 6P_{3/2} state of ^{133}Cs using coherent control,” Europhys. Lett. 72, 740–746 (2005).
[3] H. Ravishankar, S. R. Chanu, and V. Natarajan, “Chopped nonlinear magneto-optic rotation: A technique for precision measurements,” Europhys. Lett. 94, 53002 (2011).
[4] U. D. Rapol, A. Wasan, and V. Natarajan, “Loading of a Rb magneto-optic trap from a getter source,” Phys. Rev. A 64, 023402 (2001).
[5] S. Brandt, A. Nagel, R. Wynands, and D. Meschede, “Buffer-gas-induced linewidth reduction of coherent dark resonances to below 50 Hz,” Phys. Rev. A 56, R1063–R1066 (1997).
[6] U. D. Rapol, A. Wasan, and V. Natarajan, “Observation of sub-natural linewidths for cold Rb atoms in a magneto-
optic trap,” Europhys. Lett. 61, 53–59 (2003).

[7] S. M. Iftiquar, G. R. Karve, and V. Natarajan, “Subnatural linewidth for probe absorption in an electromagnetically-induced-transparency medium due to Doppler averaging,” Phys. Rev. A 77, 063807 (2008).

[8] S. R. Chanu, K. Pandey, V. Bharti, A. Wasan, and V. Natarajan, “Polarization-rotation resonances with subnatural widths using a control laser,” Europhys. Lett. 106, 43001 (2014).

[9] D. Das and V. Natarajan, “High-precision measurement of hyperfine structure in the D lines of alkali atoms,” J. Phys. B: At. Mol. Opt. Phys. 41, 035001 (12pp) (2008).

[10] M. Born and E. Wolf, Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light (Cambridge University Press, Cambridge, 1999), 7th ed.