Diode Lasers and Spectroscopic Applications

L. Hollberg, R. Fox, N. Mackie
National Institute of Standards and Technology, Boulder CO. 325 Broadway
80303, USA

A.S. Zibrov, V.L. Velichansky
Lebedev Physical Institute, 53 117924 Moscow, USSR

R. Ellingsen
Norwegian Institute of Technology, N7034, Trondheim, Norway.

H.G. Robinson
Department of Physics, Duke University, Durham, N.C.

ABSTRACT

We discuss the spectroscopic application of semiconductor diode lasers operating in the wavelength range from 0.640 to 1.55 μm. Amplitude and frequency noise reduction techniques are mentioned. Saturated absorption with a red diode laser is demonstrated on the Calcium intercombination line at 657 nm.

The past five years have seen a rapid increase in the application of diode lasers to scientific and spectroscopic applications. Diode lasers that were designed for consumer electronics have been transformed into precision spectroscopic instruments with various techniques. Much of this basic technology for using diode lasers has been reviewed in the literature.[1-4] GaAs and InP based semiconductor lasers continue to advance rapidly; with improved power, narrower linewidths, lower costs, and better availability. New wavelength regions have also become accessible (near 630 and 980 nm) but at the same time some manufacturers have narrowed the distribution of wavelengths that are available for a given product.

Some characteristics of diode lasers make them very unique sources of light. First of all they are extremely small with typical gain volumes of 10^{-17} m^3. They are very efficient in terms of electrical conversion to light. In addition their cost is usually low enough and they are simple enough to use that one can consider using many lasers in a single experiment. Their small size results in characteristic optical and electronic time scales that are very short, and conversely and unfortunately laser linewidths that are very broad (10 to 400 MHz). The advantage is that the devices are very fast and allow for high speed modulation of the laser's amplitude and frequency (up to a few GHz). Cw diode laser output powers range from about 3 to 150 mW which is usually adequate for most spectroscopic and precision measurement applications. Unfortunately there is still the problem of incomplete spectral coverage.

The spectral characteristics of both the frequency and amplitude noise of semiconductor diode lasers are unique and affect the way we use them. A

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consequence of their small size is that noise components extend out to Fourier frequencies as high as a few GHz. The amplitude and the frequency noises are coupled and they peak at low frequencies then fall off toward higher frequencies. The distribution of noise reaches a plateau at a few MHz that extends out to another peak in the noise at the relaxation oscillation (about 3 GHz). The noise falls off rapidly above the relaxation oscillation frequency. For a typical AlGaAs laser the integrated frequency noise results in a laser linewidth of about 30 MHz. This linewidth is adequate for many spectroscopic applications but it is a significant problem for high resolution measurements.

Over the past 20 years a number of techniques have been developed to reduce the linewidth, improve the tuning, and stabilize the frequency of diode lasers. Many of these frequency control techniques are simply applications of ideas that have been used with other types of lasers, but because of the unique characteristics of diode lasers these may not be totally satisfactory. Both optical and electronic methods have been used to control the frequency of diode lasers.[5-10] Trade-offs are made in all of these systems with various advantages and disadvantages for each. Table 1 is a qualitative comparison of some of the popular diode laser systems. In this table we make many simplifying assumptions, in particular distinguish between stabilizing the center frequency and narrowing the laser's linewidth. The unmodified solitary diode laser actually has very good performance characteristics other than the broad linewidth and incomplete spectral coverage. A system that is popular for spectroscopic applications is the extended cavity diode laser.[5-7] This typically means a diode laser

Table 1. Qualitative comparison of various diode laser systems. The +, - indicate positive and negative attributes respectively, and both present indicates some positive and some negative characteristics.

TYPICAL PARAMETERS							
	Solitary Diode Laser	**Electronic lock slow**	**Electronic lock very fast**	**Extended Cavity Grating**	**Optical lock**	**Full External Cavity**	**Simple Mirror feed back**
Linewidth	30 MHz	30 MHz	100 Hz	100 kHz	10 kHz	10 kHz	100 kHz
Scanning Range	+ 30 GHz	+ 30 GHz	10 GHz	1 to 10 GHz	1 to 10 GHz	2 GHz	2 GHz
Wavelength Coverage	~ 30%	30%	30%	100%	30%	100%-	80%+
Frequency Stability	+	+ + +	+ + +	+-	+ +	+-	--
Output Power	+ +	+ +	+ +	+-	+	--	+-
Simple	+ + +	+ +	--	+-	+-	---	+ +
Modification Required	+ + +	+ +	+ -	+-	+-	---	+ +
Modulation	+ + +	+ + +	+ +	-	+	--	+-
Amplitude Noise	+	+	+	+ +	+	+ +	+

