

# Ph 77 ADVANCED PHYSICS LABORATORY

## – ATOMIC AND OPTICAL PHYSICS –

### Diode Laser Characteristics

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#### I. BACKGROUND

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. 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 ( $\sim \$100,000.00$ ) and expensive to operate and maintain. Some solid-state dye 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, since these lasers are inexpensive, easy to operate, and produce high-power, tunable, narrow-bandwidth radiation ( $\Delta\nu < 1$  MHz,  $\Delta\lambda < 1.5 \times 10^{-6}$  nm). For these reasons tunable diode lasers have rapidly become commonplace in modern research laboratories.

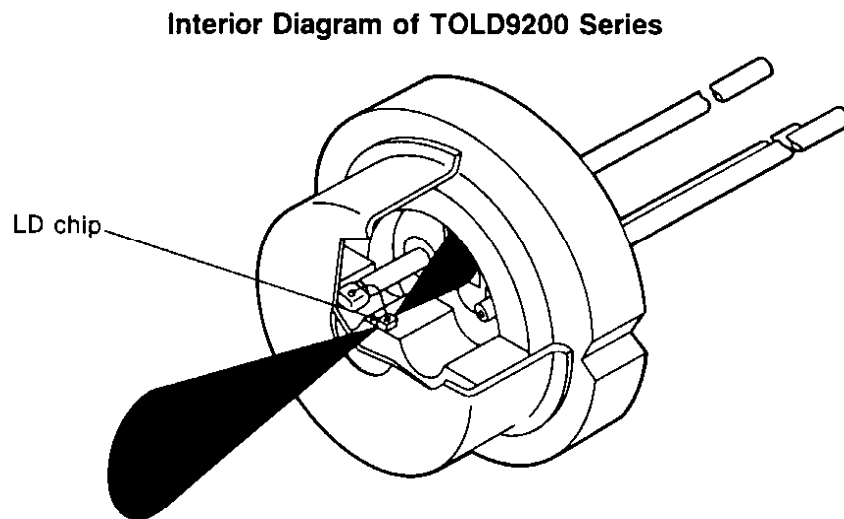


Figure 1. Cut-away view of a typical laser diode can, like those used in the Ph76 lab lasers.

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

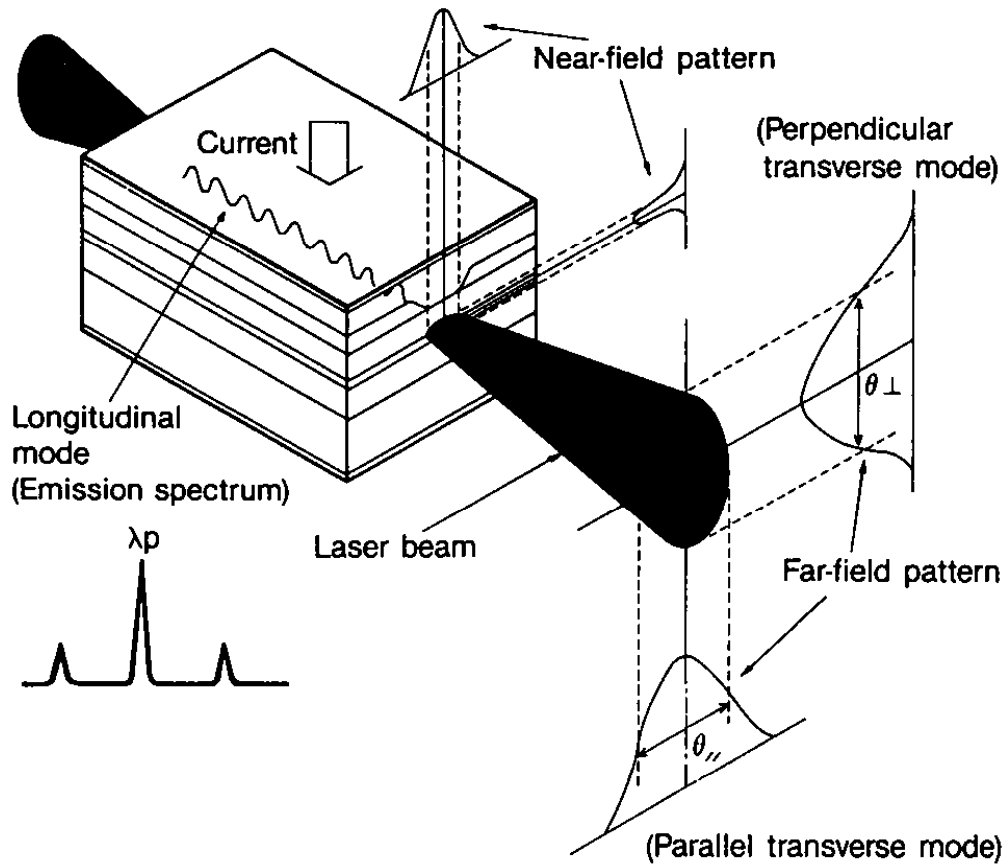


Figure 2. A close-up schematic view of a laser diode chip.

the ones used in this class. 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 close-up 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,  $\sim 2$  microns high,  $\sim 10$  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.

