Mode transitions of an external cavity diode laser

by Steven Carl Sahyun

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Physics
Montana State University

Abstract:
Control over a diode laser's wavelength can be accomplished by an external cavity grating system whereby light of the desired frequency can be systematically returned into the lasing medium of the diode. This feedback augments a particular mode in the diode's spectrum and allows for tuning of the laser. Two possible configurations will be mentioned, Littrow and grazing incidence, with the emphasis of the study on the former. There are several graphs demonstrating the tuning characteristics of the external cavity laser. Also, the tuning range of the Littrow cavity will be shown to be greater than 11 nm for a 780 nm laser and have a frequency peak width of less than 1.7 MHz.

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Steven Carl Sahyun

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ABSTRACT

Control over a diode laser's wavelength can be accomplished by an external cavity grating system whereby light of the desired frequency can be systematically returned into the lasing medium of the diode. This feedback augments a particular mode in the diode's spectrum and allows for tuning of the laser. Two possible configurations will be mentioned, Littrow and grazing incidence, with the emphasis of the study on the former. There are several graphs demonstrating the tuning characteristics of the external cavity laser. Also, the tuning range of the Littrow cavity will be shown to be greater than 11 nm for a 780 nm laser and have a frequency peak width of less than 1.7 MHz.

CHAPTER 1

INTRODUCTION

A wide range of diode lasers are now manufactured which have lasing wavelengths in the regions of 450, 670, 780, 1300, or 1500 nm. The advantages of these lasers are their extremely compact size, high efficiency, and relatively high output powers (maximum outputs range from 3 to 250 mW) which make them one of the most convenient lasers ever developed.

Despite these advantages, diode lasers can be somewhat unpredictable. The particular wavelength that lases not only varies between diodes, depending on the precise manufacturing details, but also varies for an individual laser depending on injection current and temperature of the diode. Some lasers have even been found to spontaneously change their wavelength in mode hopping experiments.[1]

Because there is a wide range of wavelengths where a diode will lase, and the possibility that a diode will lase at several wavelengths at once, some control of the diode is desirable. The addition of an external cavity provides the ability to single out and change the wavelength at which the diode will lase. The construction and tuning properties of several diodes are studied in this work.

The applications for a diode laser which is tunable over several nanometers are numerous. A stable, single wavelength is necessary in holography. For optical communications, many separate frequencies can be transmitted on the same optical fiber thus increasing the communication bandwidth of the line. In many atomic transition experiments, the absorption of a particular energy is needed. By tuning a diode across this transition energy, valuable information can be gleaned. A tunable diode is also useful in the trapping and cooling of single atoms where precise control of energy is necessary.[2]

CHAPTER 2

THEORY

Each diode laser produces a broad spectral emission. The peak of this emission varies between lasers due to the dopant levels in the GaAlAs which makes up the diode, differences in the p-n junction, and the physical size of the laser.[3]

The broad spectral emission region is constrained by a necessary intensity level whereby the diode will have enough gain at a particular wavelength to produce a population inversion with resulting lasing action.[4] This amount of gain is called the lasing threshold level. A discussion and sample calculations on the gain profile across the p-n junction of a diode laser are found in Appendix A.

The particular wavelength at which the diode will lase is further constrained by the diode-air interfaces called the laser facets. The spacing of these regions creates a cavity in which the photons can circulate with a resultant lasing action. The laser facets are generally either made by polishing the ends or, preferably by cleaving the chip,[5] creating a mirrored surface due to the index change at the interface. However, some higher powered lasers have one highly reflecting facet and the other anti-reflection coated,[6] which proves advantageous for tuning purposes.

Ideally, the wavelengths which can exist within the cavity facet walls must have an integral number of half wavelengths: $nL = m\lambda/2$, where n is the index of refraction of the lasing medium. Now, different wavelengths exist for different values of m given a constant L. The different wavelengths therefore correspond to the facet modes of the laser. The resulting difference in the wavelengths of two successive modes is $\Delta\lambda = \lambda^2/2Ln$. Conversely, if the wavelength difference is known, the cavity length can easily be found. These calculations are shown in Appendix B.

