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

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APPROVAL

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Steven Carl Sahyun

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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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.

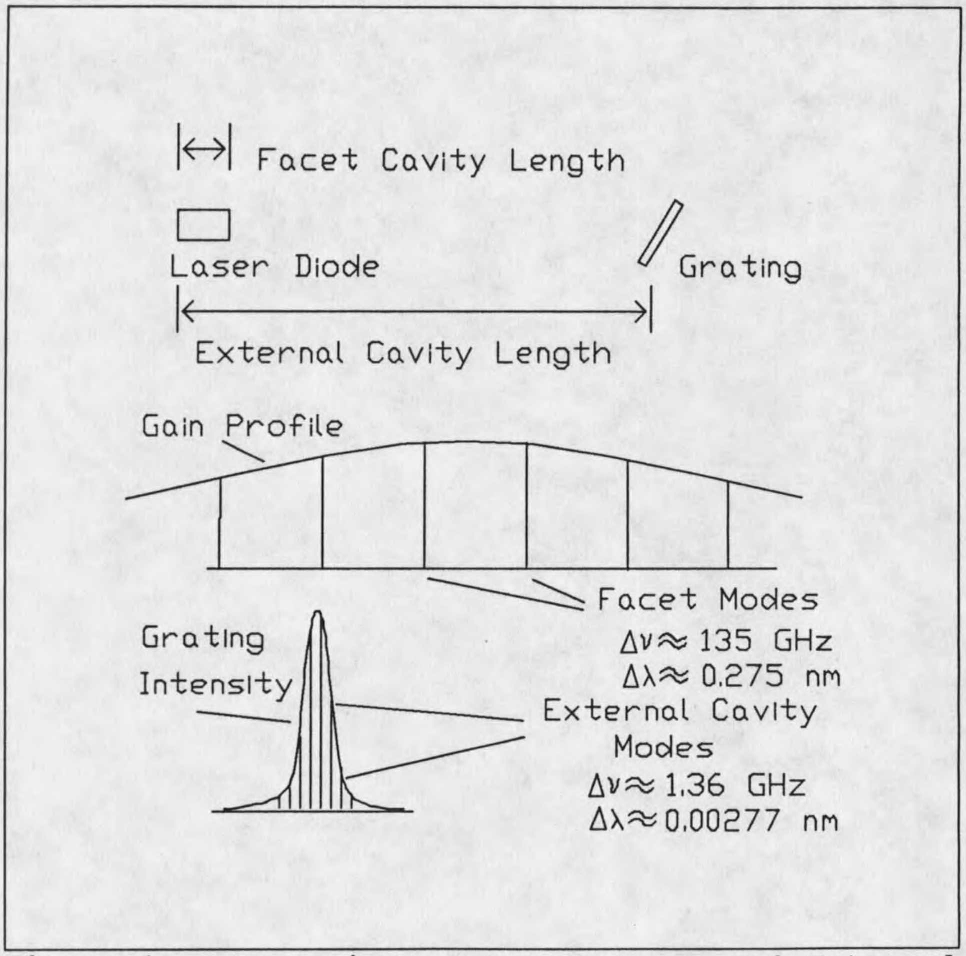

Figure 1. Comparison Between Facet and External Cavity Modes

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)

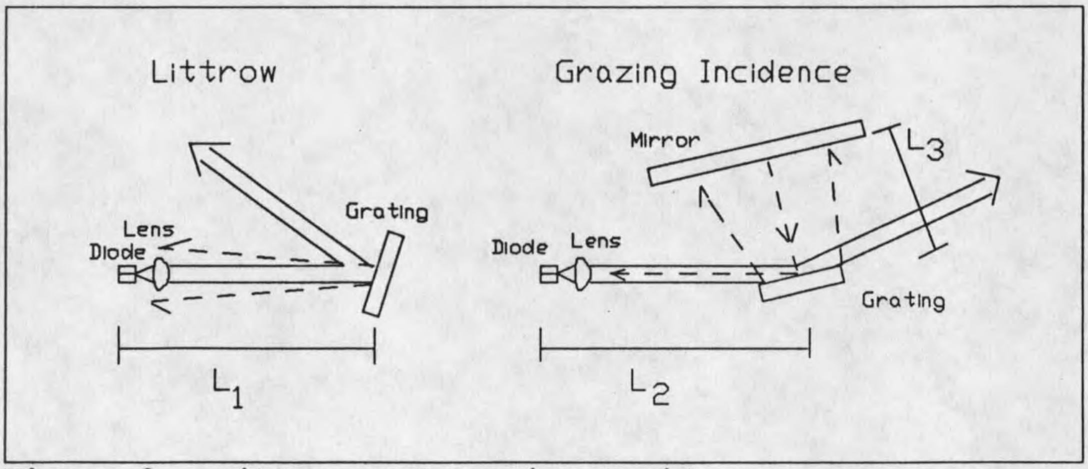

Figure 2. Littrow and Grazing Incidence External Cavities.

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 tuning to be successful, a diffraction efficiency of at least 21% was necessary. Operating at the lower efficiencies generally was undesirable since the greater the amount of feedback, the more likely the diode was to tune to the desired frequency and the wider the tuning range.

Both tuning arrangements required a collimated beam. Several types of lenses were tried: Newport Microscope objective lenses L-65x, M-40x, L-10x, F-LA40; ILX 4014; and Meredith Instruments LDC-10. Only two of these lenses were found to have a reasonable far-field beam profile; M-40x and LDC-10. The disadvantage with the M-40x lens is that since its working distance is so short, the diode's protective can must be removed. The laser is then exposed to the air which oxidizes the facet surfaces and reduces the laser's life span. The LDC-10 seems to work well and has a working distance large enough so that can removal is not necessary.

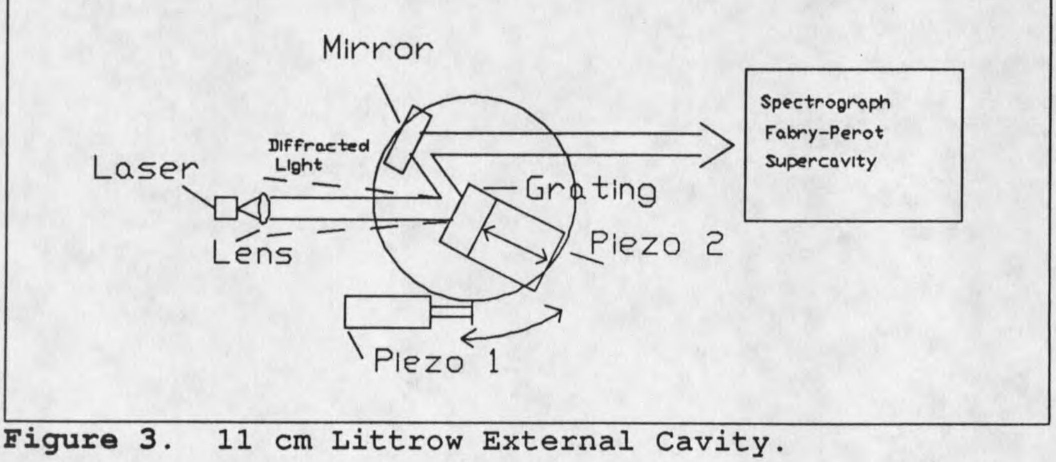

Figure 3. 11 cm Littrow External Cavity.

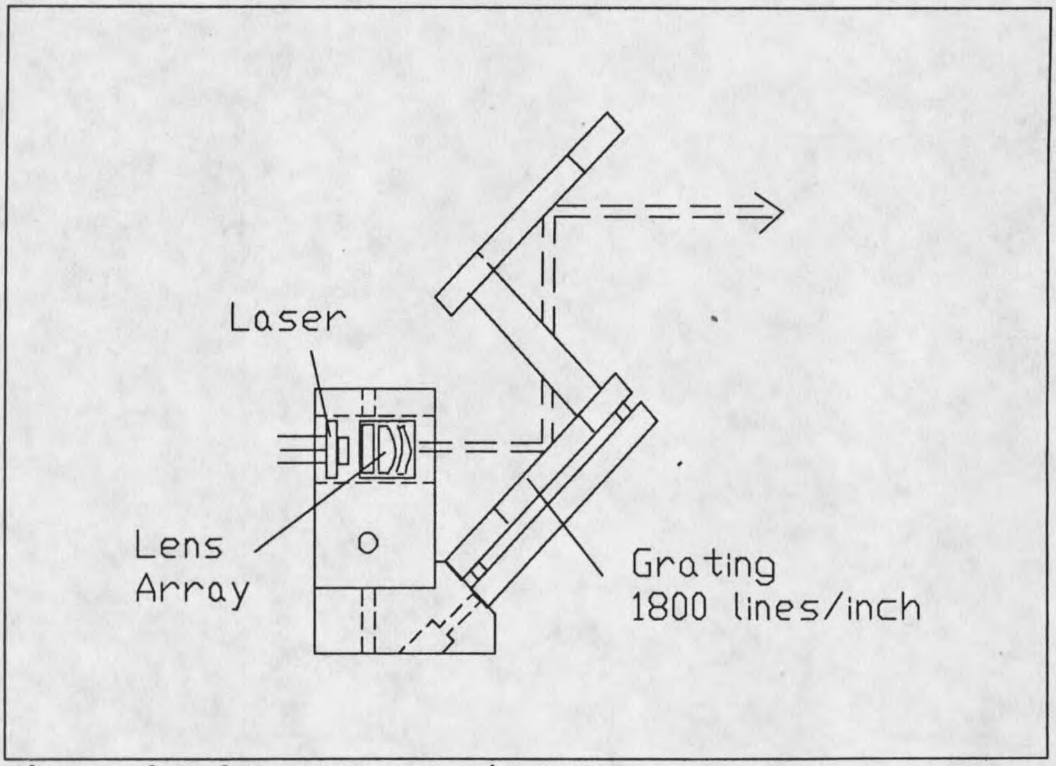

Figure 4. 3 cm Compact Littrow

The Littrow configuration that was most often used is shown in Figure 3. This design has an external cavity length of 11 cm. Originally, the external cavity was over a meter long and consisted of large bases and unstable platforms. Tuning of the laser was possible but reducing the cavity size has helped immensely. The most recent development is the 3 cm external cavity system shown in Figure 4. This was possible because of the smaller lens array from Meredith Instruments. The reduction of the cavity size from the original system is on the order of 97%, with the result of a much more stable laser system.

The external cavity shown in Figure 3 does have a few advantages that the most recent system has not yet acquired. Foremost is the thermal control of the laser by thermistors which are built into the ILX Lightwave laser mount. Secondly, there are no piezoelectric controllers for the grating angle or cavity length in the compact version.

The first piezo controls the grating's rotational stage. Coarse tuning is accomplished by a micrometer, and the piezo was computer-controlled via a Stanford Research Systems SR510 and a Burleigh RC-44 ramp generator. This system was used to effectively study the facet and external cavity mode transitions. The second piezo controls the external cavity length; however the piezo's length change was only enough to modify the external cavity modes. A mirror was added to the rotational stage to transform the angular change of the 0^{th} order into a very small translational change. Lab equipment connections, grating and mirror calculations are found in Appendix D.

The Littrow configuration was the preferred design in that it was fairly easy to align for tuning and provided stable, consistent results. The aluminum base to which the component parts were attached was later found to have observable thermal expansion effects.

A second configuration was briefly explored. The grazing incidence set-up (Figure 5) essentially used the same components but in a different order. The tuning and cavity length adjustments were accomplished by rotation and translation of the mirror while the grating was held at a fixed angle of 75°. This angle was chosen as a compromise between the maximum number of lines illuminated while retaining a diffraction efficiency greater than 21%. Alignment for this configuration was somewhat easier than for the Littrow case, but there were some instabilities in the external mode structure that made this system less desirable.

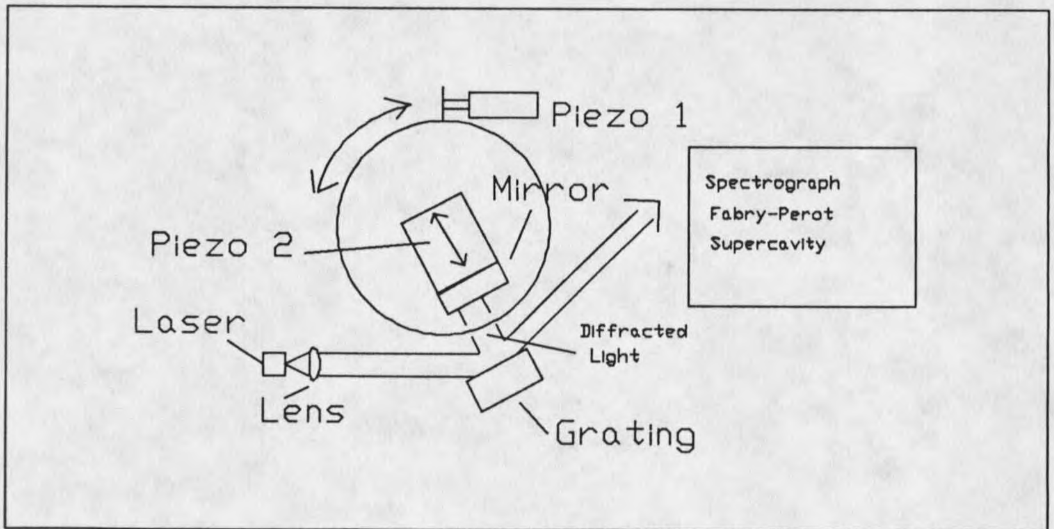

Figure 5. Grazing Incidence External Cavity

Other Considerations

To increase the stability of the external cavity against unwanted vibrations which would cause mode transitions, several inches of foam padding were placed between the table and the cavity's base plate. This helped, but it was also necessary to enclose the cavity in a box to shield it from unwanted air temperature variations caused by drafts from the air conditioning system. Even with these measures, long term (2 hour) studies showed that thermal variations of a degree Celsius still caused mode shifts on the order of several GHz.

