DIODE LASER SPECTROSCOPY

LASER PHYSICS

Diode Laser Physics

I. LASER BASICS

Beginning in the mid 1960's, before the development of semiconductor diode lasers, physicists mostly used tunable "dye" lasers in pioneering atomic physics experiments needing tunable laser light. Farbstofflaser Dye lasers use a chemical dye as the active medium, *i.e.* the material which produces the laser emission. A population inversion in the dye is created, typically, with a fixed-frequency "pump" laser. An individual dye will lase over a limited wavelength range, and different dyes are available to make tunable lasers at essentially all visible and near-infrared wavelengths. Unfortunately dye lasers are large, cumbersome instruments that are both very expensive to purchase (~$100,000.00) and expensive to operate and maintain. Some of the solid-state lasers used as dye laser replacements, such as the popular Ti:sapphire crystal (titanium-doped sapphire), work better than dyes, and other techniques using non-linear crystals exist to generate tunable laser light (Yariv 1991). However, while these may be less difficult to use than dye lasers they are still very expensive options.

The recent development of tunable, narrow-bandwidth, semiconductor diode lasers dramatically changed this picture. These lasers are inexpensive, easy to operate, and produce high-power, tunable, narrow-bandwidth radiation ($\Delta\nu < 1$ MHz, $\Delta\lambda < 1.5\times10^{-6}$ nm). For these reasons, tunable diode lasers have rapidly become commonplace in modern research laboratories.

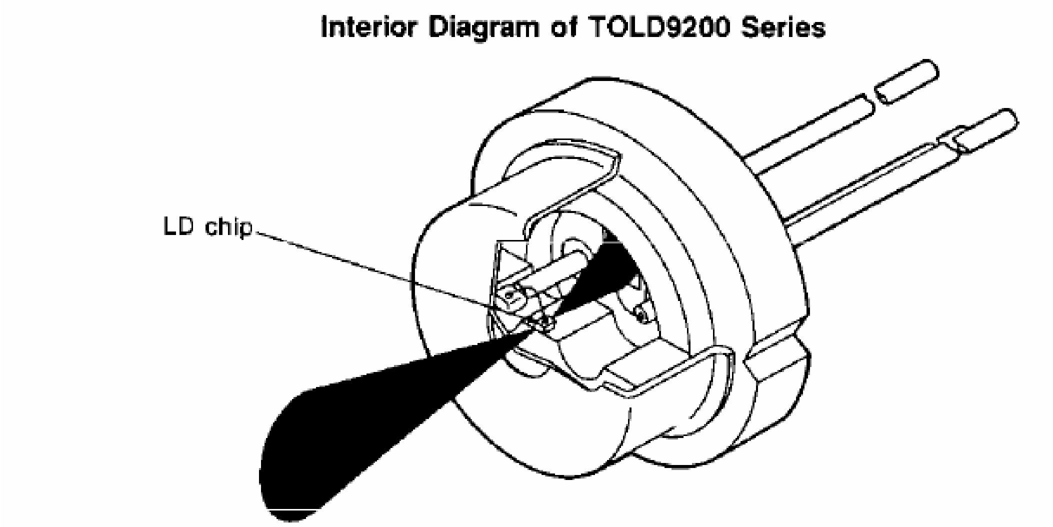

Figure 1: Cut-away view of a typical laser diode can, like those used in the TeachSpin laser

The basic physics of diode lasers is presented in several review articles and books, such as Wieman and Hollberg (1991) and Camparo (1985). Figure 1 shows a cut-away view of a typical diode laser, similar to the ones used in this experiment. The actual semiconductor device is a small chip (LD chip in Figure 1), bonded to a heat-sink. Tiny wires connect the chip to the outside world. Most of the light emitted by the laser comes out the front facet, and a small amount also comes out the back facet. (The two facets are constructed to have different reflectivities). Often, a photodiode is placed at the back of the can, to monitor the laser output power. The main laser beam, which is elliptical and strongly diverging, comes out a window in the front of the laser diode can.