Thus, from a broad spectrum of possibilities, only those wavelengths matching the facet boundary conditions give rise to possible lasing action. In most lasers which circulate photons within their cavity only the mode which has the highest gain will lase. This can be due to only a very small difference between the intensities of two neighboring modes. After only a few round trips through the amplifying medium, a huge difference in the mode intensities results which has a ratio on the order of 10^{12}. A particular mode can then be preferentially selected, and once this happens there is a strong partiality for the laser to remain in the selected mode.[7]

There are two ways to change the mode which lases in the diode. One way is to change the gain profile and where the modes are in relation to it. This can be accomplished by several methods which alter the diode. If the effective cavity length of the diode is changed, either by modifying the index of refraction or by thermal expansion, a different wavelength will then fit inside the cavity and the mode will shift. Also, by changing the diode's input current (thus the applied voltage,) a change in the gain profile will occur and alter which mode has the maximum gain.[8]

The alternate method for mode selection is to change the lasing threshold with respect to the wavelength gain profile. If the threshold level can be altered such that the gain necessary for a mode in which the diode preferentially lases is substantially increased, and the neighboring mode's threshold is reduced, then the laser will switch to the new mode. This is because the determining factor as to which mode will lase is the gain above the threshold level.

One way this tailoring of the threshold level can be accomplished is by the use of a diffraction grating. The grating will return light of a particular frequency to the diode which effectively increases the reflectivity of one of the laser's facets and results in a reduced threshold level. The gain above the threshold level is thus increased at the desired wavelength and this is seen as tuning of the diode's wavelength. The reduction in the threshold level also allows for the ability to lase over a larger range of the diode's spectrum than is seen in a free-running diode. Details are provided in Appendix C.

The reduction of the threshold level for a particular wavelength by a grating can also be viewed as an increase in the circulating power in the laser at the desired wavelength. This increase of the intensity at a particular wavelength due to the grating is commonly called feedback. By changing the frequency of the feedback, the laser is in effect tuned to that wavelength.

The application of a grating also creates an external cavity. If reflection from the front facet of the diode did not exist, perhaps due to a very good coating process, then the cavity formed by the diode's back facet and the grating would have many modes spaced close together. In Appendix B it is shown that the cavity length $L = \lambda^2/2n\Delta\lambda$. For a cavity, the frequency spacing is $\Delta\nu = c/2Ln$, or substituting L, $\Delta\nu = c\Delta\lambda/\lambda^2$. An example of how this affects the mode structure of the plain diode and the external cavity lasers here is shown in Figure 1.

The differences between the modes shown in Figure 1 are for a diode which lases at 781 nm. This corresponds to the Mitsubishi laser studied. The facet mode separation for this laser was $\Delta\lambda = 0.275$ nm $\Rightarrow \Delta\nu = 135$ GHz. This value is compared to an 11 cm external cavity which has $\Delta\lambda = 0.00277$ nm $\Rightarrow \Delta\nu = 1.36$ GHz. Thus there are about 100 external cavity modes in the spacing between 2 facet modes.