The mode structures of the various diode lasers, free running and in external cavity systems, were studied with three apparatus: spectrograph, Fabry-Perot, and a Supercavity Fabry-Perot. In the spectrograph, a collimated beam passed through a single slit of 10 μm, continued for 1.5 m to a 450 line/mm concave reflection grating and back another 1.5 m to a 1024 diode Reticon array whose signal was displayed on an oscilloscope. For the Fabry-Perot, the laser's beam was expanded by a microscope objective lens and recollimated by a 5 cm focal length lens. The beam passed through a Burleigh Fabry-Perot, and was focused onto a photodiode whose signal was sent to an oscilloscope. The Supercavity's configuration and calculations are found in Appendix F. The light was sent to the Supercavity by optical fiber so that a consistently mode matched signal would be provided even when the diode was moved. As with the Fabry-Perot, the resulting signal was focused onto a high-gain photodiode and the output sent to an oscilloscope.

The resulting spectra from these three instruments were displayed on a Tektronix 2230 storage oscilloscope which was able to capture a picture of the screen. The data was then transferred to an AT&T 6300 Plus computer and stored. Most of the data acquisition was automated to a certain extent by the AT&T controlling the experiments via GPIB interfaces. A lab schematic is in Appendix D. Appendix E has a listing of the main controlling program that was used.

After the data was transferred from the oscilloscope into an (x, y) array, conversion of the data into graphical form was necessary. Generally this involved two steps: first, simultaneously converting the oscilloscope values of x into nm or GHz and offset y to represent the changing configuration (grating angle, cavity length, time, temperature, etc.) as well as the intensity at a given wavelength or frequency; second the many separate data files were combined into a single unit which the Grapher program could display as a three dimensional plot. This tended to be a tedious process as the resulting data files were on the order of 20,000 data points. The data conversion and compilation was usually performed on a Zenith 386 20 MHz computer so that the process could be accomplished in a reasonable length of time.

CHAPTER 4

EXPERIMENTAL RESULTS

Inherent Spectra of Several Diode Lasers

The first studies are of the free-running spectrum of various diode lasers. As can be seen in Figure 6 for a Toshiba TOLD 9211 laser diode which is centered at about 670 nm, the gain profile is fairly evident as well as the individual modes created by the facet cavity. Since one mode has a higher gain than the neighboring modes, it tends to dominate in the spectrum. If the current is increased, there is often an even greater dominance of one mode as is evident in Figure 7. However, neighboring modes still have enough gain to lase and for many applications this multiple mode response is undesirable. A composite graph showing how the gain profile changes for a particular laser is seen in Figure 8. This image clearly shows several interesting features. By measuring the spacing between the modes, the laser diode's cavity length can be found as shown in Appendix B.

As the current increases, the gain profile should shift to shorter wavelengths if only the carrier density is taken into account. However, the mode structure has an obvious

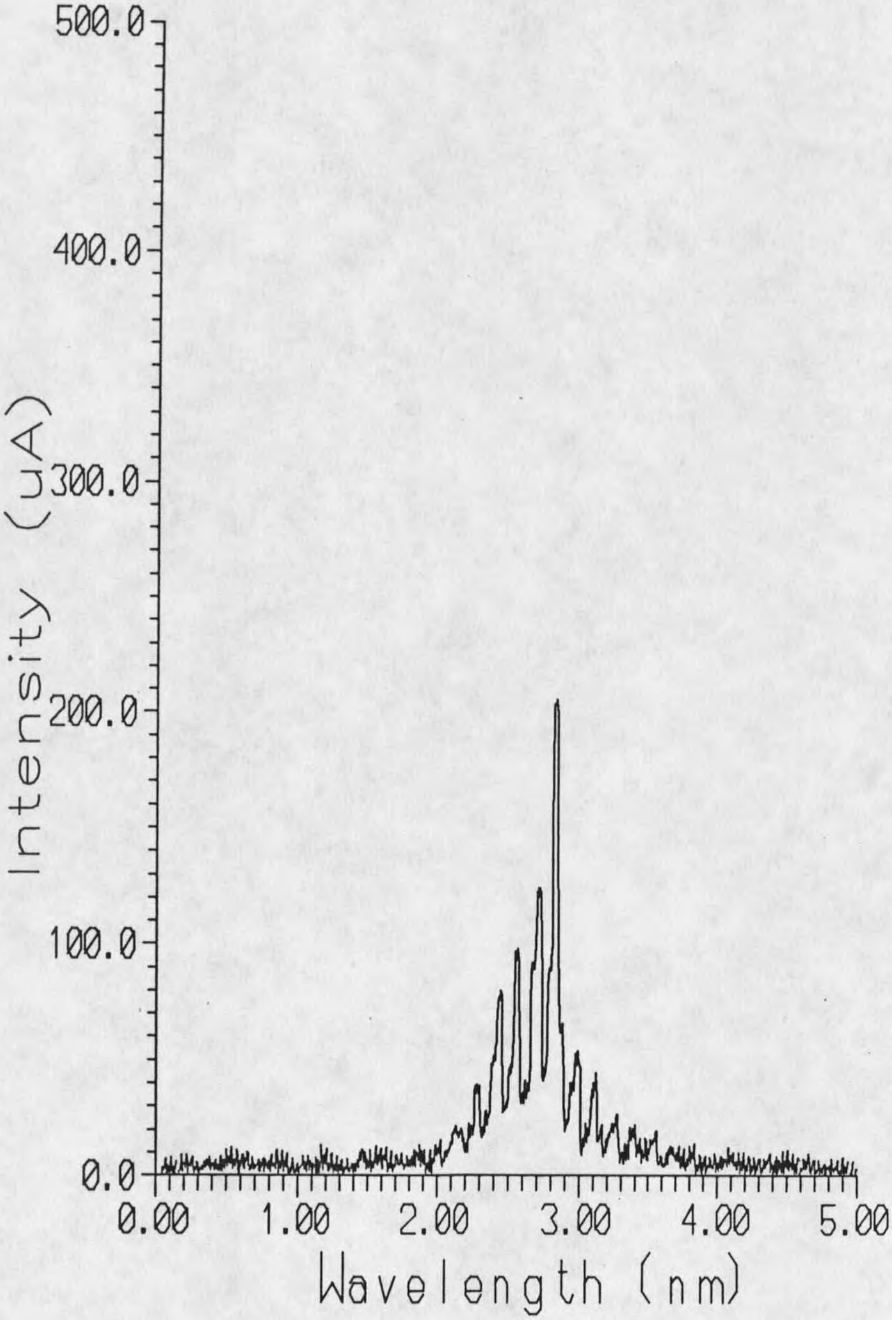

Figure 6. TOLD 9211 Multimode Spectrum

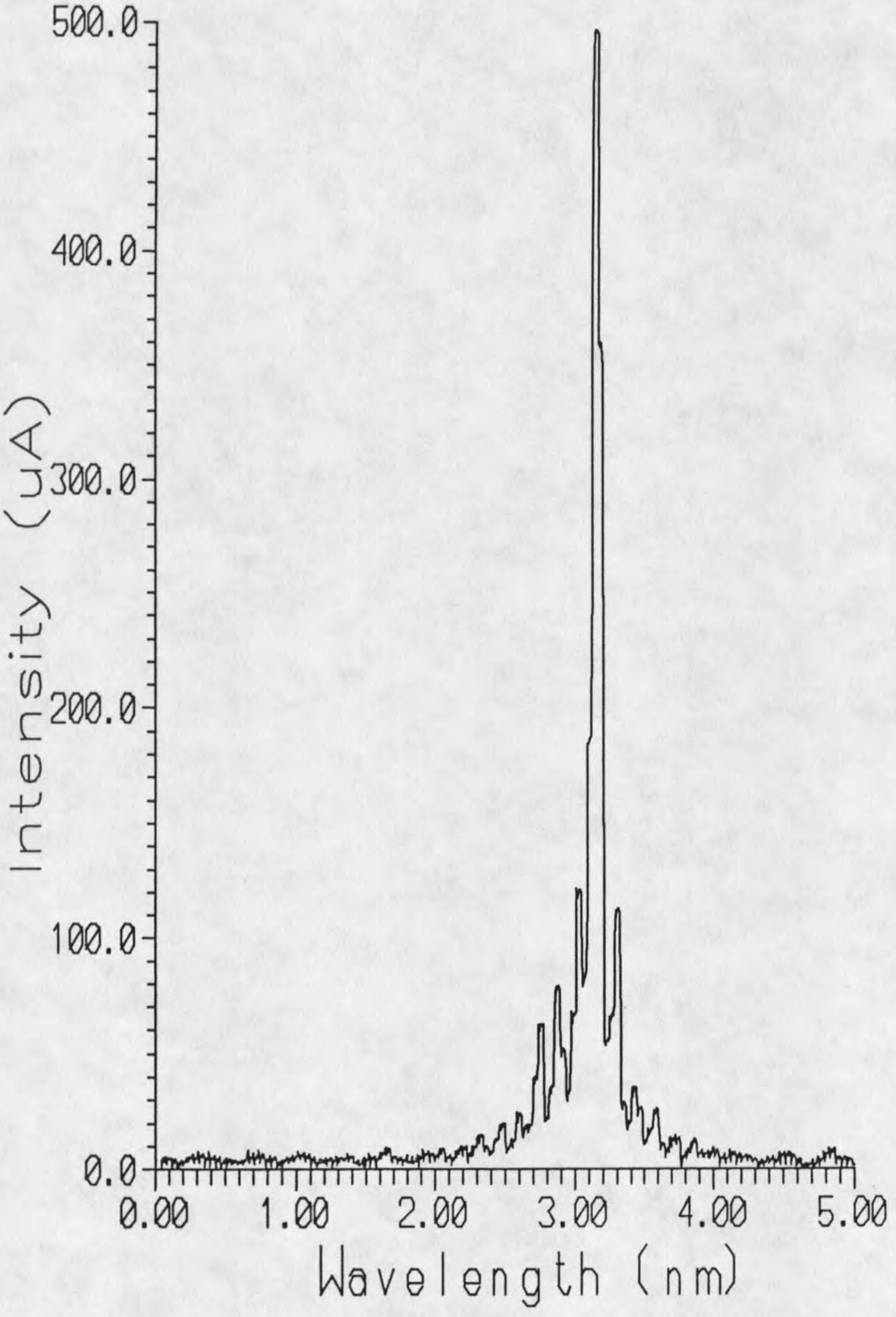

Figure 7. TOLD 9211 "Single Mode"

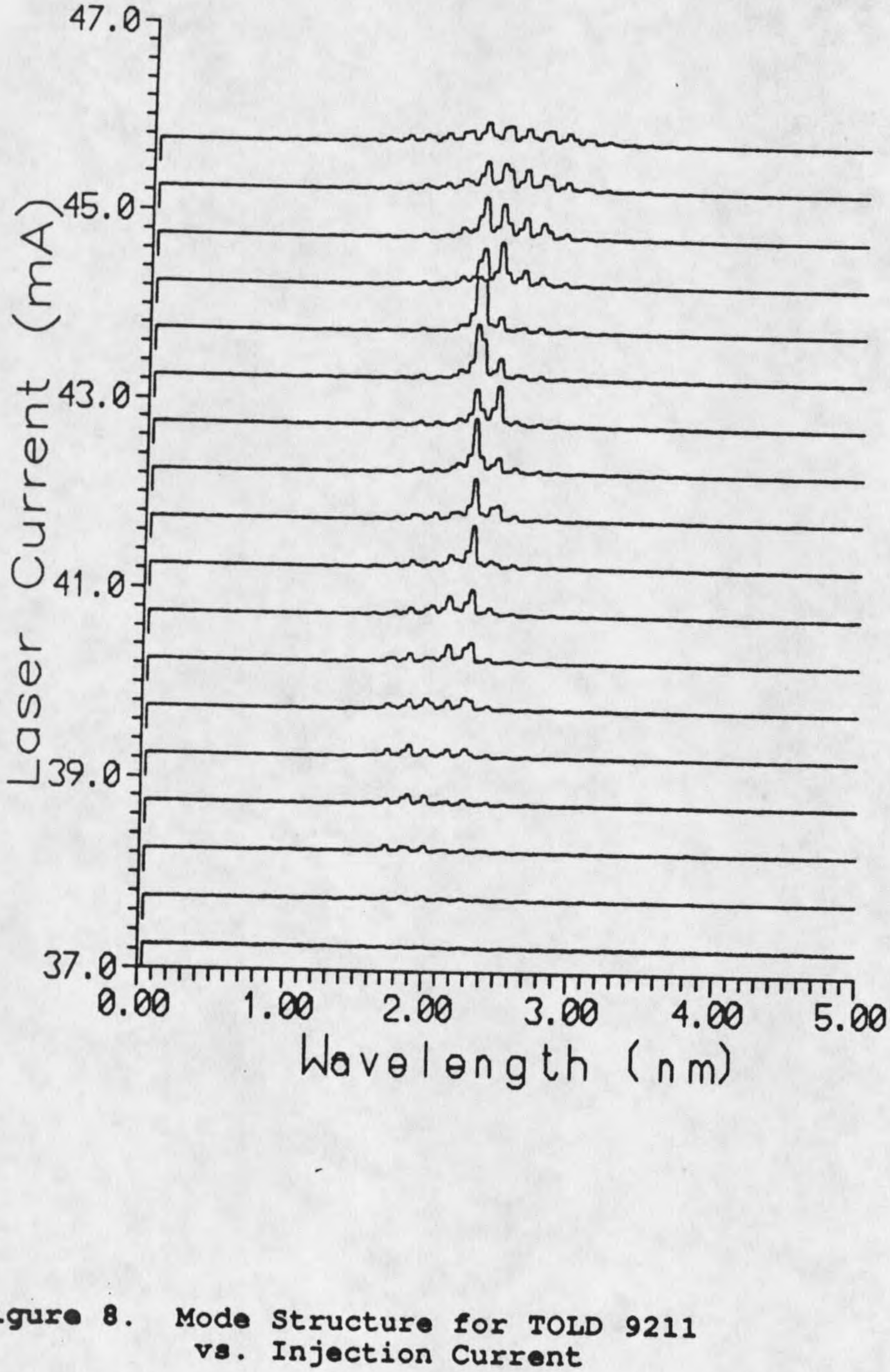

Figure 8. Mode Structure for TOLD 9211 vs. Injection Current

shift to longer wavelengths by about 0.75 nm for the current increase seen in Figure 8. Although this type of shifting seems to be in contradiction with models due to the carrier density,[11] thermal expansion effects are known to have a much more significant effect.[12] It would seem that the increased current must raise the temperature of the diode even though there is a temperature control on the diode's heat sink. An increased temperature would give rise to thermal expansion of the diode, thus creating the shift to longer wavelengths.

