Abstract:
Spectral analysis of laser sources can be accomplished using Fabry-Perot interferometry. When high finesse levels are reached, these interferometers, sometimes referred to as super cavities, have as much or greater resolution than other spectrometers such as a diffraction grating. In this study a Fabry-Perot design is equipped with mirrors that are very highly reflective and have flat, precision polished substrates. The mirrors are closely spaced with the spacing modulated via piezoelectric crystals. Experimental results reveal resolution capabilities at several wavelengths of laser light, and stability issues are investigated. Some design work and numerical approximations to multiple-beam interferometry are also presented.
HIGH FINESSE FLAT-PLATE CAVITIES

by

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APPROVAL

of a thesis submitted by

Michael Steven Barrett

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

Spectral analysis of laser sources can be accomplished using Fabry-Perot interferometry. When high finesses are reached these interferometers, sometimes referred to as super cavities, have as much or greater resolution than other spectrometers such as a diffraction grating. In this study a Fabry-Perot design is equipped with mirrors that are very highly reflective and have flat, precision polished substrates. The mirrors are closely spaced with the spacing modulated via piezoelectric crystals. Experimental results reveal resolution capabilities at several wavelengths of laser light, and stability issues are investigated. Some design work and numerical approximations to multiple-beam interferometry are also presented.
CHAPTER 1

INTRODUCTION

The increasing use and popularity of diode lasers in the lab and in industry have prompted a need for better, less expensive ways to analyze the spectra of these lasers. The utilization of lasers to propagate information in fiber optics in particular will demand convenient, inexpensive means to display these spectra. Success of systems using multiple channels, several closely spaced frequencies, to increase the capacity of the system will depend on the resolution and accuracy of spectrum analyzers used to monitor these systems. High-finesse Fabry-Perot cavities have this resolution, are very compact, and are relatively inexpensive.

Multiple-beam interferometry was investigated by Charles Fabry and Alfred Perot in the late eighteen hundreds. The theory behind these interferometers is well established and will be revealed. The narrow linewidth of gas lasers and the multi-mode operation of diode lasers requires greater resolution from spectrometers. In this work I will show how flat mirrors that are coated and polished with the latest technologies can be incorporated in a Fabry-Perot design to provide this higher resolution.

Key differences between this configuration and traditional designs are the spacing of the mirrors, which determines the spectral width of the instrument, and the
size of the light source entering the cavity. The reflectivity of the mirrors has increased from a typical value of ninety percent to 99.9995%, which serves to improve the finesse or the ability of the interferometer to resolve spectral lines. In addition, the polish of the substrates is controlled to a much greater precision than was previously possible, providing for improved resolution. In a high finesse design, the source is focused down to a small spot size to reduce the size of the surface area being used on the mirrors.
CHAPTER 2

THEORY

Plane wave Approximation

Fabry-Perot interferometry is well known. The following is a basic outline needed for the understanding of the essentials behind flat-plate Fabry-Perots. For a more complete treatment see Hecht\textsuperscript{2}. To begin, the flat-plate refers to the shape of the mirrors. Other configurations call for a radius of curvature in one or both of the mirrors but this leads to complications in the transmission signal, and the device would then require mode-matching to be useful. For an introduction to mode matching see Appendix C, or Larry Watson’s excellent paper on High Finesse Cavities\textsuperscript{3}. It was the need to mode match which prompted the investigation into the flat-plate regime.

Figure 1. Multiple beams are generated in a flat-plate cavity
Figure 1 demonstrates how multiple beams are generated in the cavity. The mirrors are partially transmissive with a transmissive coefficient $t$. Similarly the reflective coefficient is $r$ such that

$$R = rr^*$$

and

$$T = tt^*$$

where $R$ is the reflectivity and $T$ is the transmissivity. $R$ and $T$ are the usual parameters specified in industry when mirrors are selected. It is assumed here that the mirrors are identical.