Figure 2 shows a more detailed view of a typical laser diode chip. Current is driven from the top to the bottom of the chip (see arrow in Figure 2), creating electron-hole pairs that recombine in the active layer, emitting light in the process. The light is confined to a narrow channel in the chip, ~2 Mikrometer microns high, ~10 microns wide, and about 400 microns long (wavy line in Figure 2). The facets of the chip, at the ends of the channel, act as partially reflecting mirrors enclosing the laser cavity.

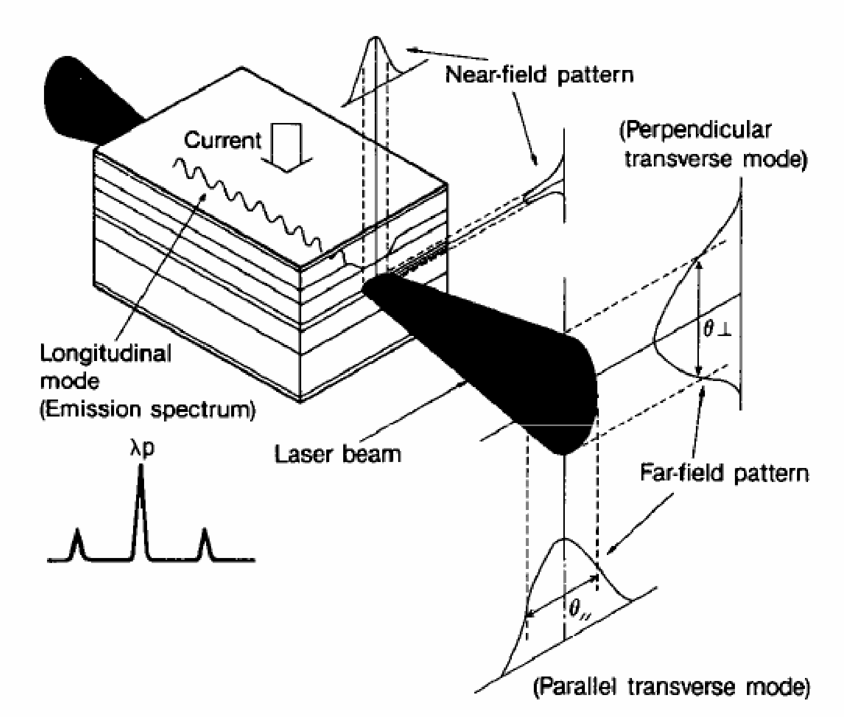

Figure 2: Schematic view of a laser diode chip

Figure 3 shows a schematic picture of the actual semiconductor layer structure in a diode laser. How all this *really* works, the nitty-gritty semiconductor technology, is not something we will concern ourselves with in this discussion. Since light generation in a diode laser results from the recombination of electron-hole pairs injected into an active layer at the diode's n-p junction, the wavelength of the emitted light is approximately that of the band gap of the material. The electron-hole population inversion is restricted to a narrow strip in the active layer, so the laser's optical gain is spatially localized. Gain is the amount that an optical wave is amplified by stimulated emission as it passes through the laser cavity. The diode heterostructure also serves as an optical waveguide; the active layer has a higher index of Brechung refraction than its surroundings, so light is confined to the channel by total internal Totalreflexion refection. The gespalten cleaved facets at the end of the chip serve as the cavity mirrors and output couplers. These can be coated to increase or decrease the facet reflectivity.