that has an antireflection coating on one facet so that the laser's resonator can be extended (which reduces the linewidth) while maintaining optical stability. Some frequency selective element (such as a grating) can then be for tuning. Extended cavity lasers with a resonator lengths of a few centimeters typically can be tuned stepwise over a range of about 20 nm and have linewidths of a few hundred kilohertz. By varying temperature and injection current as well as grating tuning an extended cavity laser can provide complete spectral coverage over this range.

Some of the recent work in our laboratories and others has been to develop hybrid optical and electronic systems to control the frequency of diode lasers. For example, by using electronic feedback in conjunction with a grating extended cavity laser one can have broad tunability and very narrow linewidths.[11] By using resonant optical feedback from a high-Q Fabry-Perot resonator it is possible to obtain frequency control and very narrow linewidths,[7-9] and combining that optical locking method with an extended cavity system it may be possible to obtain very high spectral purity while retaining the broad tunability. Figure 1 is a diagram of such an optically locked extended cavity laser system. We have obtained good optical locking with this system and have experimentally measured its ability to suppress the residual frequency noise on the extended cavity diode laser. Preliminary results with an unoptimized system now show stable optical locking but relatively small linewidth reduction factors (about 3). By changing parameters in the extended cavity laser and by increasing the Q of the external Fabry-Perot resonator, we expect that much narrower linewidths will be obtained.

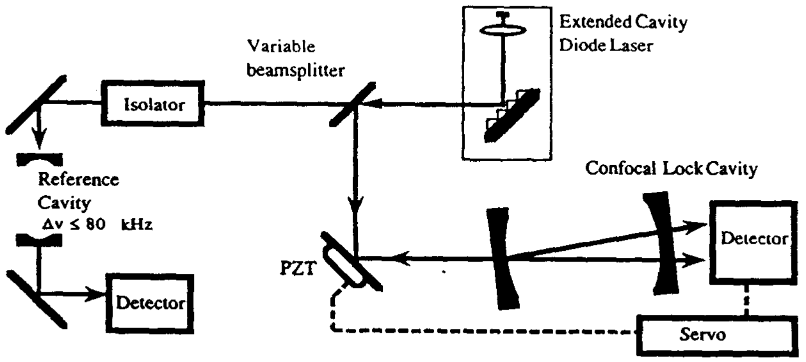

fig. 1. Extended cavity diode laser with resonant optical feedback locking to a confocal Fabry-Perot resonator.

Diode laser's amplitude noise is usually much less than the typical noise level found on other tunable laser sources, at least at low frequencies. Typically amplitude noise levels for AlGaAs diode lasers are approximately 20 dB above the shot noise level for detection frequencies above a few kHz. Both the amplitude and frequency noise depend on Fourier frequency, temperature, and operating point relative to threshold. They are also <u>very</u> sensitive to even small amounts of optical feedback.

As a result the character of the noise on extended cavity diode lasers can differ significantly from the solitary devices as has been reported by Bogatav.[12]

Amplitude fluctuations on diode lasers typically limit direct detection of absorption features to a fractional absorption of about 10 ppm. To improve detection limits we have been exploring the use of electronic feedback to reduce the noise. Using the rapid response of the lasers output power to changes in the injection current it is simple to use a beamsplitter to send part of the laser's output to a detector and then feed back to the injection current to remove amplitude fluctuations. The remaining beam reflected from the beamsplitter is available and has reduced fluctuations. Vacuum fluctuations introduced by the beamsplitter can be viewed as the source of "shot noise", which in the servo controlled case is the limiting noise in the useful transmitted beam. As expected the photocurrent noise within the servo loop appears to be below the shot noise level but the noise in the useful reflected beam is always above the shot noise level for that beam. Using a 50/50 beamsplitter the best the servo can do is to reduce the noise in the useful reflected channel to within 3 dB of the shot noise level. Increasing the transmission of the beamsplitter sends more light to the servo channel and the noise in the useful reflected beam approaches the shot noise level (see fig. 2).