What is disturbing is that another diode of the same brand and model behaved rather differently. Figure 9 shows a second TOLD 9211 (this one was labeled 7669) but this diode does not exhibit as much of a multimode tendency. The preferred mode does display an equivalent shift ($\approx$ .75 nm) to longer wavelengths. However, it was noticed that shortly after data was taken for a tuning experiment, and after the diode was briefly subjected to a current of 52 mA while in a Littrow arrangement, the diode behaved oddly. It would only lase at higher currents (> 50 mA) and exhibited a multimode spectra as the first laser did.

This type of sudden change was also noticed on another TOLD 9211 laser. It seems as though these lasers undergo a partial change to their gain profile, perhaps a type of flattening so that several modes are allowed to lase simultaneously. Since these lasers must thereafter be run

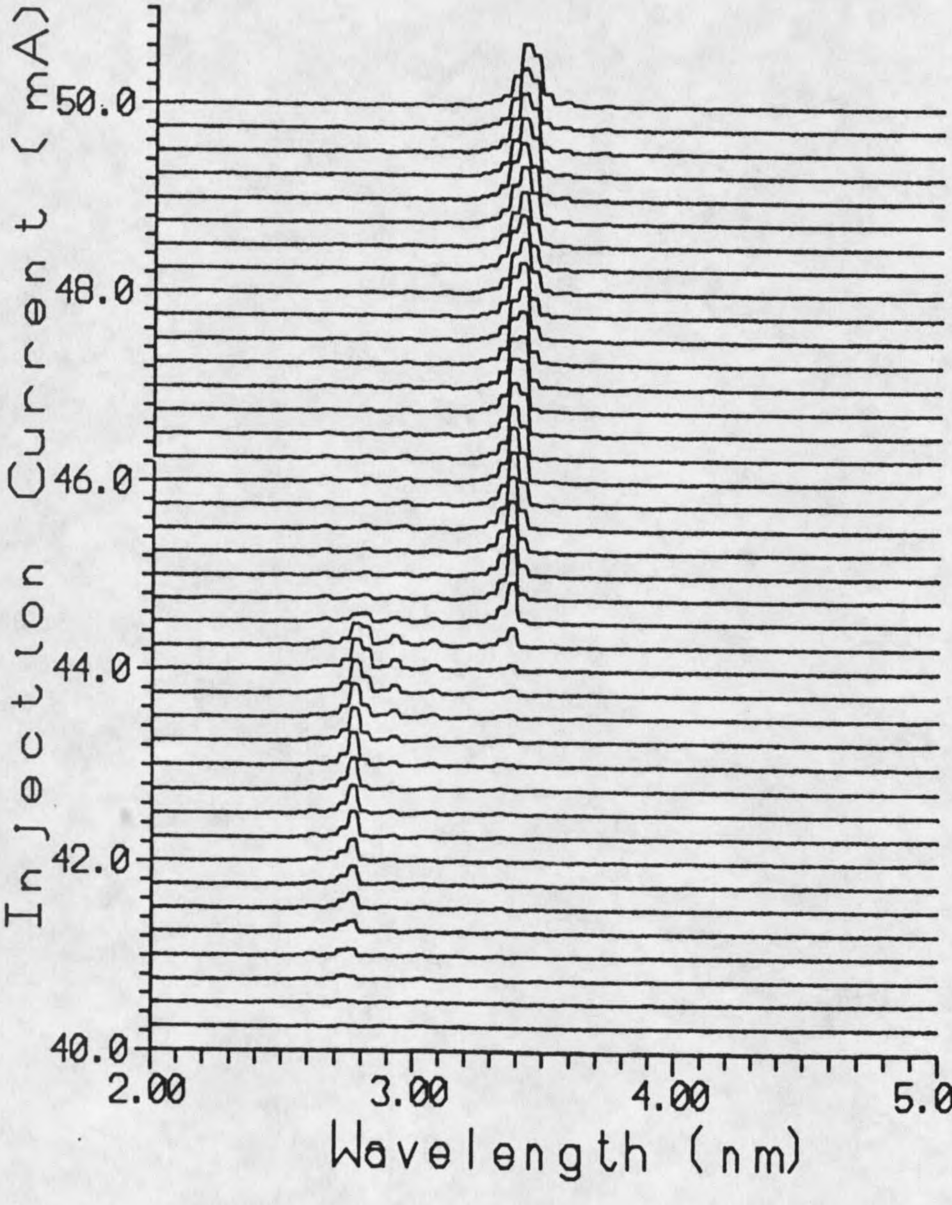

Figure 9. Mode Structure for a Second TOLD 9211 vs. Injection Current

at higher currents, it has been common to refer to them as having had "strokes" as they weren't quite dead, but they didn't function as they had earlier. Only TOLD 9211 diodes seemed to have strokes; when other laser types had accidents, they completely died.

Figure 10 shows the behavior of a Mitsubishi 4402-01 laser. The main peak is near 781 nm. Again, as the laser current is increased, the mode spectrum moves to a longer wavelength, but the shift this time is only by one facet mode (.33 nm.) Figure 11 is the last laser studied, it is a high powered (20 mW maximum output) IR laser. This laser has a unique behavior in that the mode actually shifted to a shorter wavelength as the current increased. This could be a result of the unique coating structure on the diode's facets. One facet has a highly reflective coating of $\lambda/4$ layers of alternating Al_2O_3 and amorphous Si while the other has an antireflection coating of the Al_2O_3.[13]

Although this laser may be following the expected movement of the gain profile to shorter wavelengths at higher currents, careful inspection of the graph does reveal that there is a shorter wavelength mode which would lase at the lower currents but does not have quite enough gain. As the current is increased the longer wavelength dominates thus suggesting that there is a "desire" for some sort of a shift to longer wavelengths resulting from thermal expansion.

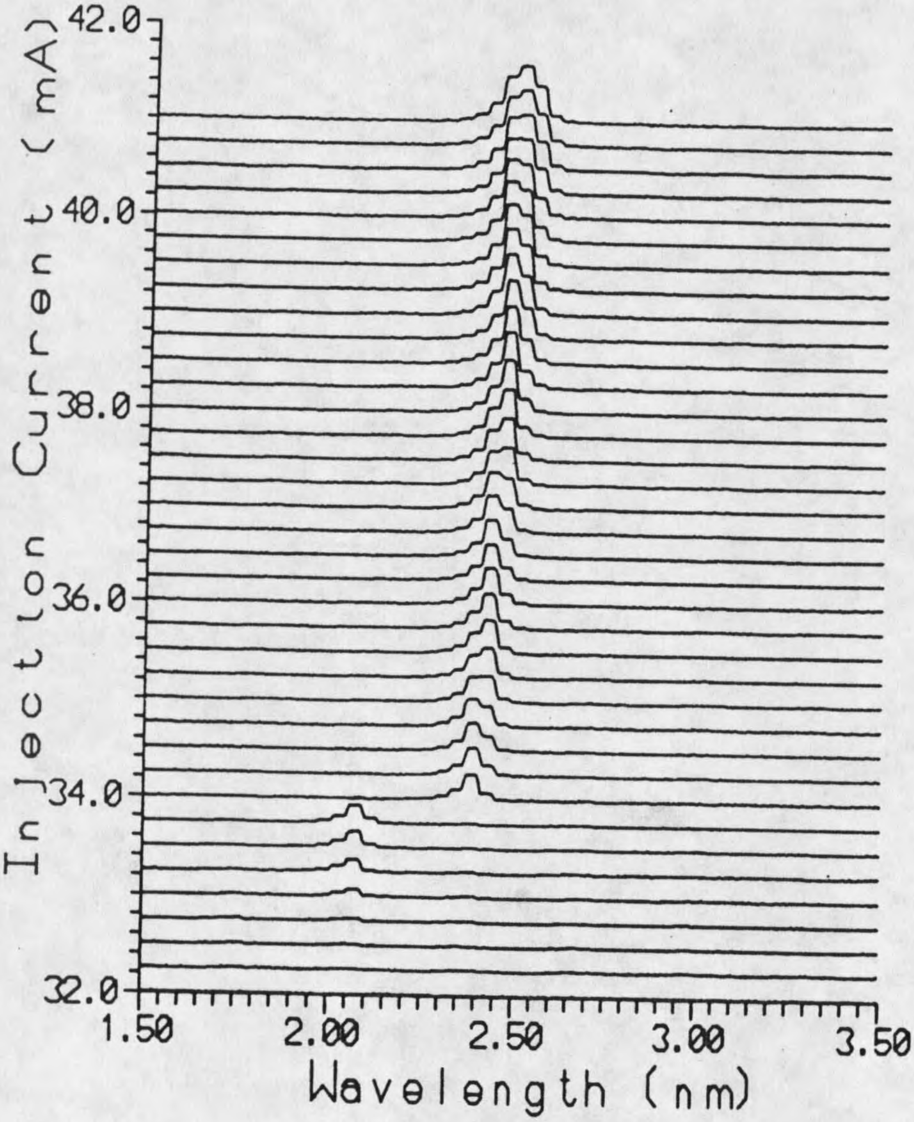

Figure 10. Mode Structure for a Mitsubishi 4402-01 vs. Injection Current

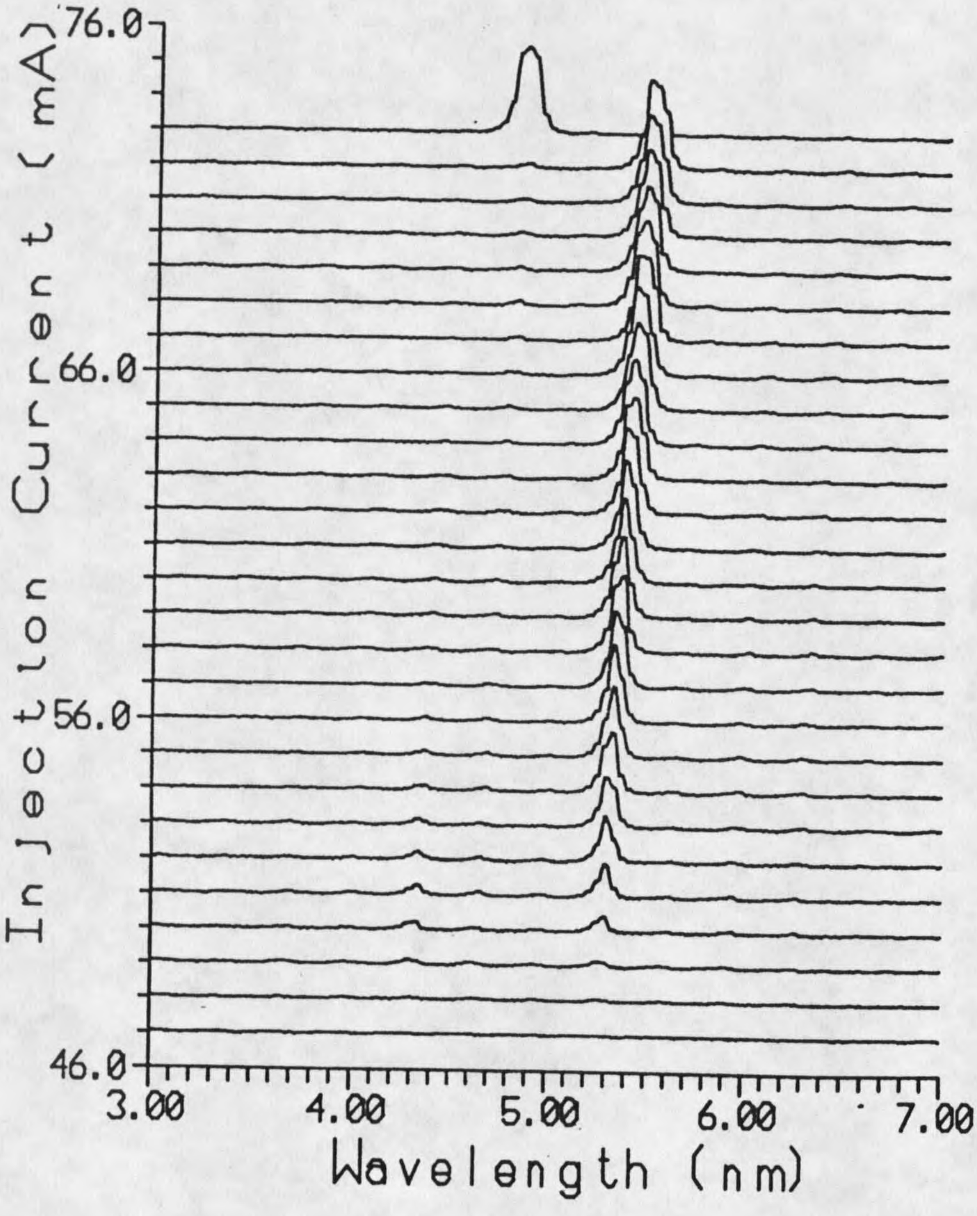

Figure 11. Mode Structure for a Sharp LT024MD0 vs. Injection Current

Mode Transition Experiments

The application of an external cavity dramatically alters the spectra of even some quite multimode profiles. For example, Figure 6 of a TOLD 9211 laser clearly shows at least 12 modes, but when the Littrow configuration external cavity was applied, the spectrum becomes that of a single, dominant facet mode. (Figure 12) This ability to choose a single mode is a direct consequence of the reduced threshold level allowing the wavelength associated with that particular mode to have an artificially augmented gain level as was mentioned in Appendix C.