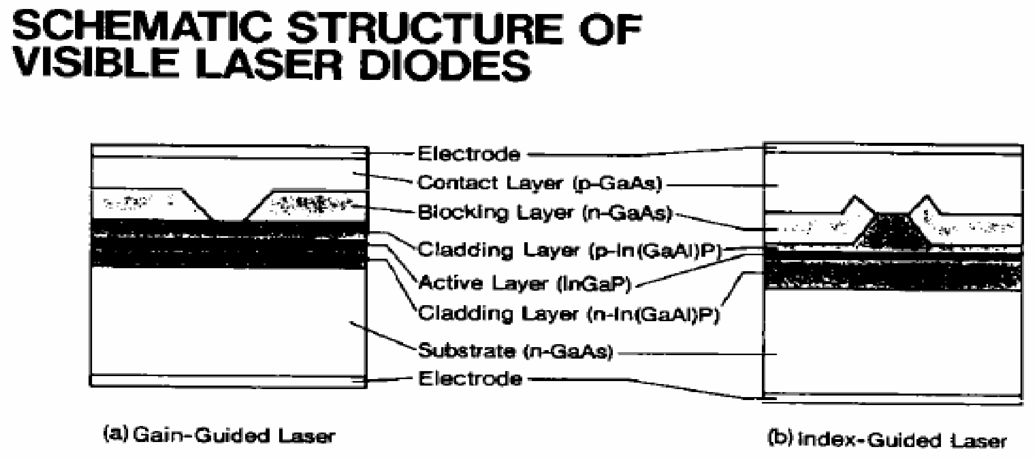

Figure 3: Schematic picture of the internal semiconductor structure of some typical laser diodes. This view is looking into one facet of the laser cavity.

By careful construction of the diode cavity, the laser can be made to emit in a single longitudinal cavity mode (*i.e.* a standing wave inside the cavity, with a fixed number of nodes along the cavity axis and no nodes in the transverse direction). A "bare" diode laser has a linewidth of typically $\Delta\nu \sim 50$ MHz. The räumlich spatial mode of the laser, and thus the shape of the output beam, is defined by the narrow channel that confines the light. Since the channel is rectangular, and not much larger than the light wavelength, the output beam is elliptical and strongly divergierend diverging (see Wieman and Hollberg 1991).

At low levels of injection current, the optical losses überschreiten exceed the gain and a population inversion is not achieved. The light output is then broad-band, spontaneous emission, similar to that of an LED. But, above a "threshold" current, the laser emits a coherent beam, which increases in intensity linearly with injection current. The output power in coherent radiation can be as high as 50 percent of the input electrical power, which is very efficient compared with other methods of producing laser light.

Diode lasers have many uses; primary among these are abrufen retrieving data stored on optical disks (for instance all compact disk players use diode lasers) and sending light pulses down optical fibers for telecommunications. At present, one can purchase diode lasers that operate at wavelengths from the blue to the infrared; there is a big push in industrial labs to produce shorter wavelength lasers, in order to increase the density of optical disk storage. Power levels for single-mode diode lasers are typically a few mW, but can be as high as 1 Watt.

The TeachSpin diode lasers (Sanyo DL-7140-201S) emit up to 70 mW of output power near 785 nm. The back surface of the tiny semiconductor laser cavity is highly reflecting, while the front surface is often coated with a thin antireflection layer to enhance its transmission. (Only the manufacturer knows exactly how the facets are prepared; such details are often carefully guarded industrial trade secrets.)*

* It is possible to get an approximate measure of the reflection coefficient, R = 16.5% ± 5%. (See section A4-2 for details.)

II. LASERS WITH GRATING FEEDBACK or External Cavity Diode Lasers (ECDL)

A. Introduction

Bare diode lasers have two undesirable properties: 1) their linewidths ($\Delta\nu \sim 50$ MHz) are large compared to the linewidths of atomic transitions (in our case $\Gamma \sim 5$ MHz); and 2) they are extremely sensitive to optical feedback – as little as 10^{-6} of the output light scattered back into the laser may affect its frequency stability. As shown in Figure 4, we overcome both these problems by using a diode laser with a small amount of controlled feedback from a diffraction grating. Beugungsgitter