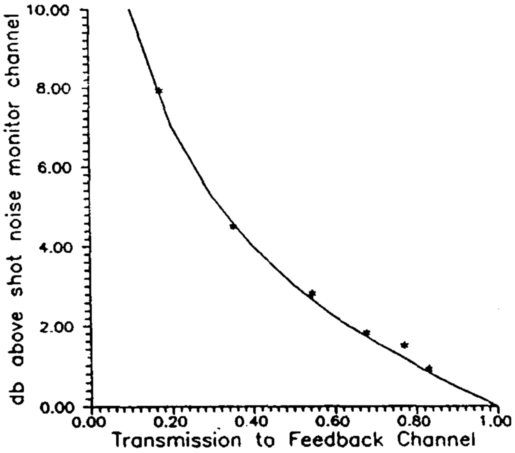

fig. 2 **Intensity noise on the useful output beam as a function of beamsplitter reflectivity. The *'s are experimental data and the solid line is a simple theory assuming a lossless system.**

For example with a typical 10 mW diode laser, a 50/50 beamsplitter and a simple servo system one easily suppresses the typically 20 dB of excess noise and obtains a useful 5 mW output beam with noise that is within 3 dB of the shot noise level (within the servo bandwidth).

The relatively new red diode lasers operating in the wavelength range from 660 to 680 nm (now reported near 630 nm) are of particular interest for precision spectroscopic applications. Noteworthy results in applying these lasers have now been achieved by a number of groups.[13,14] In our collaborative work here at NIST we have been using these red diode lasers to look at absorption in Li, Ca, and I_2.

The Ca intercombination transition at 657 nm is of metrological interest as a wavelength/frequency standard because of its very narrow natural linewidth (400 Hz) and simple spectroscopic structure. Work on this transition by Bergquist et al.[15] and Helmcke et al.[16] demonstrated the potential for using this transition as a optical standard. Limitations in the resolution and accuracy up to now are dominated by velocity dependent effects and the fact that Ca is relatively light and requires a high oven temperature. Fortunately Ca can be laser cooled[17,18] using the resonance line at 423 nm which is easily accessible with dye lasers (now even with frequency doubled diode lasers). Laser cooled Ca can make an important contribution to optical frequency/wavelength standards and with diode lasers the system could be portable and practical.

In recent experiments we have done traditional saturated absorption spectroscopy on the Ca transition using an extended cavity diode laser. Our experience with the red diode lasers is that their spectral properties are much worse and they are much more difficult to control than typical AlGaAs diode lasers operating near 0.8 μm. A scan of the saturated absorption feature on the 657 nm Ca transition is shown in figure 3. The Doppler broadened absorption was approximately 30% and the saturation feature was approximately 2% of the laser power. For these measurements we used 0.4 mW of laser power and the beam retro-reflected back through the calcium vapor served as the "probe" beam.

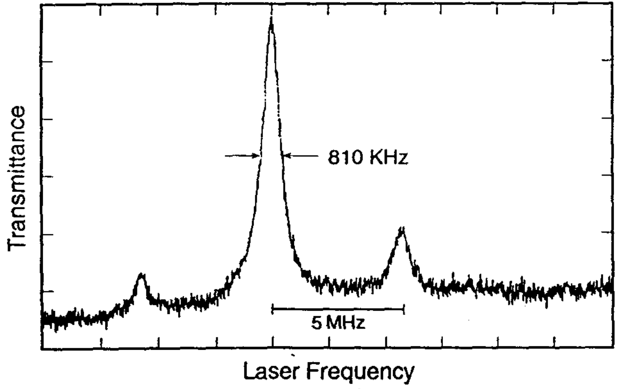

fig. 3 Calcium intercombination line saturated absorption signal taken with a diode laser at 657 nm. The two smaller peaks are modulation sidebands put on the laser for a frequency scale.

Our extended cavity diode laser system is of a rather traditional design[9]. It consists of a laser that we have antireflection coated (single layer Al_2O_3), a collimating objective, and a grating which provides optical feedback to tune and narrow the laser's output. The grating is a special high quality holographic grating that has been designed to work efficiently in Littrow.[19] The diode laser's low noise allowed us to detect the saturation signal with a high signal to noise (S/N ~ 20 in a 300 kHz detection bandwidth). The Ca was heated to approximately 1000 K in a