Figure 13 is the composite of many mode structure graphs, each taken at a separate grating angle. At the bottom center of the graph many modes can be seen. This is essentially the free running spectrum similar to a single line in Figure 8. The grating has little effect on the laser because the reduced threshold level from the grating does not reach the gain profile. As the grating angle shifts, the threshold level crosses more of the gain profile and a particular mode is excited. The odd shift in the second quarter of the data was due to human error; there should be no overlapping or missing modes. The tuning range of 9 nm is centered about the 670 nm wavelength. The modes seen at the top of the graph are believed to be caused by reflections off the edge of the microscope objective lens used to collimate the beam. The reasoning is that these

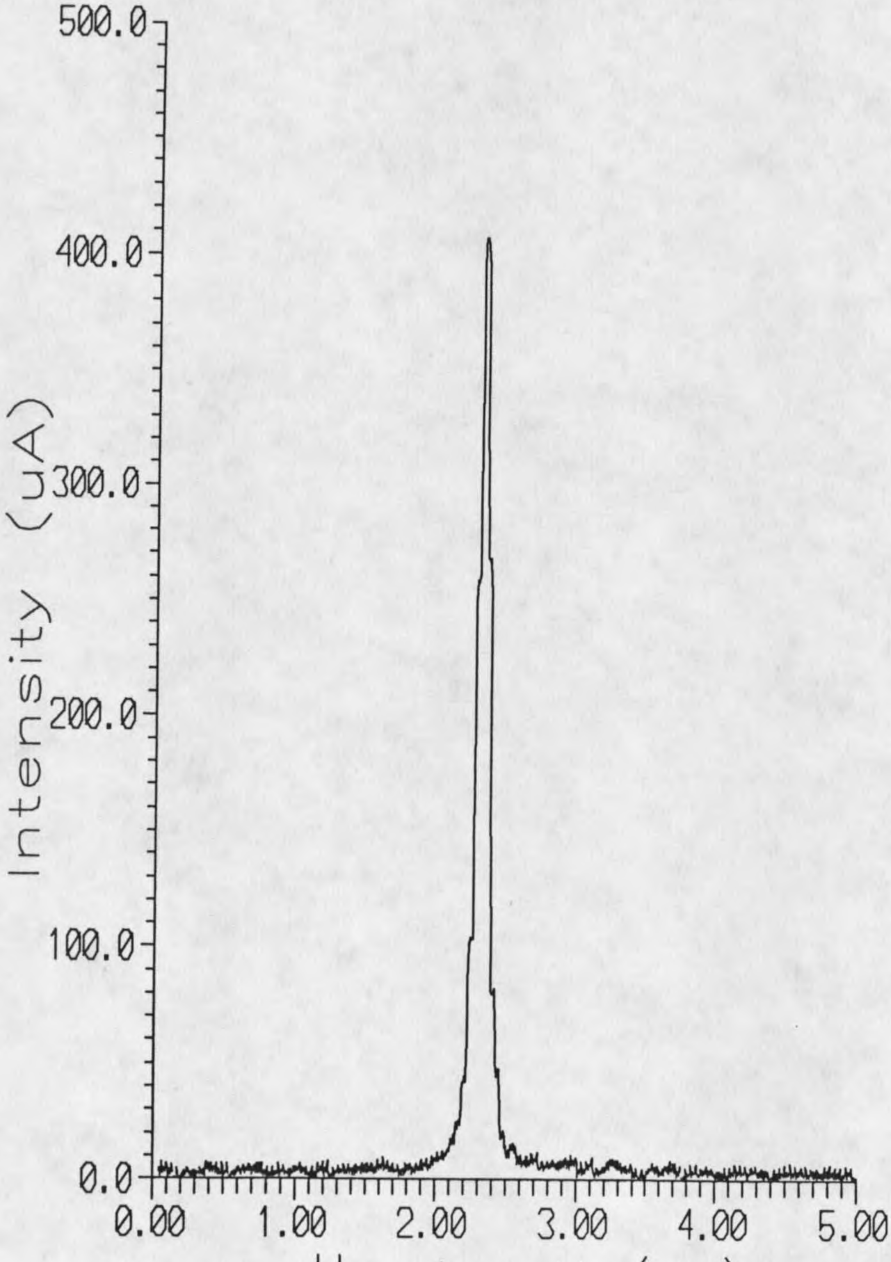

Figure 12. Single Mode from a Littrow Cavity

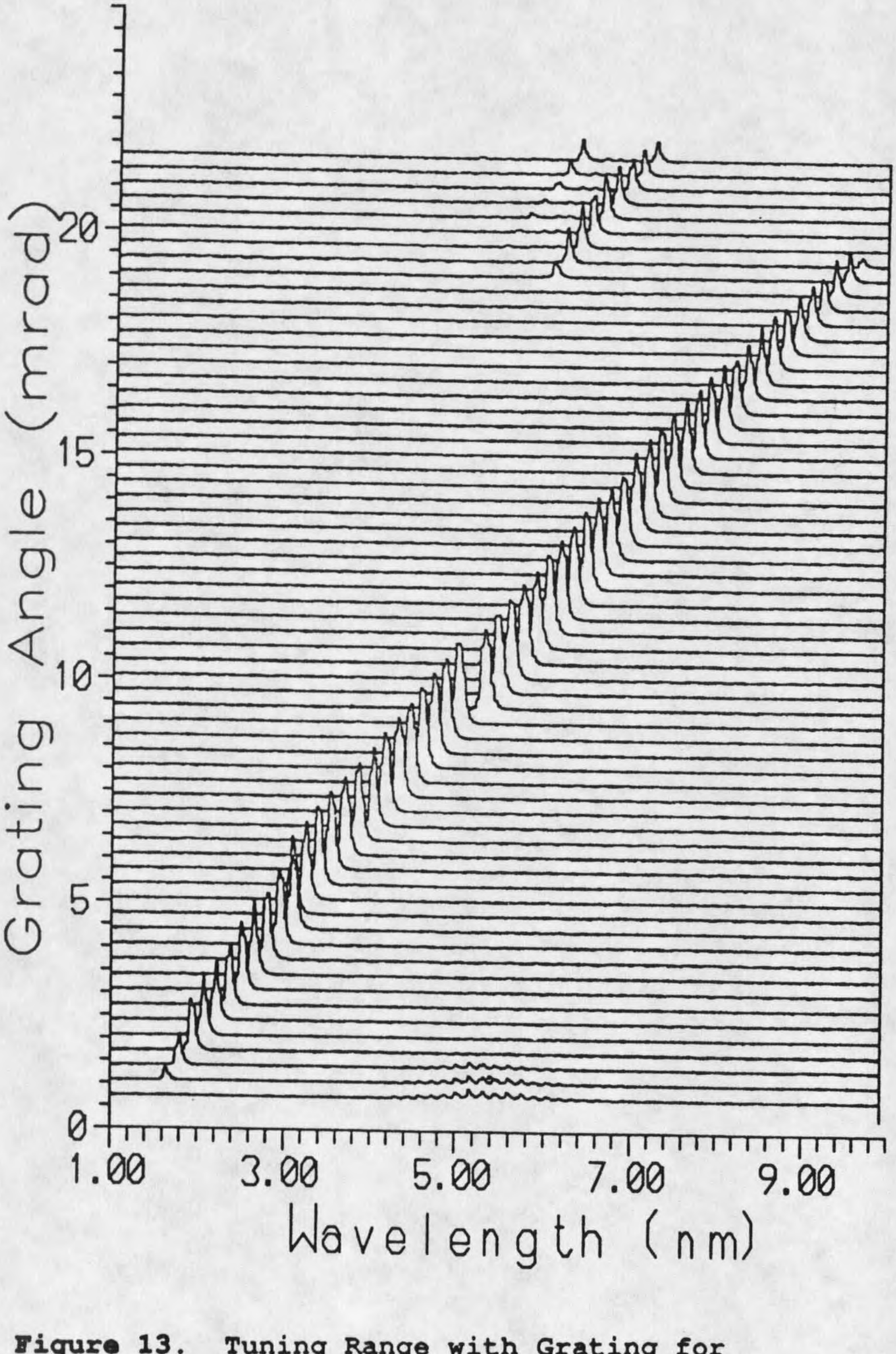

Figure 13. Tuning Range with Grating for TOLD 9211; λ = 670 nm

modes are weaker than most of the main modes, they follow the same general pattern as the main modes, and they are close to the wavelength of the last modes in the main sequence. Also, at the grating angle used to tune to this structure, the diffracted light was at the lens edge.

Better alignment of the collimating lens seems to be evident for the case of the Mitsubishi 4402 laser as seen in Figure 14. At the bottom of the graph the free running mode is clearly visible and the tuning is symmetric about this wavelength. These modes are spaced farther apart due to a shorter diode cavity. Again, the tuning range is about 9 nm. In both Figures 13 and 14, at the extreme ends of the tuning ranges, the central modes start to make an appearance since the gain is at the unmodified threshold level.

The tuning range spectra of the Sharp LT024MD0 was made with the 3 cm external cavity of Figure 4. The angular change of the grating in all three tuning graphs is similar: 12 to 20 milliradians. The larger peak heights of Figure 15 are due to the scaling factor used to make comprehensible graphs in 13 and 14. The mode spacing of the Sharp was similar to that of the Mitsubishi laser, as was the output wavelength, although the tuning range was wider at 11.4 nm.