When a plane wave is incident on the cavity at some angle $\theta$, with initial amplitude $E_0$, multiple beams are seen in transmission $E_1, E_2, E_3, \text{etc.}$ These have amplitudes

$$E_1 = E_0 TR$$
$$E_2 = E_0 TR^2$$
$$E_3 = E_0 TR^4$$

.....

and will have path length differences and phase shifts according to the incident angle and the mirror separation $d$. This path length difference, $\Lambda$, is given as

$$\Lambda = 2nd \cos \theta$$

with the index of refraction $n$ set equal to 1. If $\delta$ is the phase difference arising from the different paths according to

$$\delta = k_0 \Lambda$$

where $k_0$ is the wavenumber given by
\[ k_0 = \frac{2\pi}{\lambda_0}, \]

then the transmitted beam can be rewritten as a sum of the multiple beams:

\[ E_t = E_0 e^{i\pi} T \left[ 1 + \operatorname{Re}^{-i\delta} + R^2 e^{-2i\delta} + \ldots + R^{n-1} e^{-(n-1)i\delta} \right] \]

where \( n \) denotes the \( n \)th term of the sum. When \( n \) is allowed to go to infinity, it converges to a nice closed form:

\[ E_t = E_0 e^{i\pi} \left[ \frac{T}{1 - \operatorname{Re}^{-i\delta}} \right]. \]

To get the intensity \( I_t \), multiply by the complex conjugate \( E_t^* \) to give

\[ I_t = I_0 \left[ \frac{T^2}{(1 + R^2) - 2R \cos \delta} \right]. \]

Now introduce a factor \( F \) called the coefficient of finesse

\[ F \equiv \left[ \frac{4R}{(1 - R)^2} \right] \]

and use a little algebra to finally rewrite this as:

\[ \frac{I_t}{I_0} = \frac{1}{1 + F \sin^2(\delta / 2)}. \]

The denominator is found in the literature as the Airy function. Figure 2 is a plot of the Airy function for various reflectivities. As \( R \) approaches 1 the peaks get sharper and more defined. Here the sharpest correspond to a reflectivity of \( R=0.96 \) and progress down to a value of \( R=0.07 \). As seen here a peak in the transmission will occur when \( \delta \) is an integral multiple of \( 2\pi \). Remember the phase \( \delta \) is dependent on
the incident angle and on the mirror spacing \( d \). In all the work presented here the incident angle is near normal. The mirror spacing \( d \) is varied using piezoelectric crystals which change their length in response to an applied voltage.

\[
\begin{align*}
R &= 0.96 \\
R &= 0.07
\end{align*}
\]

Figure 2. Airy function

With this qualitative groundwork completed the next step is to describe the various parameters associated with Fabry-Perots when they are used as spectral analyzers. Consider a plane wave, monochromatic source incident on the cavity with normal incidence, and \( \lambda_0 \) the wavelength. To deviate from ideal, introduce an
absorptance \( A \) to account for losses at the mirror due to induced surface currents in the dielectric coatings. Now

\[
T + A + R = 1
\]

to satisfy conservation of energy.

With this added consideration a complication arises in the phase shift \( \delta \). The reflections at the mirrors will suffer an additional phase shift \( \phi \), which may not be zero or \( \pi \) as before. \( \phi \) is a constant however, and the near normal incidence angle combined with the condition \( d >> \lambda_0 \), renders \( \phi \) negligible. If the Airy function is denoted \( A(\delta) \) then the above expression for the relative transmission intensity can be rewritten as

\[
\frac{I_t}{I_0} = \left[ 1 - \frac{A}{(1 - R)} \right] A(\delta).
\]

This expression determines the efficiency of the cavity. It is important to remember here that this closed form was based on the fact that the sum of transmitted fields was allowed an infinite number of terms. This fact will become important later when experimental results on transmission intensities are explored.

Referring back to figure 2, the distance between two successive peaks is called a free spectral range and is the spectral width of the cavity in Hz. It is a function of the cavity length \( d \) and is defined as

\[
\nu_{fsr} = \frac{c}{2d}.
\]
This is an important quantity as it establishes the maximum frequency difference that can be unambiguously resolved. Lines with a spectral separation greater than $v_{fr}$ will overlap and cannot be resolved. Remember the width of the line was related to the reflectivity of the mirrors. This leads to another important quantity called finesse.