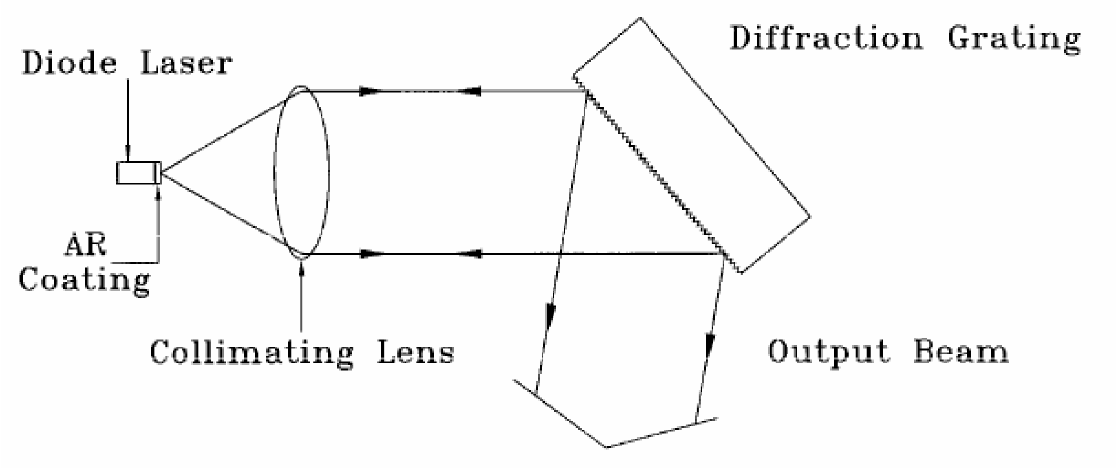

Figure 4: Basic configuration of the diode laser system

A lens in front of the laser collimates the output into a nearly nondiverging elliptical beam. After the lens, the beam strikes a diffraction grating, which is a holographic (no blaze) grating with 1800 lines/mm. Most of the light is directly reflected by the grating (m=0 grating order), but roughly 15 percent is reflected back into the laser (m=1 order). The grating forms an "external cavity" (*i.e.* external to the laser's own internal semiconductor cavity), which serves to frequency-stabilize and Fokussieren? line-narrow the laser output (see Wieman and Hollberg 1991, and references therein, to understand how this happens). With the simple addition of the diffraction grating, the laser is much less sensitive to stray light feedback, and its linewidth will be reduced to $\Delta\nu < 1$ MHz, much smaller than the atomic transition linewidths we will be observing.

B. Laser Tuning:

With grating feedback, the frequency of the laser output depends on a number of factors. In order for you to effectively tune the laser to an atomic transition, it is helpful to understand how these factors determine the laser output frequency. The laser will tend to lase at the mode frequency with the greatest net gain (*i.e.* stimulated emission minus optical losses) (see Yariv 1991). Once the laser begins to lase in this mode, stimulated emission limits the number of electron-hole pairs which are available for lasing in other modes, and the result is a laser with a single-mode (*i.e.* single frequency) output beam. (Note: This does not always happen. Our lasers will sometimes lase in two or more modes at the same time, and sometimes the output frequency will vary rapidly and chaotically over a broad frequency range. While these behavior patterns are interesting, and the subject of some amount of research, we will mainly try to find a place in parameter space where the laser operates in a single mode.) To determine the laser operating frequency (assuming single-mode operation), we need to find the frequency with the highest net gain. Figure 5 shows, schematically, the different contributions to the net gain. These contributions are best explored individually.