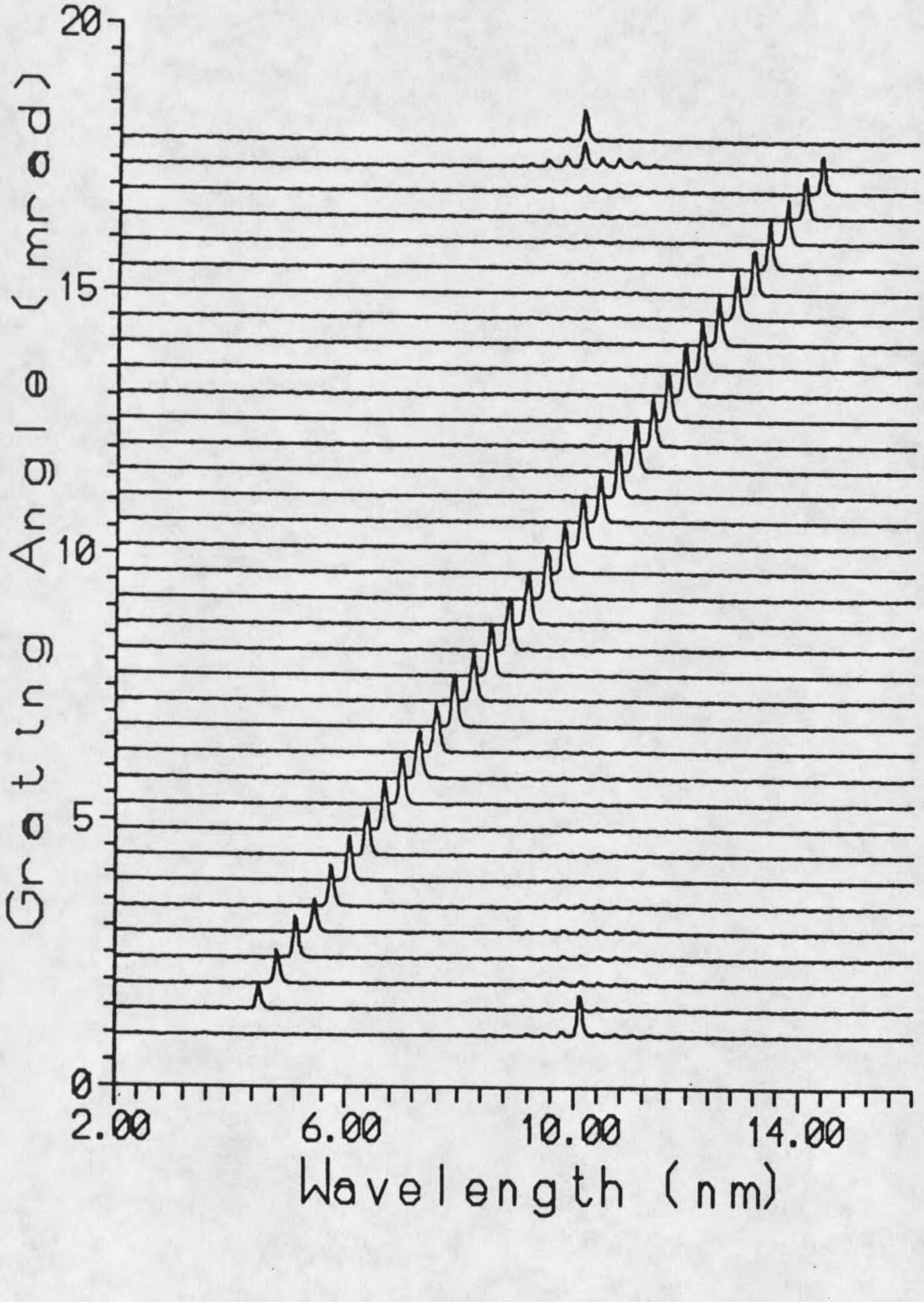

Figure 14. Tuning Range with Grating for Mitsubishi 4402-01; $\lambda = 781$ nm

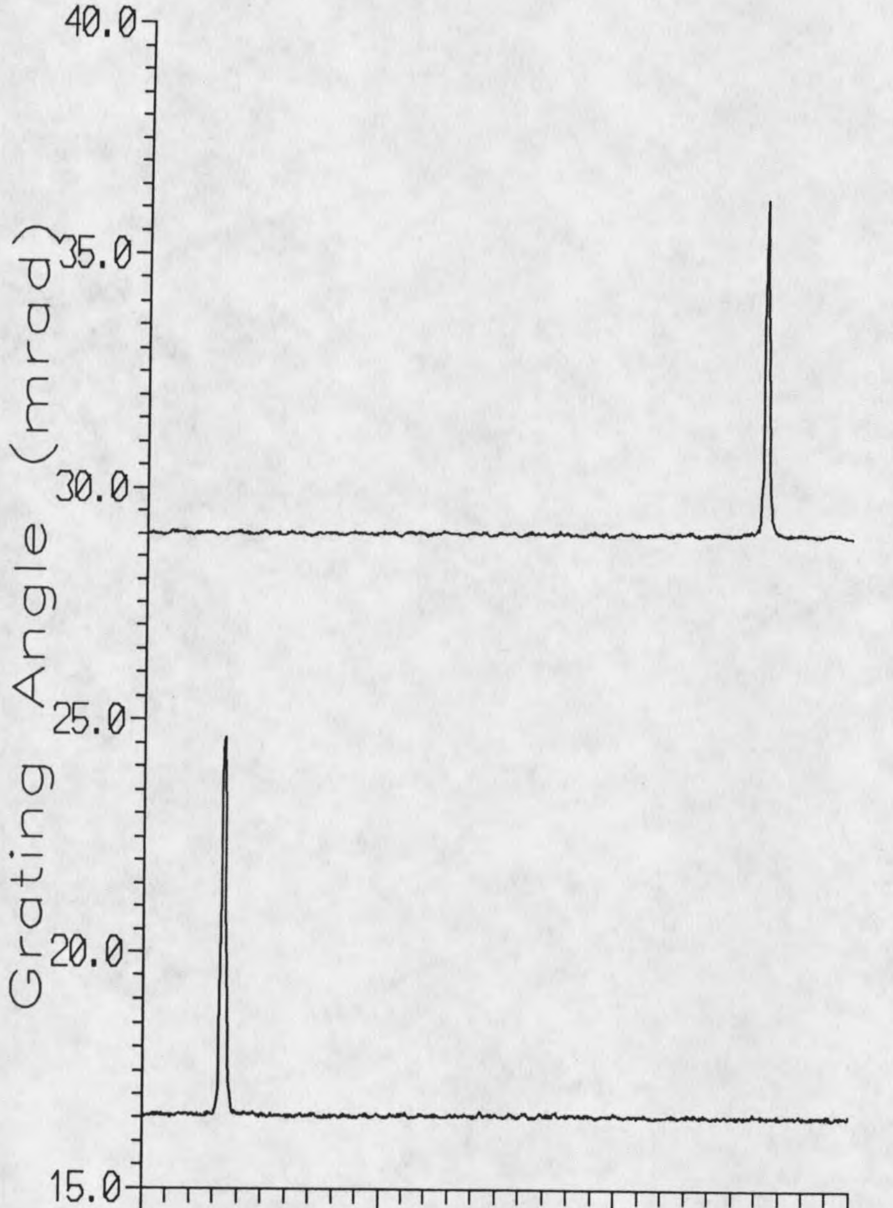

Figure 15. Tuning Range for Sharp LT024MD0 in 3 cm Littrow; λ = 788 nm

The transitions of the facet modes for the lasers were interesting. In Appendix D, a many slit diffraction pattern with 7000 lines has a full peak width of 0.2 mrad is shown. The mode separation of adjacent facet modes in the TOLD 9211 is also 0.2 mrad so the grating is just able to resolve the separate facet modes. However, when the grating is tuned between two modes, both modes may receive enough feedback to lase. This leads to a transition that is not absolute, but rather to one that shifts its preference gradually. Instead of a quick switch, or mode hop, there is a slow change, a mode ooze, which is clearly evident in Figure 16. If the facet between the grating and the back facet could be removed, a continuous transition would easily result. A similar effect is evident for the Mitsubishi laser, but because the modes are spaced farther apart, the transition is more abrupt. (Figure 17) The mode oozing is characteristic of the change between facet modes for all the lasers studied. For a shorter transition period, the modes need to be spaced farther apart or more lines of a grating need to be illuminated to reduce angular dispersion.

The mode structure of the diode lasers when viewed with a Fabry-Perot had a surprising result. In Appendix D, it is calculated that the angular movement of the grating to change one facet mode is on the order of 3 μrad. However, experimentally the angular change is closer to 30 μrad.

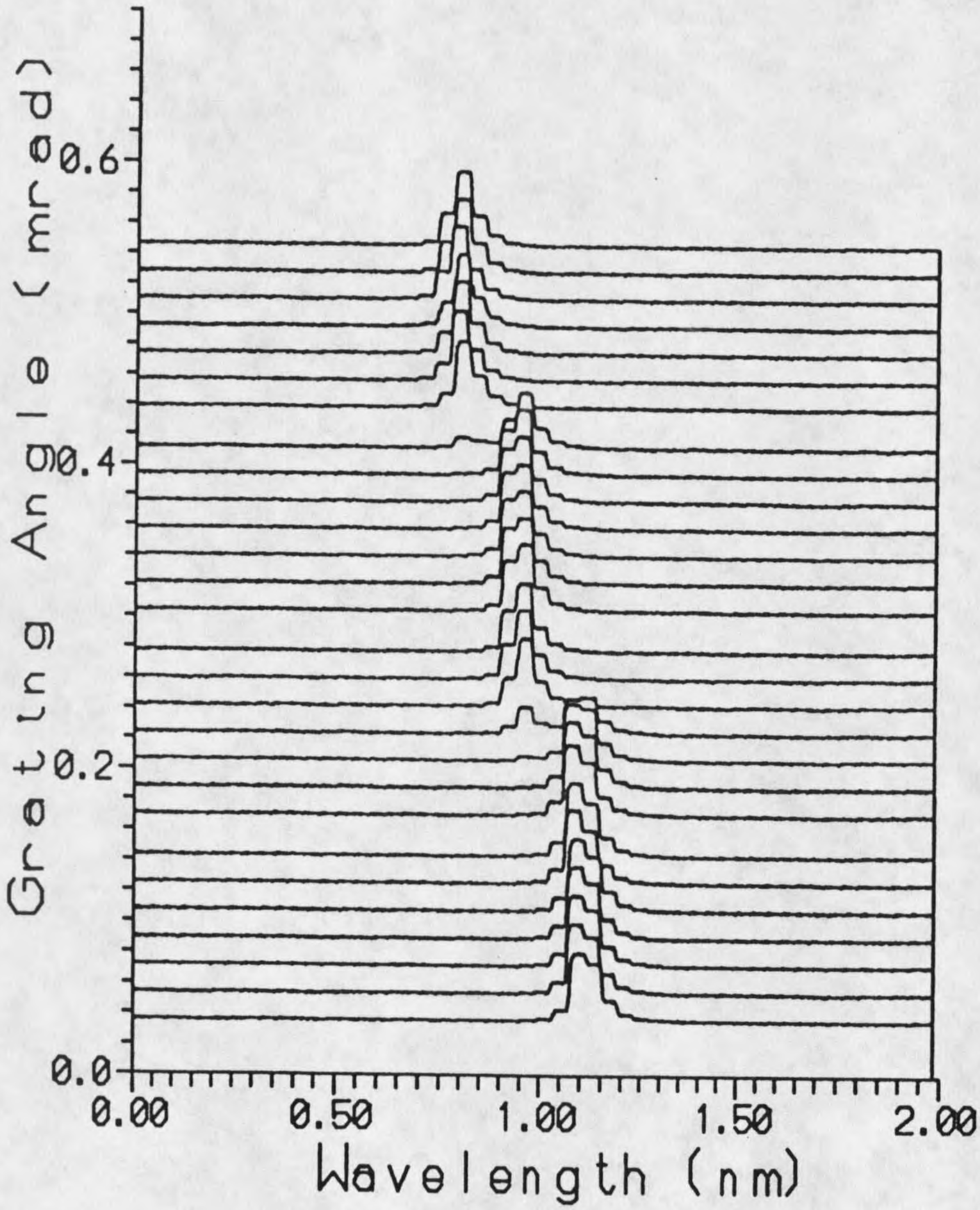

Figure 16. Mode Transition for TOLD 9211

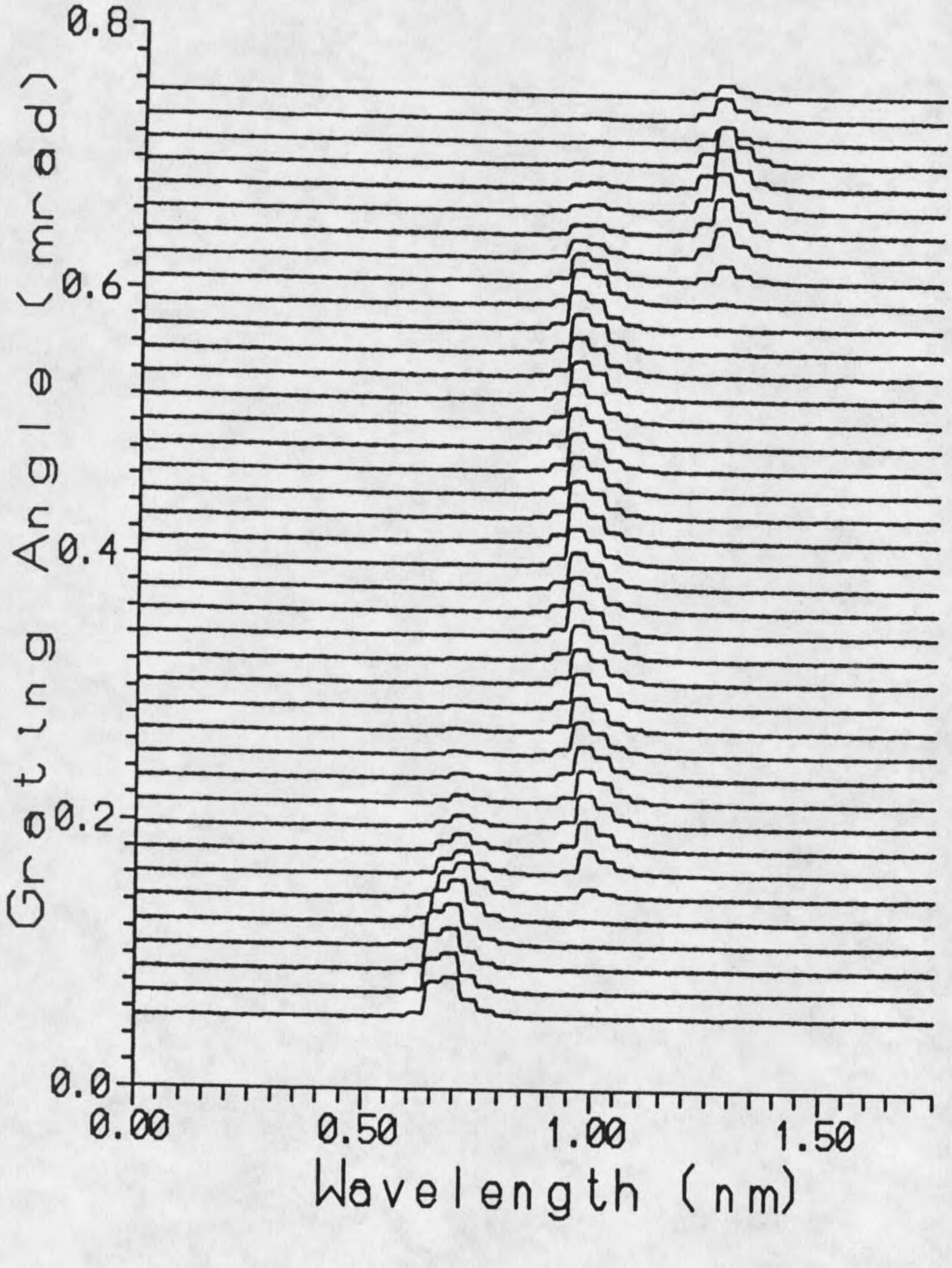

Figure 17. Mode Transition for Mitsubishi 4402-01

The tendency for a laser to stay in one mode seems to be a result of the relatively large angular change necessary to change the threshold profile since its peak width is large compared to the angular change necessary for the external modes. The Toshiba (Figure 18) and Mitsubishi (Figure 19) lasers display similar characteristics in their external cavity mode transitions. Both show a penchant for remaining in the tuned mode, as mentioned above, even though there are traces of neighboring external cavity modes. Also, during the transition from one mode to the next, there is a region of ambiguity where the laser briefly runs in a number of modes before locking into the next mode. The facet mode transition is seen to be about 1 GHz which is consistent with the 11 cm cavity used.

The spectra for the Sharp laser (figure 20) is much cleaner during the external cavity mode transitions and no neighboring modes can be seen. This is believed to be due to the antireflection coating on the front facet surface and the higher power levels of the laser's output. There is an even stronger tendency for this laser to remain in a given mode. The shift and slight curvature of the mode are similar to effects seen with temperature variations. Near the top of this graph, there is a radical movement of the mode. The movement may actually be an 11 GHz leftward jump.