The finesse of the cavity is defined as the free spectral range divided by the full width at half maximum of a given transmission peak. Thus a more narrow peak increases the finesse and indicates a greater resolving power (peaks are less likely to be overlapped if they are narrow). It is related to the reflectivity of the mirrors as reflective finesse $F_R$

$$F_R = \frac{\pi \sqrt{R}}{1 - R}.$$ 

Unfortunately the finesse of the instrument is also dependent on the form (flatness) of the mirror $F_f$

$$F_f = \frac{m}{2}$$

where $m$ is specified by the manufacturer as the flatness of the mirror in $\lambda/m$. Total finesse of the cavity is $F$:

$$\frac{1}{F^2} = \frac{1}{F_{fr}^2} + \frac{1}{F_{fr}^2}.$$ 

Finally, the resolution of the cavity is given as

$$v_{min} = \frac{c}{2dF}.$$
This implies that spectral characteristics with spacings smaller than $\nu_{\min}$ will not be resolved.

This is a convenient place to explain why the flat-plate cavities discussed here deviate from traditional Fabry-Perots with lower finesses. Typically finesse ranges from fifty to one hundred in common laboratory designs. These cavities are illuminated with broad sources to get better interference and the reflectivity is down around ninety percent or less. By decreasing the spot size of the beam to fractions of a millimeter the surface area being used on the mirror is consequently reduced. This effectively minimizes the dependence of the total finesse on the mirror form. Improved coating and polishing technologies have driven the reflectivity to very high values of $R>99.99\%$ while improving form flatness to $\lambda/200$. Finesse values of greater than one thousand are presented below.

**Gaussian Optics**

The above development is what is typically found in the literature for Fabry-Perots, that is the plane-wave approximation is adopted. The sources used in this project, the HeNe and diode lasers, are not emitting plane wave beams however. In fact they emit a beam with a Gaussian structure, but the above parameters describing the interference effects are still valid. That is, an Airy type pattern is still observed in transmission and the resolution is described by the finesse, and so on. Here a little effort is expended to familiarize the reader with Gaussian beams.
A complete derivation is not necessary when only the characteristics of the Gaussian beam need be explored to reveal the departure from the above plane-wave approximation. For a rigorous development see Saleh and Teich\(^6\). As implied above, the beam of a laser is Gaussian. Mode matching a non confocal or high finesse cavity involves matching the phase fronts of the beam to the curvature of the mirrors. This is a key point in the flat-plate regime: the radius of curvature is infinite thus the cavity cannot, or need not be mode matched.

Consider a paraxial wave in a resonant cavity such as a laser with complex amplitude \( U(r) \), wavenumber \( k_0 = \frac{2\pi}{\lambda} \). \( U(r) \) satisfies the Helmholtz equation \( \nabla^2 U + k_0^2 U = 0 \). One solution is the paraboloidal wave:

\[
U(r) = A_0 \frac{\omega_0}{\omega(z)} \exp\left[-\frac{\rho^2}{\omega^2(z)}\right] \exp\left[-ik_0 z - ik_0 \frac{\rho^2}{2R(z)} + i\zeta(z)\right].
\]

\( \rho^2 = x^2 + y^2 \)

This is the \( TEM_{00} \) wave. See figure 3 to illustrate some of the quantities involved.

\[\text{Figure 3. Gaussian beam}\]
At the waist of the beam, \( \omega_0 \), \( z \) is zero. \( z_0 \) is the Rayleigh range and is the distance along the beam axis \( z \) where the beam radius has increased to \( \sqrt{2} \omega_0 \). Sometimes a similar quantity called the confocal parameter is referred to in the literature\(^7\) and is simply twice the Rayleigh range. This is the region of the beam where it is relatively collimated and most resembles a plane-wave source.