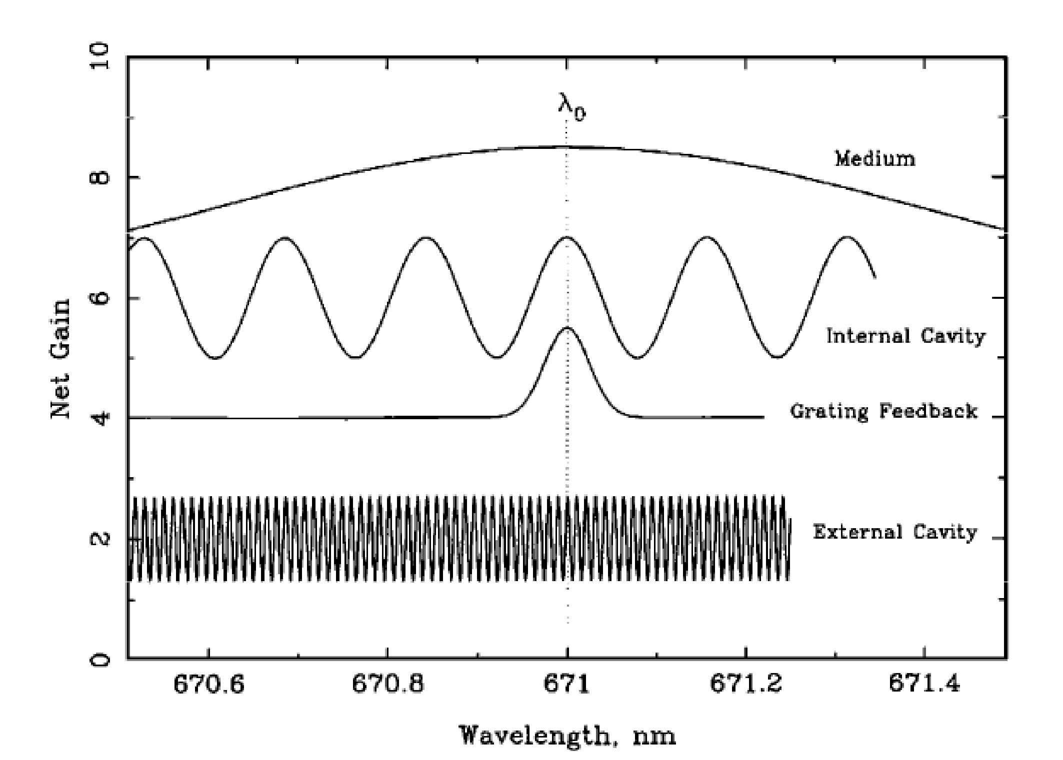

Figure 5: Schematic of the different contributions to the net optical gain of an arbitrary laser as a function of frequency. The curves are displaced relative to one another for clarity.

1. The medium gain

This depends on the properties of the semiconductor material from which the laser is made, in particular the band gap. The medium gain shows a broad peak in frequency space, whose position depends mainly on laser temperature. Since we are aiming for the rubidium atomic transition, we must set the laser temperature, using the temperature controller, so that it operates near 780 nm, the wavelength of the rubidium resonance lines. This temperature is recorded on the antistatic bag in which each diode is shipped. The temperature for the diode that was shipped in your laser is listed on the data sheet included in your manual.

A plot of Wavelength versus Temperature for a typical laser is shown in Figure 6. The overall slope of this data is about 0.23 nm °C^{-1}, which should be about equal for all the Sanyo diodes. From this slope and the temperature set point for 780 nm, you can determine an appropriate temperature for any desired wavelength for that specific diode. Once this is done, the medium gain curve is so broad that it is unimportant for determining the precise wavelength of the laser.

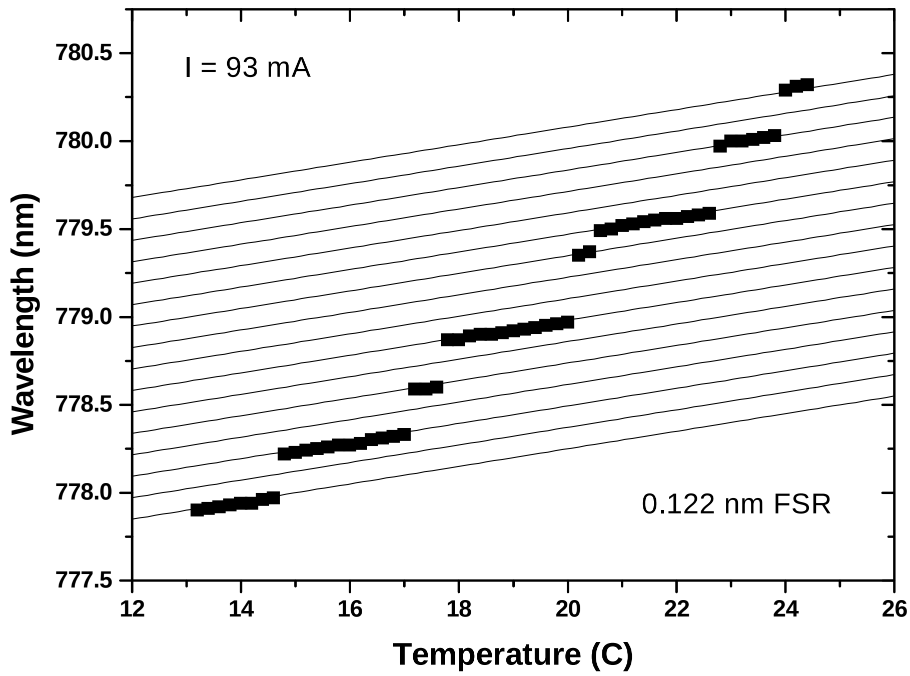

Figure 6: Output wavelength of a free-running (*i.e.* no external optical feedback) Sanyo DL-7140-200S diode laser as a function of diode temperature. (The behavior of other diode lasers is similar.)