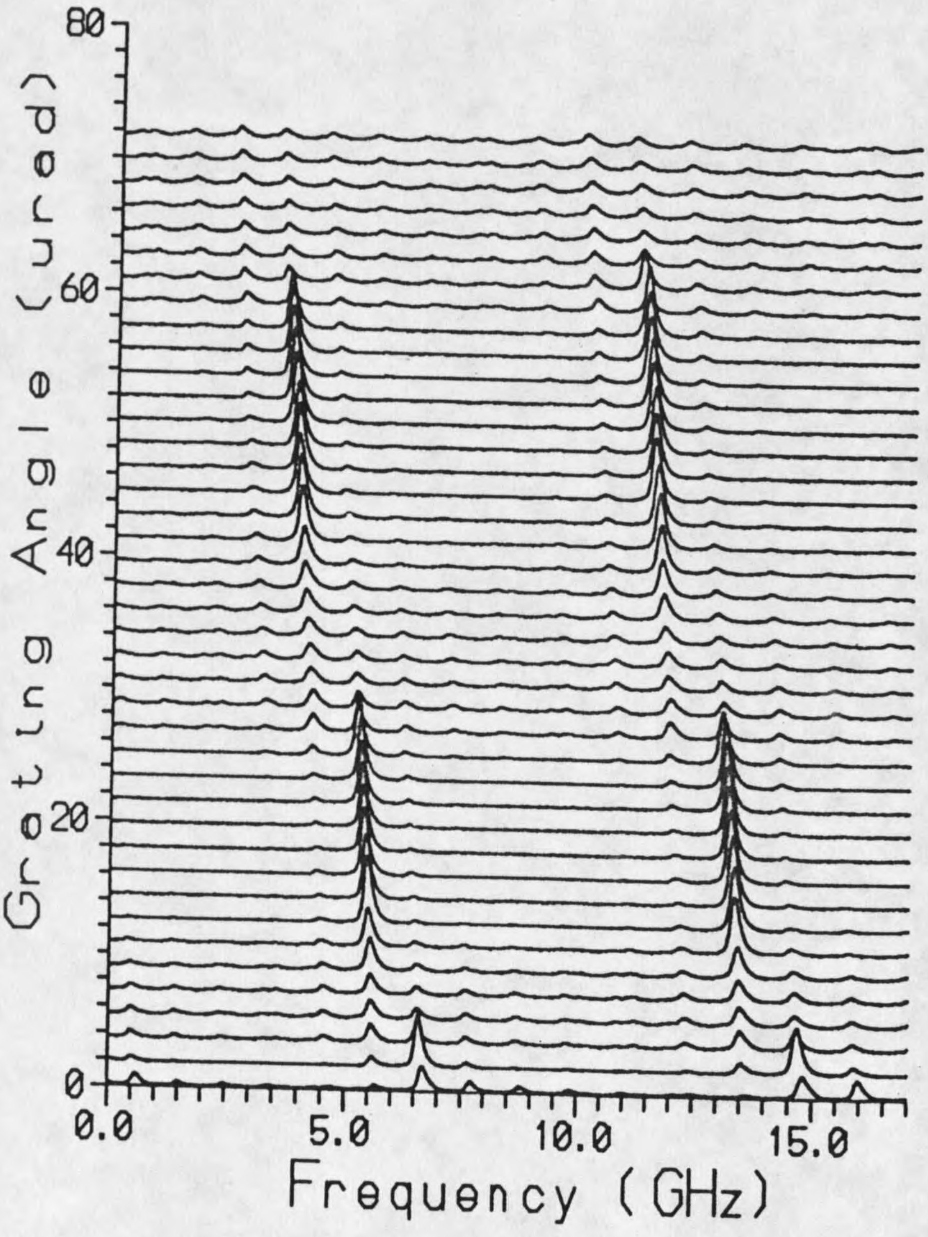

Figure 18. External Mode Tuning: TOLD 9211

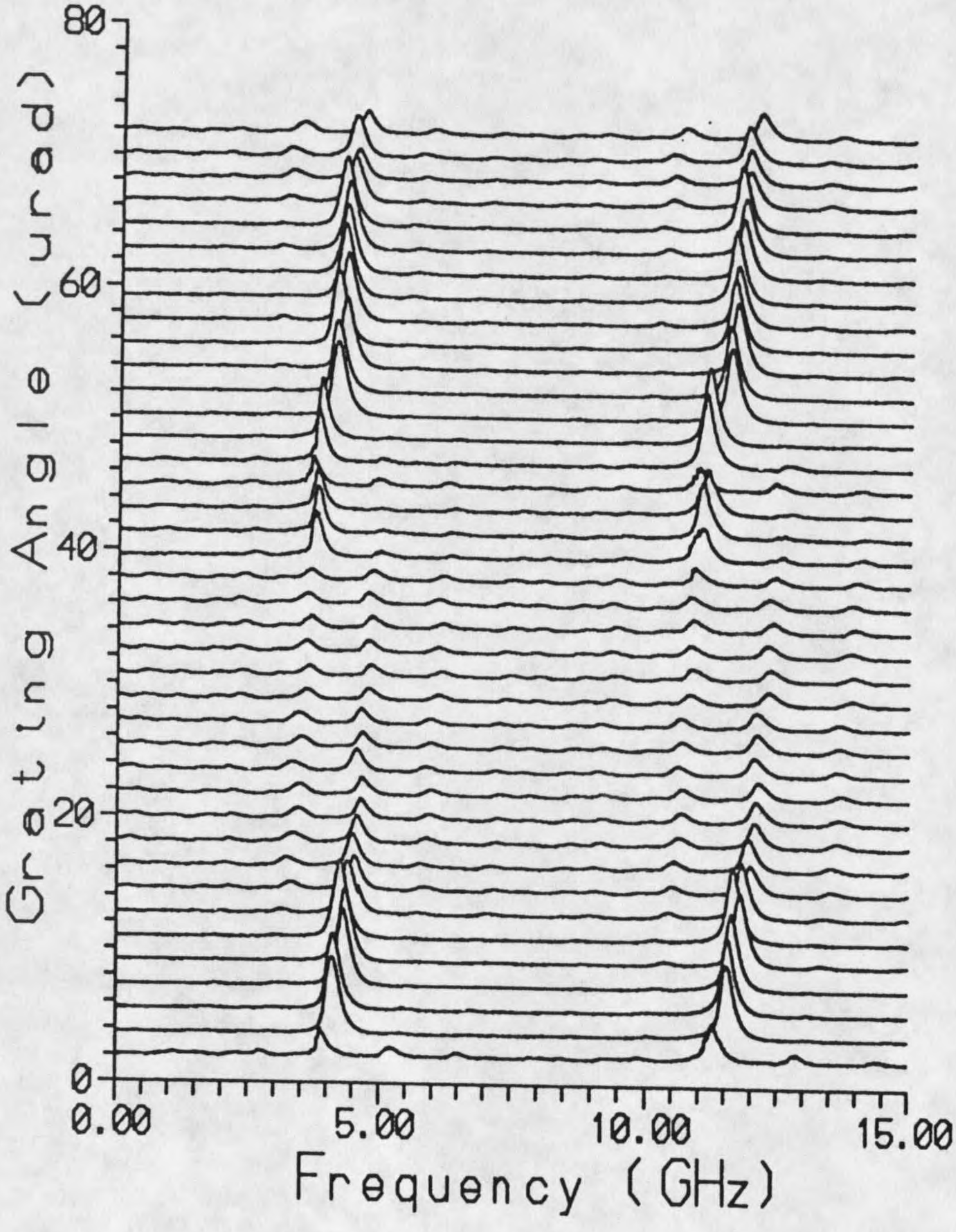

Figure 19. External Mode Tuning: Mitsubishi 4402-01

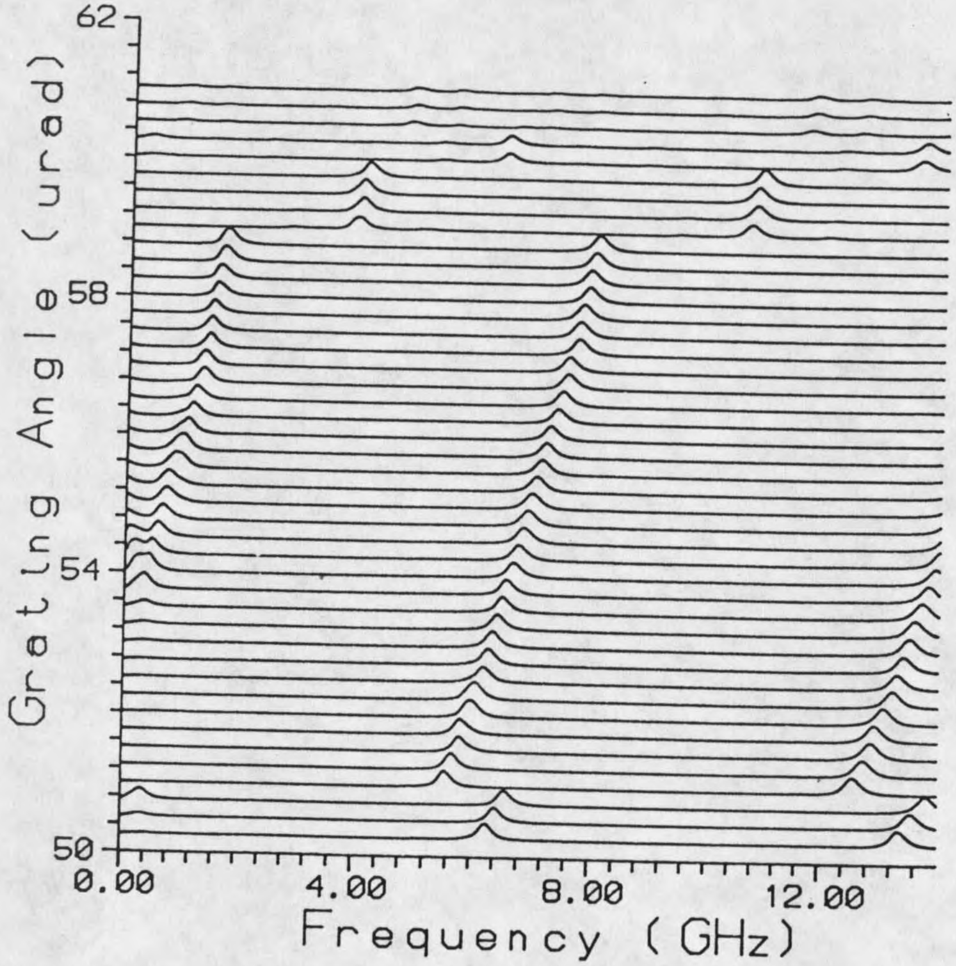

Figure 20. External Mode Tuning: Sharp LT024MD0
Fabry-Perot at 2 cm

Figure 21, taken with a shorter Fabry-Perot spacing of 1.55 mm, shows that larger shifts are possible. The behavior at the upper quarter of Figure 21 shows the transition between facet modes. The region without substantial mode structure is where this laser is running with multiple external cavity modes as well as changing between two facet modes.

Transitions between the facet modes were easy to obtain and both the Littrow and grazing incidence systems worked well to accomplish this task. But there was a difference between the two when it came to tuning the external cavity modes; the Littrow configuration was far more stable. The grazing incidence system was able to tune to a single external mode, but as conditions changed, either from temperature variations or by grating rotation, the mode became unstable.

The effect in Figure 22 is for an expanding cavity length, but similar results were seen when trying to tune to a successive external mode or when watching the system's intrinsic stability. The mode would start in a stable, locked pattern, then it would become erratic before going multimode. Because of this behavior, not only with the TOLD laser, but also with the Sharp, the grazing incidence system was not extensively studied.

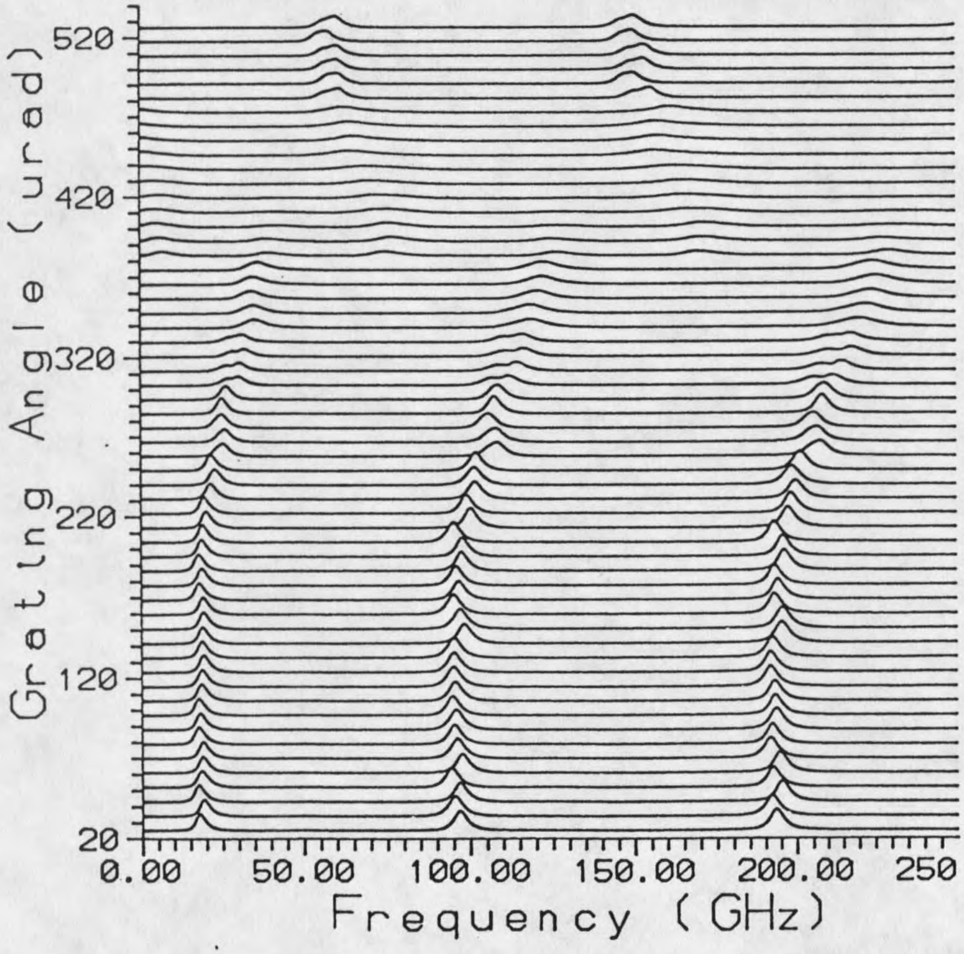

Figure 21. External Mode Tuning: Sharp LT024MD0 Fabry-Perot at 1.55 mm

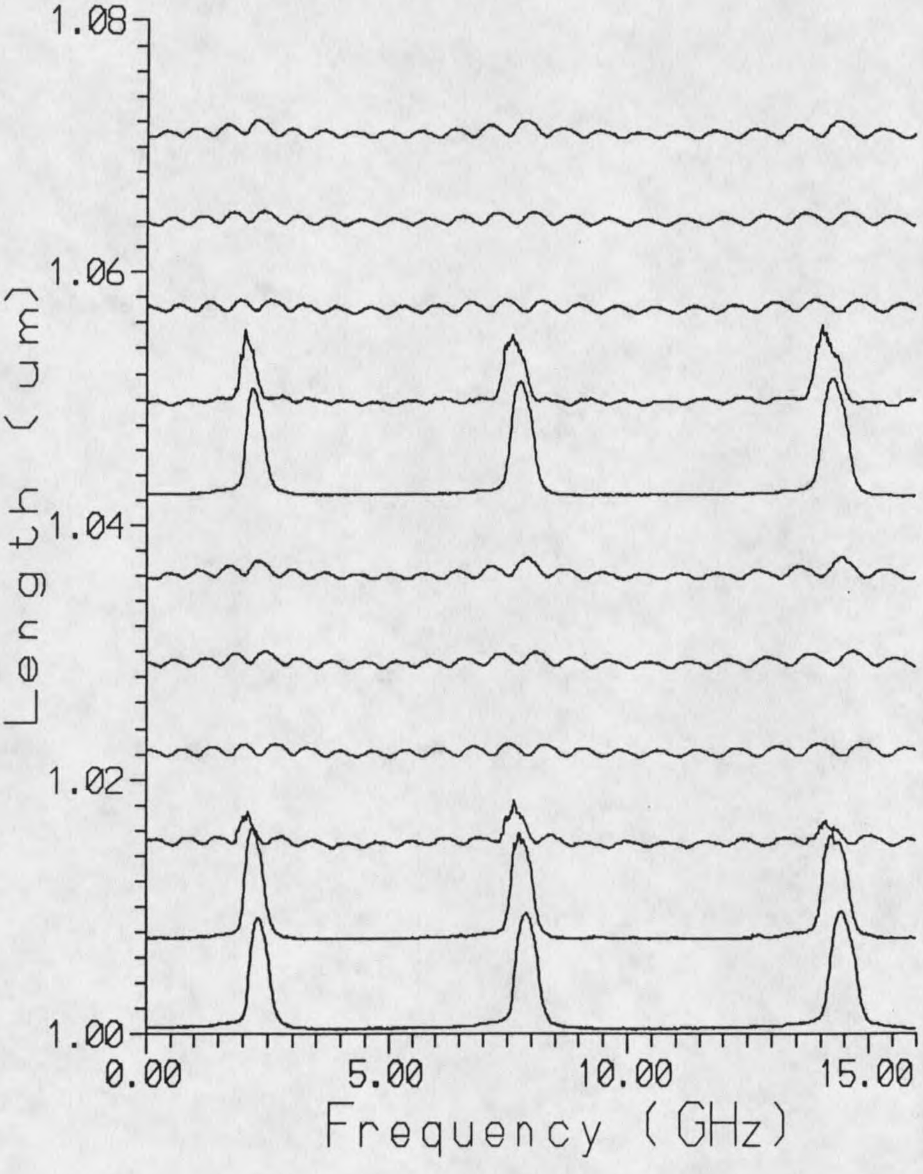

Figure 22. Grazing Incidence Cavity Expansion

Frequency Peak Width and Stability

The frequency peak width of the external cavity mode was narrower than that which the Fabry-Perot could resolve. The modification of a second Fabry-Perot into a Supercavity is discussed in Appendix F. The results from the Supercavity are encouraging as to the ability of the Sharp laser to run single mode in an external cavity.