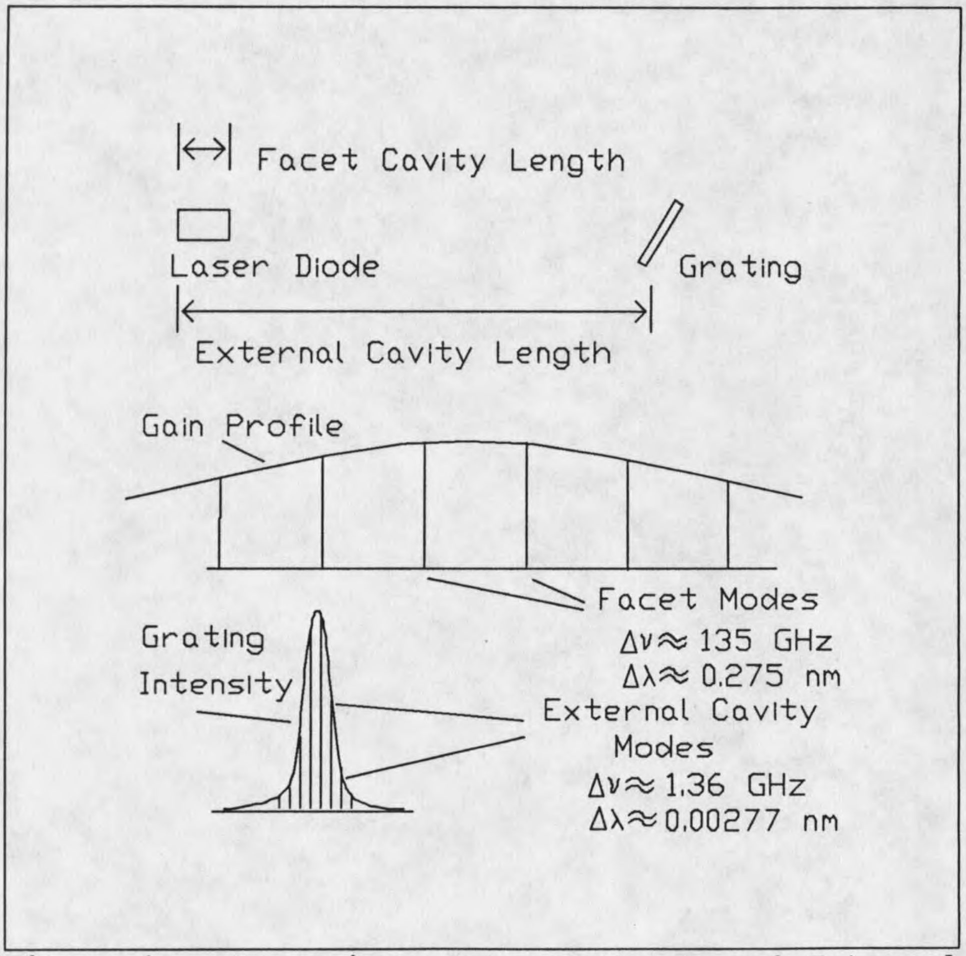

Figure 1. Comparison Between Facet and External Cavity Modes

The front facet of the diode plays a strong part in determining where one will find lasing modes, and only a few external modes will lase about the facet mode regions. For lasers which have an anti-reflection coating, the facet modes do not give as strong a mode confinement so more external modes are allowed. In an ideal case, the effect of the front surface would be completely removed and any external cavity mode could then be chosen.

Also, if the length of the external cavity is changed, there will be a corresponding alteration of the lasing frequencies. Any frequency under the gain profile could be picked. Unfortunately the front surface does play a strong role and only modes close to the diode's cavity modes can be selected.

CHAPTER 3

EXPERIMENT

External Cavity Configurations

The first order diffracted light from a grating will separate the cavity modes, both facet and external, of the diode. If the proper geometry is used, a particular laser mode can be selected by redirecting that light back into the diode. This has the effect of increasing the reflectivity of one of the facets and the threshold level of that wavelength is reduced. Two geometrical configurations, Littrow and grazing incidence, are generally utilized to accomplish this process.[9,10] (Figure 2)

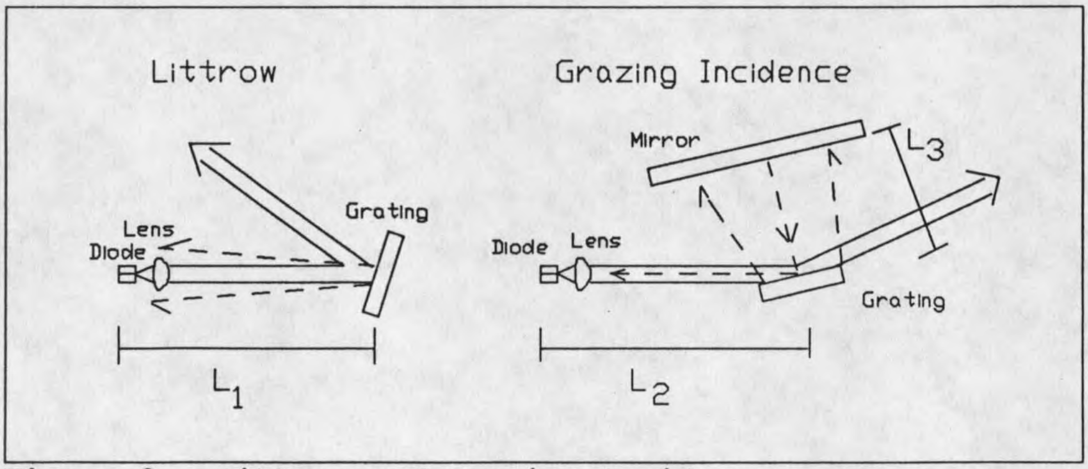

Figure 2. Littrow and Grazing Incidence External Cavities.

In this picture, the emitted light from the laser is represented as a solid line and the first order diffracted light is the dashed line. In the Littrow case, the first order returns directly to the diode so the external cavity length is simply L_1. In the grazing incidence system, the first order is sent to a mirror and then returned to the laser. The external cavity length in this case is $L_2 + L_3$.

Table I. Diffraction Efficiencies in the First Order for Three Gratings at Two Wavelengths.

Grating	Lines/mm	Polarization in relation to grating lines	% Diffraction 633	789
Littrow	1200	‖	89	45
		⊥	63	43
Littrow	1800	‖	21	8
		⊥	62	25
Grazing	1800	‖	15	9
		⊥	45	34

Note: Polarization is parallel to diode interface.

As can be seen in Table I, the Littrow system has a higher diffraction efficiency when compared to the grazing incidence, but the latter has the advantage that the output beam remains at a constant angle. It was found that for