2. The internal cavity

The diode junction forms a small Fabry-Perot etalon, or optical cavity, and like all optical cavities, it has a normal mode structure. This translates to an effective frequency-dependent net gain function which is periodic in frequency, as shown in Figure 5 (see Yariv 1991 or Möller 1988 for a discussion of optical cavities). The period is called the "free spectral range", and is given by $\Delta\nu_{FSR} = c/2Ln$, where *c* is the speed of light, *n* is the index of refraction ($n \approx 3.6$ in the semiconductor), and *L* is the cavity length. For this particular laser we have $\Delta\nu_{FSR} \approx 60$ GHz ($\Delta\lambda \approx 0.122$ nm). The internal cavity gain function will shift in frequency with changes in the diode temperature at roughly 0.05 nm °C^{-1} this is measured from the small scale slope the individual steps in Figure 6. Unfortunately, the temperature of the laser head can not be changed very quickly. The thermal time constant of the laser head can be estimated to be on the order of 10 seconds.* The internal cavity modes will also change with the diode current. (See Figure 7.)

* Estimated from the mass (≈170grams), heat capacity and thermal conductivity, assuimng the laser head is a solid cube of aluminum with the TEC on one face and the diode and temperature sensor at the center .

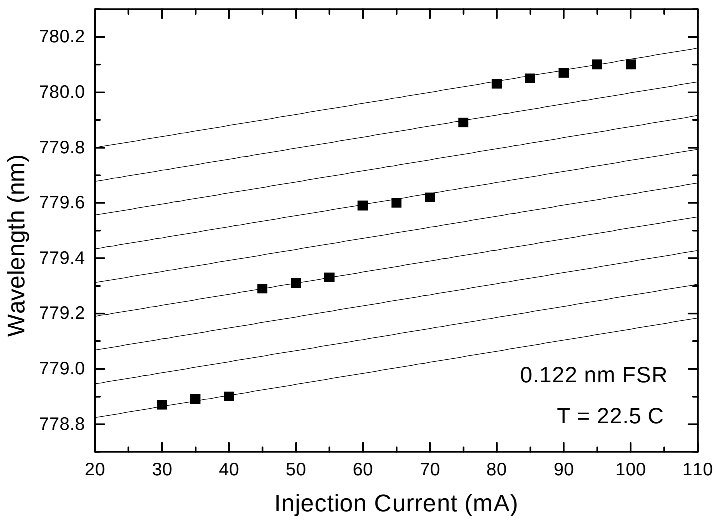

Figure 7: Free-running laser Wavelength versus Injection Current at a fixed temperature

The current affects a diode in two ways. First, increasing the current causes simple heating, which changes the temperature of the diode and thus the wavelength in much the same way as heating the laser head directly. With respect to wavelength, modulating the current can be thought of as a means of rapidly changing the diode temperature. This effect predominates for time scales longer than 1 µs and tunes at roughly 2 GHz/mA as shown in Figure 7. The second means by which the current changes the free-running laser wavelength is by changing the carrier concentration in the active region. This modulates the optical path length of the diode, with a tuning rate of about 200 MHz/mA, up to a maximum frequency that is set by the relaxation oscillation frequency of the diode, typically several GHz.

Taken together, Figures 5 - 7 demonstrate the interaction of several influences. Figure 6 shows a plot of the wavelength of a free-running laser as a function of temperature. As the temperature is increased, the maximum gain of both the medium and the internal cavity modes shown in Figure 5 will shift to longer wavelengths. They do not, however, shift at the same rate. This creates laser "mode hops" to different peaks of the cavity gain function. In practice, we would like to set the temperature and injection current so that the laser operates at the rubidium resonance frequency. But, as can be seen from Figure 6, this is not always possible with a free-running laser. With the addition of an external grating, the laser can be made to operate at any wavelength within a reasonably broad range.