Figure 23 shows the free spectral range of the Supercavity and the single lasing mode. When using a Sharp LT024MD0 20 mW diode, the maximum power output was 0.84 mW. The apparent large difference between the diode's maximum rating and the final output is due to several effects. First, for the currents at which the diodes were typically run (50 mA), the power output after collimation of the laser was measured at 4 mW. Since the first order diffraction efficiency for the grating is typically around 40%, the possible output is reduced to under 3 mW. Other losses must account for the remainder of the 66% decrease. Higher outputs can be obtained by running the laser at a higher current but this may shorten the diode's life.

Figure 24 is an expanded view of one of the peaks from Figure 23. The peak width is measured to be 1.69 MHz. This width gives the Supercavity a finesse of 4,400. The expected finesse for the cavity is 10,000 so it should be possible to see a peak width of 750 kHz. The discrepancy seems to be due to the R-C time constant of the

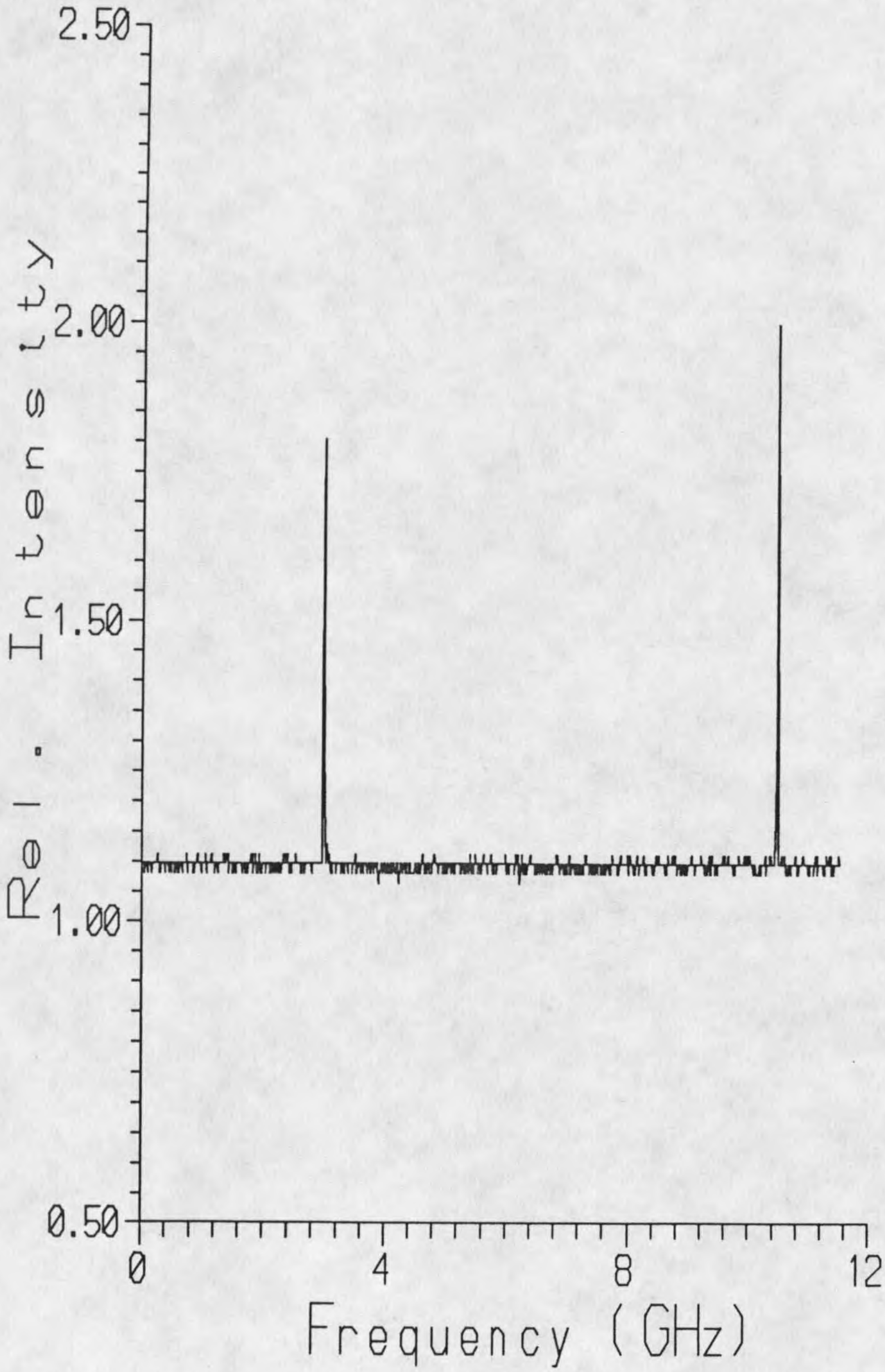

Figure 23. Supercavity Free Spectral Range for Sharp LT024MD0

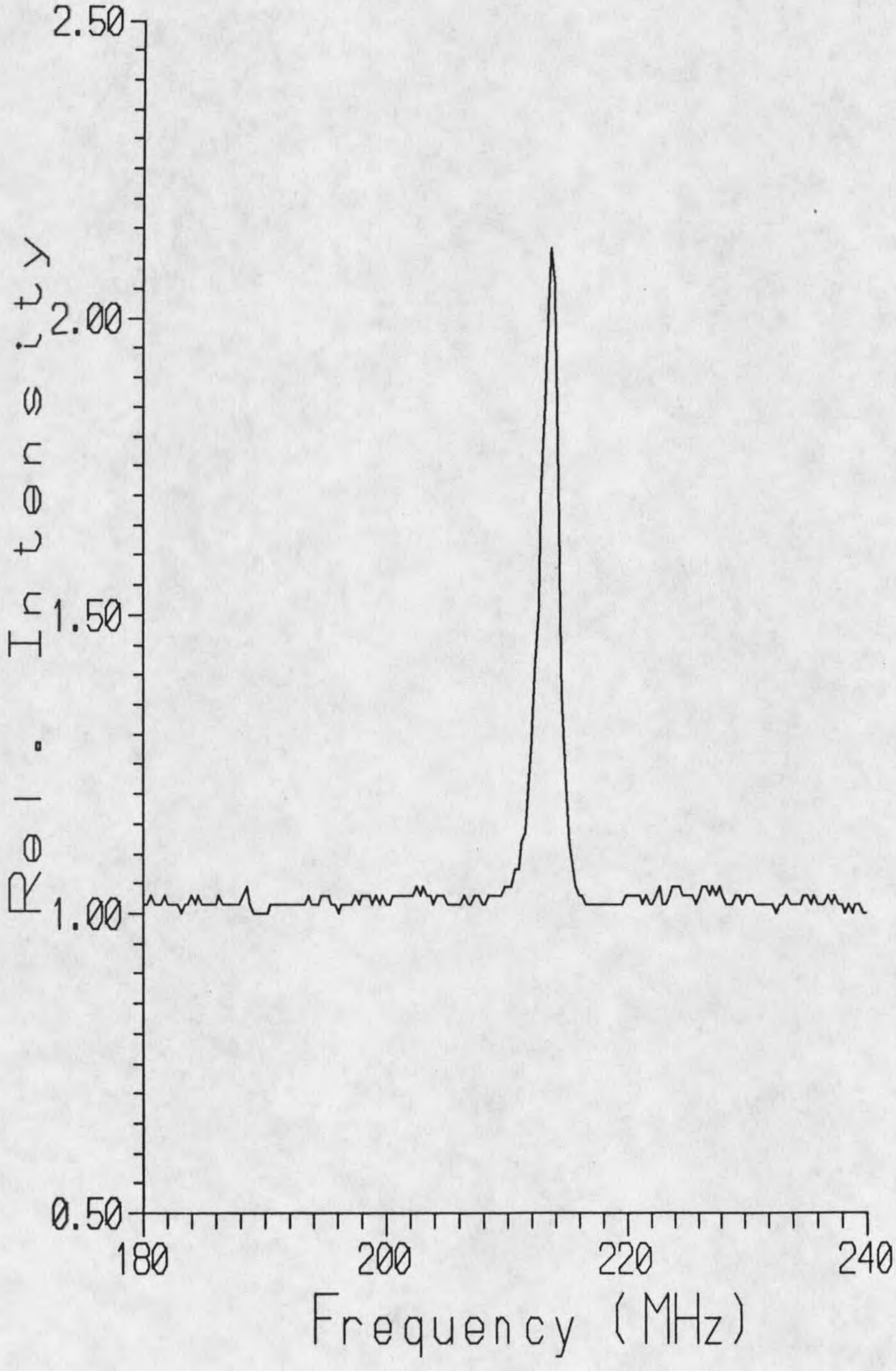

Figure 24. Supercavity Line Width for an External Cavity with Sharp LT024MD0

photodetector and connecting cable measuring the signal.

In studying the external cavity's modes, it was noticed that there were some unexplained shifts. When a free running Sharp laser, which is inherently single mode, was viewed in the Supercavity over the course of two hours, a definite change in the mode position occurred. (Figure 25) This shift is not primarily due to the laser, but rather to the effect of variations in the room temperature which changed the Supercavity. For this graph, there was a 1.4°C change in the room temperature, with a peak change at a somewhat higher level. The mode shifting is related to the thermal expansion of the aluminum parts used in the Supercavity. Aluminum was chosen over Invar, which has a much smaller thermal expansion coefficient, because of the abundance and ability to be easily machined.

As the base of the 11 cm external cavity was also made of aluminum, thermal expansion plays a part in the mode characteristics. In Figure 26, the thermal shift associated with the Supercavity is seen as the broad rightward movement of the modes, while the leftward shift, and subsequent mode hops, are due to the expansion of the base plate.

The thermal expansion of the base plate for the external cavity proved to be a factor over long (2 hour) studies. In a cavity $n = 2L/\lambda$ and $\nu = nc/2L$. For cavity expansion $\Delta\nu = \nu_1 - \nu_2 = (c/2)(1/L_1 - 1/L_2) \approx c\Delta L/2L^2$.
So $\Delta L \approx 2L^2\Delta\nu/c$. Thermal expansion of aluminum is