Finally, Figure 3 gives you a schematic picture of the actual semiconductor layer structure in a diode laser, for those interested. How all this *really* works (the nitty-gritty semiconductor technology) is not something we will worry too much about in this class. 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

## SCHEMATIC STRUCTURE OF VISIBLE LASER DIODES

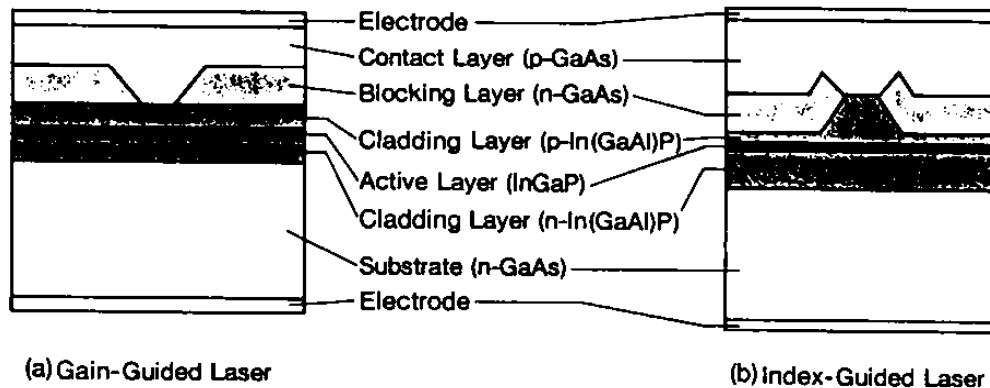


Figure 3. Schematic picture of the internal semiconductor structure of some typical laser diodes. This view is looking into one facet of the laser cavity.

population inversion is restricted to a narrow stripe 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 refraction than its surroundings, so light is confined to the channel by total internal reflection. The 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.

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 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 diverging (see Wieman and Hollberg 1991).

At low levels of injection current, the optical losses 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 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 Ph77 diode lasers, similar to those used in common laser pointers, emit up to 50 mW of output power near 670 and 780 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.)

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. We overcome both these problems by using a diode laser with a small amount of controlled feedback from a diffraction grating, as is shown in Figure 4.

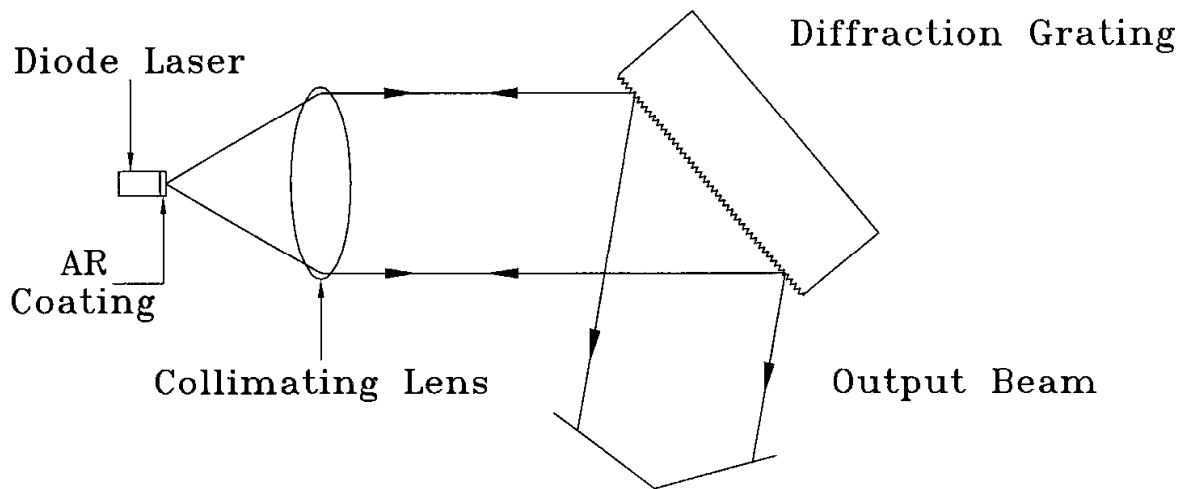


Figure 4. Basic configuration of the diode laser system used in the Ph 76 lab.