3. The Grating Feedback

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Since a grating disperses light, only light from a narrow wavelength band will be fed back into the laser for a fixed grating left/right (L/R) angle. (The grating up/down (U/D) angle should be set so that the light from the grating reflects back into the laser.) In this apparatus, the grating is used in a Littrow configuration where the first order diffraction is sent back into the diode. In this configuration, the wavelength can be found from $\lambda = 2\, d \sin\theta$, where d is the line spacing of the grating and θ is the grating angle (measured from the normal). Assuming an ideal grating, where the resolving power is limited only by diffraction, the spectral width of the first order diffraction, $\Delta\nu$, will be given approximately by $\nu/\Delta\nu = N$, where ν is frequency and N is the number of grating lines subtended by the laser beam (see Möller 1988 or any general optics book, for a discussion of grating properties). For example, with a zu Frequenz umrechnen 0.3 cm laser beam width, we will find N = 5400 and $\Delta\nu \approx 70$ GHz. The position of this peak is determined by the grating L/R angle.

4. The external cavity

This is similar to (2) above, but with the external cavity, one end of which is the grating, and the other is the highly reflective back facet of the diode. Since the external cavity is much larger we have $\Delta\nu_{FSR} = c/2L \approx 10$ GHz. for a 15 mm external cavity length. (See Section A.4 and Figure A.4.1 for the relevant dimensions.) This curve shifts by moving the grating position, which we do either with the L/R knob on the laser head or with the piezo-electric transducer (PZT) in the grating mount.

In order to force the laser into single-mode laser operation at a predetermined wavelength λ_0 (e.g. an atomic resonance line), the gain from each of the components should peak at λ_0 as shown in Figures 5.

To get a more complete understanding of how these contributions interact, how the laser tunes as the grating angle is changed, we have tried to construct an accurate "best guess" picture of the shape of the various cavity modes in the laser. This picture is shown in Figure 8. Referring back to Figure 5, the grating feedback and external cavity gains have been merged into the single solid line of Figure 8. The broad medium gain has been left out of the plot. Figure 8 is a picture of the various cavity modes with all the gains having a maximum at the same frequency.

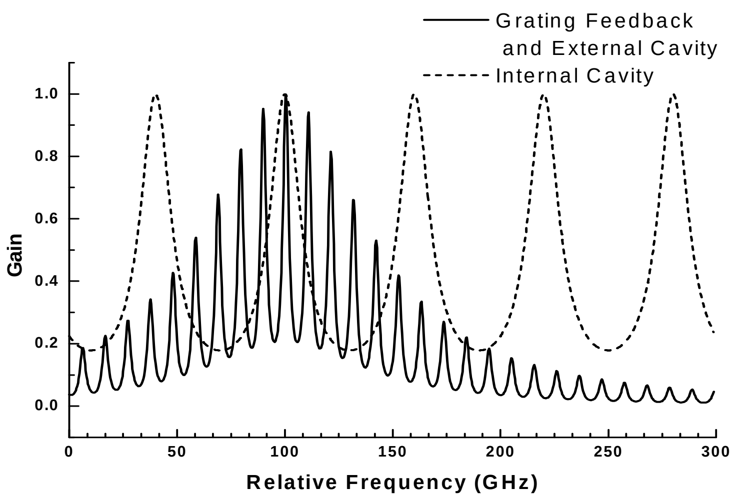

Figure 8: "Best guess" picture internal cavity, grating feed back and external cavity modes in the laser