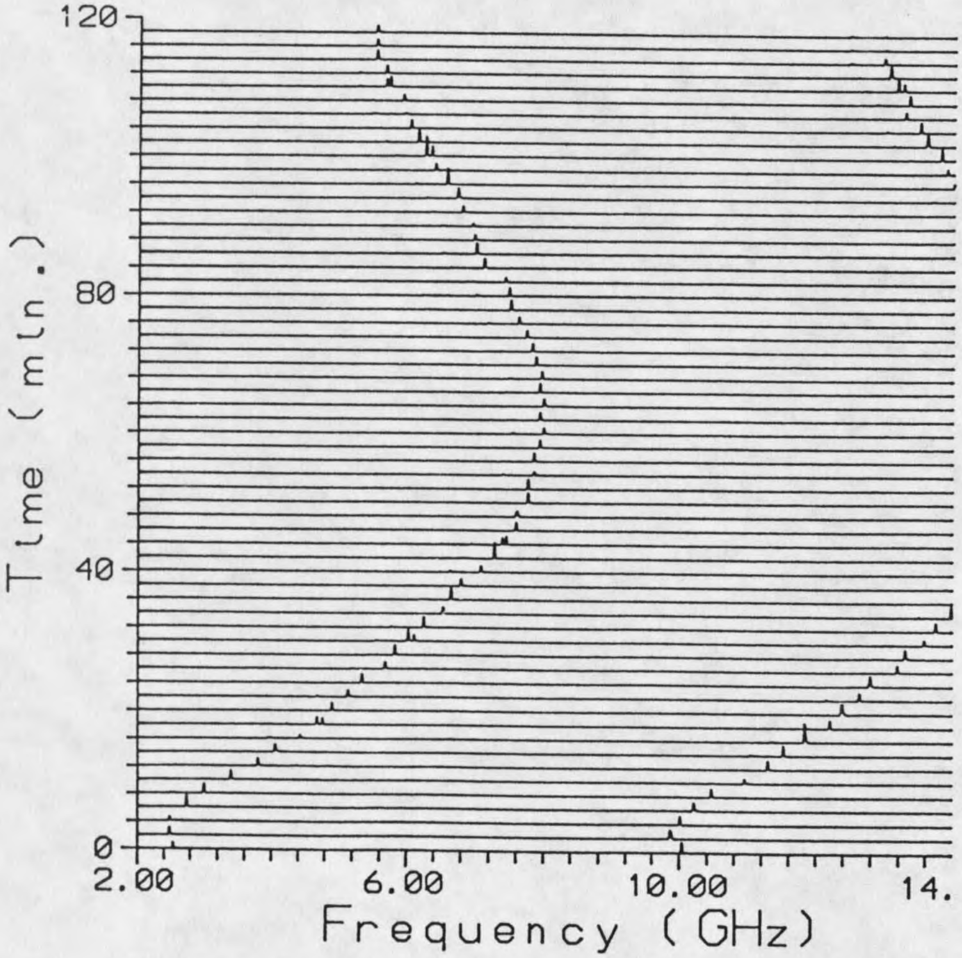

Figure 25. Supercavity Drift

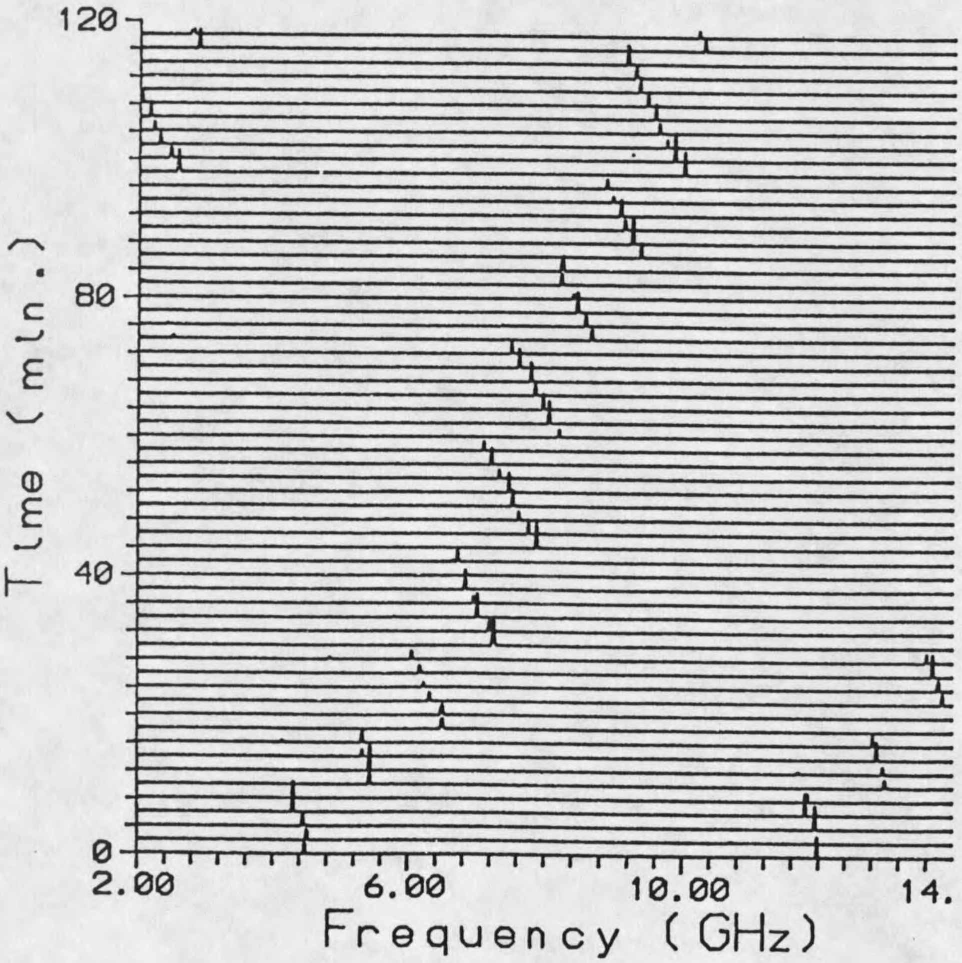

Figure 26. Supercavity and External Cavity Drift

$\Delta L = \alpha L \Delta T$ where $\alpha = 25 \times 10^{-6}$m/°C.[14]

For the 11 cm external cavity with a 1.4°C temperature change the length change is 3.85 µm. Although the frequency change measured from Figure 27 is 14.5 GHz which would correspond to a cavity expansion of 4.2 µm (and a difference of ≈ 8%) using this value would not be quite correct. The thermal shift of the Supercavity needs to be compensated for by aligning the modes shift segments in a continuous line. The reasoning for this is that if there were no temperature variation for the Supercavity, then the mode shifts would form a vertical band as each mode passed across the gain profile. Mode tuning by thermal control of the external cavity is not desirable due to the time delay for the system to settle down and because a better result can be obtained by movement of the grating.

Since it is the mode shift, and not the hops, that characterizes the expanding cavity, placement of the modes with each new mode shift segment placed above the end of the previous one should give a reasonably accurate result for the cavity length change. (Figures 27 and 28) The thermal expansion of the external cavity's base plate can be found by measuring the total resultant change and comparing this to the known temperature change.

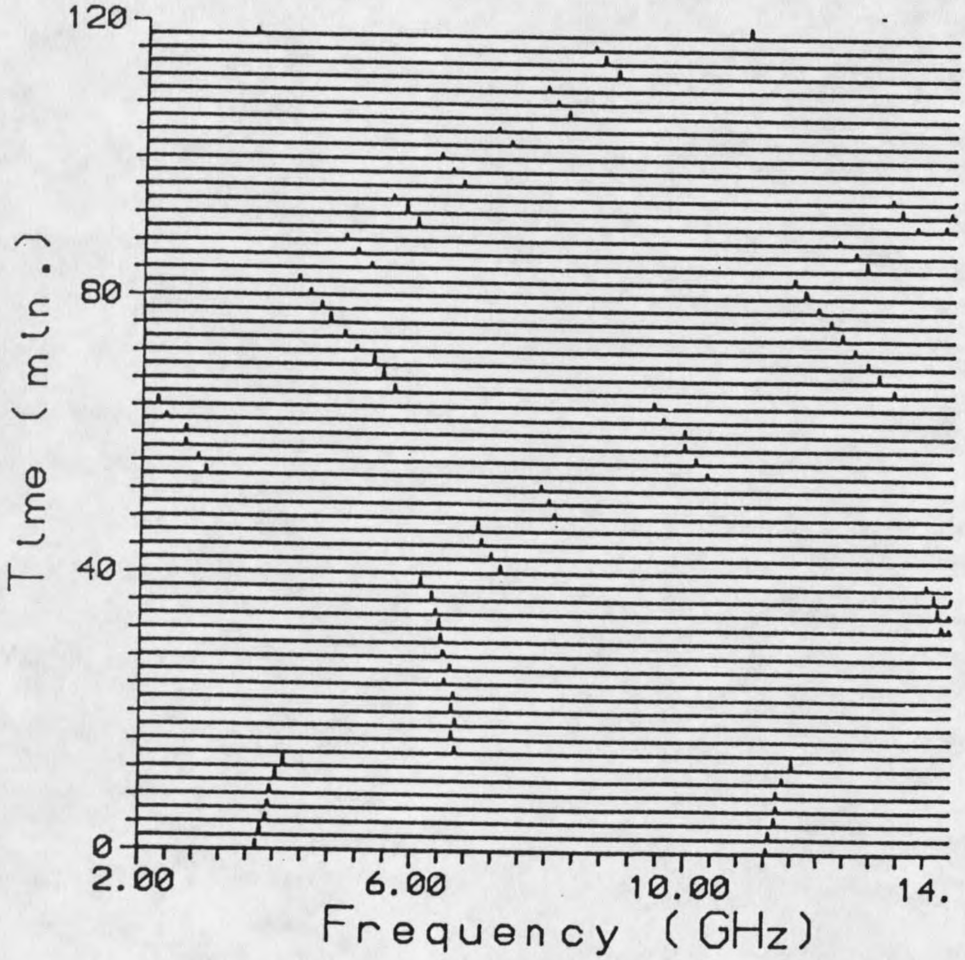

Figure 27. Drift Before Mode Alignment

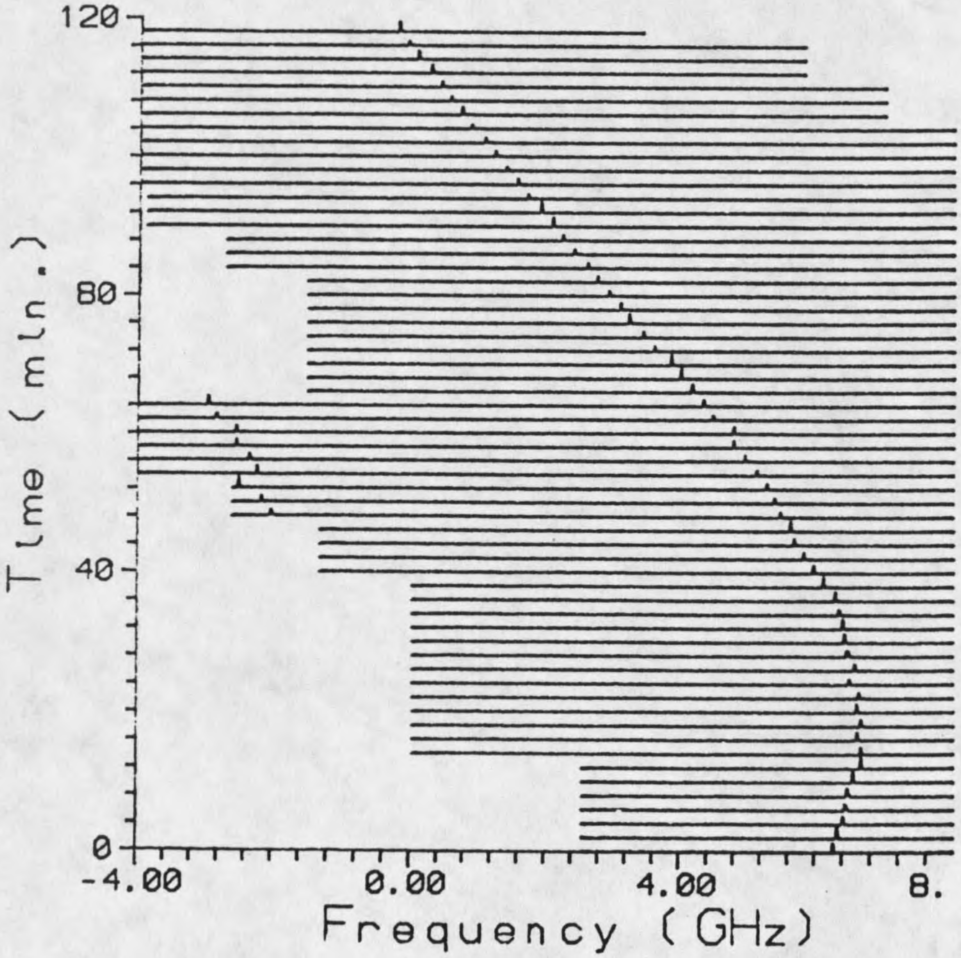

Figure 28. Drift After Mode Alignment

Unfortunately this process was only moderately successful. The shift due to cavity expansion now seems to be 5.25 GHz which is 1.52 μm. This is a difference of 60%. Part of this large discrepancy could be due to an error in measuring the temperature or to temperature induced changes to other components in the system.

CHAPTER 5

CONCLUSION

Tuning a laser diode has been shown to be relatively easy to accomplish with a high line/mm grating and a good collimating lens. Piezo controls for the grating angle and cavity length are useful for adjusting the mode structure and tuning. A mirror which rotates along with the grating is convenient to keep the beam in line with other optics.

The transition between neighboring facet modes is a gradual process owing to a shift of the reduced lasing threshold level across the diode's gain profile. Facet modes which lase are in the region where the gain is above the lasing threshold. Usually, only one facet mode will lase in a properly tuned external cavity. However, as the grating is rotated, two modes may simultaneously exist at an angle where the threshold level provides for two modes with equivalent gain. The transition between modes is often a gradual shift between the relative intensities with one mode eventually dominating.

On an expanded view, there are several external cavity modes which may exist under a single facet mode profile. The transition between the external cavity modes is similar to that of the facet modes in a general sense but there are several unique features. First is that although a simple calculation involving the grating angle is sufficient to predict facet mode transitions, external cavity modes tend to be more resistant to change than what is expected from the equation.

Second, at the transition point, the spectrum tends to either become multimode (as for the Toshiba and Mitsubishi lasers) or has a sudden transition (seen for the Sharp diode). The sudden external mode shift seems to be the result of a good antireflection coating on the diode's facet. The most stable Littrow system employed the Sharp LT024MD0 laser. An external cavity device with an "off the shelf" laser seems to work best with a high powered diode which has an AR coating already on the front facet.

In a very easily made Littrow type external cavity, the Sharp laser provided a tuning range of 11.4 nm, a single mode with a peak width less than 1.7 MHz, and an output power of nearly 1 mW. This is an easily transportable system where alignment is not extremely difficult and is therefore a very promising and relatively inexpensive system.

APPENDICES

APPENDIX A

GAIN PROFILE ACROSS A P-N JUNCTION

The most basic model of the laser diode consists of two materials, an n-type donor and a p-type acceptor, joined by an interface. When a voltage is applied across the interface, electrons pass from the n to the p sides. To do this they drop from an energy level of the conduction band (E_c) to the energy level of the valence band (E_v), with the difference being the energy of the band gap. (Figure 29[15])

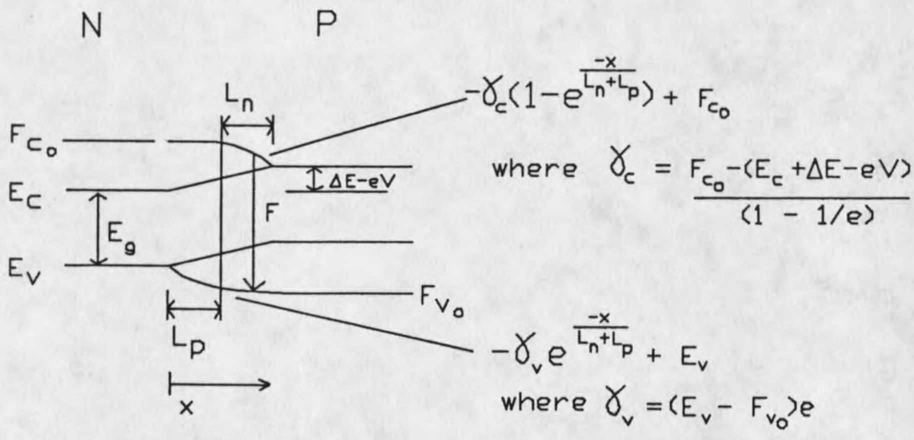

Figure 29. Energy Difference Between Fermi Levels

The electrons occupy states in the conduction band with energy at the quasi-Fermi conduction level F_c and end up with an energy of the quasi-Fermi valence level F_v. Each of