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 2400 lines/mm. Most of the light is directly reflected by the grating ( $m=0$  grating order), but roughly 20 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 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.

**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.

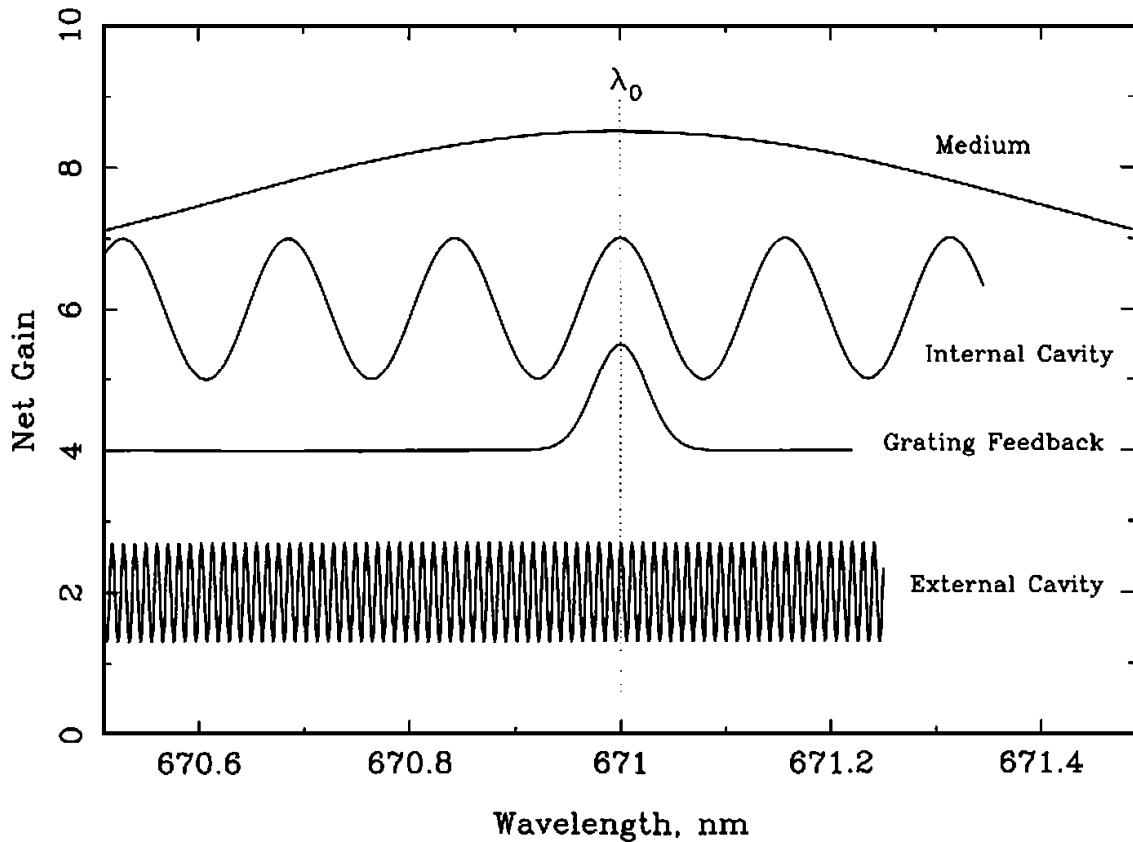


Figure 5. Schematic of the different contributions to the net optical gain of the laser as a function of frequency. The curves are displaced relative to one another for clarity.

(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. Considering these separately, as shown in the figure, we have:

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 gain from this contribution shows a broad peak, whose position depends mainly on laser temperature. If we were aiming for the lithium atomic transition, we would set the laser temperature using the temperature controller so that it operates near 671 nm, the wavelength of the lithium resonance lines. Once this is done, the medium gain curve is so broad it is unimportant for determining the precise wavelength of the laser.

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 laser we have  $\Delta\nu_{FSR} \approx 50$  GHz ( $\Delta\lambda \approx 0.08$  nm). The cavity gain function will shift in frequency with changes in the diode temperature and current; roughly 3 MHz/ $\mu$ A at fixed temperature.