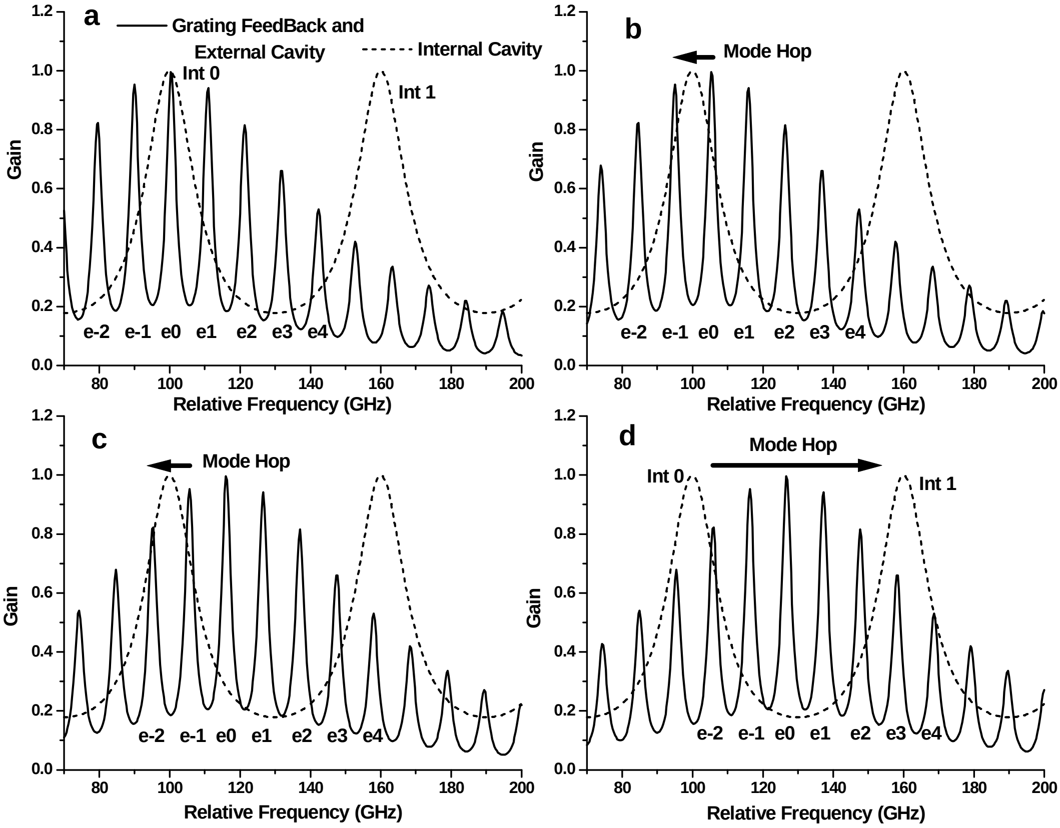

Figure 9: Series of graphs showing showing how the external and grating feed back mode shifts as the grating angle is changed.

Figure 9 shows a series of pictures of the External and Internal cavity modes as the grating angle is decreased. The pictures show only two of the internal modes labeled Int 0 and Int 1. For reference, we have also labeled some of the external modes e-2, e-1, e0, e1…e4. In Figure 9, Graph **a** is for the same grating angle shown in Figure 8, where the laser is oscillating in external mode e0. As the grating angle is decreased, mode e0 is shifted to higher frequency, shorter wavelength, until the point shown in graph b. At this point, the overall gain in external mode e-1 is about equal to that in mode e0 and, as the grating continues to move, the laser will jump into mode e-1. As the angle is decreased further, the laser will reach the point shown in graph c and the laser will hop to mode e-2. Finally, in graph d, the maximum of the grating feedback frequency is about half way between internal modes Int0 and Int1. As the angle continues to decrease, the laser will make a relatively larger mode hop and lase in external mode e3 under internal mode Int1.

You should notice that during this change in angle, the laser has swept through the same small frequency range "under" Int0 several times. After these changes, the laser moved to a new frequency defined by Int1 with a rather large gap of frequencies in between. To be able to cover the entire frequency range, we need to be able to change the position of the internal modes. This is done by changing the laser current. To tune the laser to the correct wavelength for the rubidium transitions, both the correct grating angle and laser current must be found. The procedure for doing this is discussed in the next section. The next section will also describe a clever trick in which both the grating angle and laser current are swept simultaneously at rates such that both the internal mode Int0 and the maximum of the external modes e0 change in frequency together resulting in long (20 GHz) mode hop free scans. An understanding of the Figures 8 and 9 should help you visualize how this is accomplished.

III. REFERENCES.

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