Figure 6 shows a plot of the frequency of a free-running laser as a function of temperature, for various injection currents. As the temperature is increased, the peaks of both the medium gain and the internal cavity gain curves shift to longer wavelengths. However they do not shift at the same rate, and the result is that the 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 lithium resonance frequency. However it can be seen from Figure 6 that this is not always possible with a free-running laser; however, with an external grating the laser can usually be made to operate at any wavelength within a reasonably broad range.

**3) The grating feedback** – 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 the light from the grating reflects back into the laser.) Assuming the diffraction limit of the grating, the spectral width of the grating feedback in first order will be given approximately by  $\nu/\Delta\nu = N$ , where  $\nu$  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 0.5-cm laser beam width,  $N = 9000$  and  $\Delta\nu \approx 50$  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, rather than the internal cavity. Since the external cavity is much larger we have  $\Delta\nu_{FSR} \approx 5$  GHz. This curve shifts by moving the grating position, which we do with a piezo-electric transducer (PZT) in the grating mount.

In order to force the laser into single-mode laser operation at a predetermined frequency  $\nu_0$  (e.g. an atomic resonance line), the gain from each of the components should peak at  $\nu_0$  as shown in Figure 5.

### III. REFERENCES.

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Möller, K. D. 1988, *Optics*, (University Science Books).

Wieman, C. E. and Hollberg, L. 1991, “Using Diode Lasers for Atomic Physics,” *Rev. Sci. Instrum.* **62**, 1.

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### Output Wavelength of typical TOLD 9215 Diode Laser

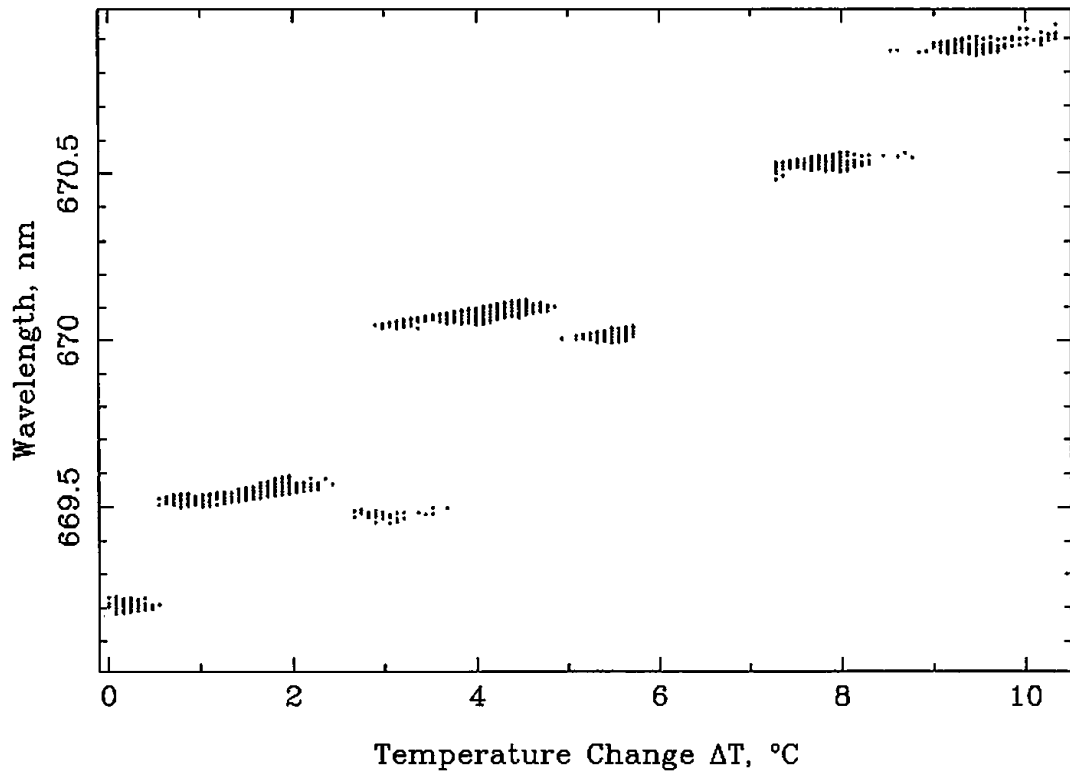


Figure 6. Output wavelength of a free-running (*i. e.* no optical feedback) Toshiba TOLD 9215 diode laser as a function of diode temperature. (The behavior of other diode lasers is similar.) The different dots at each temperature are for different injection currents; higher currents give longer wavelengths. The different ridges are for different modes of the internal laser cavity. Note the large mode hops, and the fact that at some temperatures the diode will not operate single-mode at any injection current. The details of this plot will vary from laser to laser.