The various quantities of interest are the beam radius, \( \omega(z) \), which is the radius of the beam out to where its intensity has dropped off to \( 1/e^2 \)

\[
\omega(z)^2 = \omega_0^2 \left[ 1 + \left( \frac{z}{z_0} \right)^2 \right];
\]

the wavefront radius of curvature \( R(z) \)

\[
R(z) = z \left[ 1 + \left( \frac{z_0}{z} \right)^2 \right],
\]

a phase shift \( \zeta(z) \) over what would be the plane wave

\[
\zeta(z) = \tan^{-1} \frac{z}{z_0},
\]

and the Rayleigh range

\[
z_0 = \frac{\pi \omega_0^2}{\lambda}.
\]

One more relation is useful for calculating the waist size and consequently the Rayleigh range of a beam, when the waist of a beam is placed at the focal length of a lens such as one of the microscope objectives used in these experiments. If the
incident beam has a waist size of $\omega_1$ and the focal length of the lens is $f$, wavelength is $\lambda$, then the output waist size $\omega_2$ is given by

$$\frac{\pi \omega_1 \omega_2}{\lambda} = f.$$ 

This expression is valid when the Rayleigh range of the incident beam is much larger than the focal length of the lens. This is discussed in more depth in Yariv’s Quantum Electronics$^8$.

The beam in the cavity has a small spot size or beam radius to get higher finesse. Naturally it is best to position the waist in the center of the cavity as this is where the beam radius minimum occurs. Later some interesting effects in the transmission lineshape are presented when the waist is not in the cavity, and beams with larger radii are used.

Here again there is a noteworthy point of departure from traditional designs for Fabry-Perots. Notice the intimate dependence on the beam axis variable $z$ in each term. Traditional designs have longer cavity lengths on the order of centimeters. After $n$ reflections the wavefront will now have a beam radius and radius of curvature where $z$ now equals $2nd$. If this distance is significantly beyond the Rayleigh range, collimation and phase relationships are no longer favorable for good interference. In this study the cavity spacing is on the order of 20 microns to insure against this effect and improve finesse.
CHAPTER 3

EXPERIMENTAL APPARATUS AND TECHNIQUE

One of the great beauties of Fabry-Perot interferometry is its simplicity. To hold two partially transmissive mirrors a given distance apart and then modulate that distance is indeed an easy feat to accomplish. To do this with enough stability to display spectra of light sources with micron sized wavelengths is a different matter. The small wavelength dictates how much noise can be tolerated in the device, both vibrationally and electronically. Thermal effects will change the physical dimensions of the interferometer enough to see a shift in the spectra. The laser source is sensitive to back reflection which necessitates some sort of isolation. These and other issues are addressed in the following experiments.

A schematic representation for the basic experiment is shown in figure 4. Here the HeNe laser with 632.8nm wavelength is shown launched into Newport’s model F-SV single-mode fiber with a 20x objective. For details on launching into a fiber see Appendix A. An output objective is selected to give a collimated beam with a Rayleigh range long enough to account for the distance from the objective to the cavity. The overall distance the beam will effectively travel while being reflected in the cavity must also be accounted for. With a good selection of objectives this was easy to accommodate.
Figure 4. Basic experimental setup

After collimation the beam passes through a beam splitter to combine it with the green beam from the HeNe at 543nm. The beam splitter has properties of transmission greater than 85% at 680 nm, while its reflectivity is greater than 99% at
530nm, when it is positioned 45 degrees with respect to either beam. The green beam is used to align the detector with the output of the interferometer as well as to tune the parallelness of the mirrors. Remember the mirrors in the cavity are highly reflective over a relatively narrow bandwidth of 10% of the principle wavelength. This allows the green beam to pass through easily while the red beam cannot be seen in transmission, unless the cavity is in the resonance condition. See Appendix C for details on equipment connections, operation, and alignment techniques.

Initially the cavity consisted of a modified Burleigh model which held one mirror attached to a cylindrical shaped piezo electric transducer (PZT) and positioned the opposing mirror on a floating, spring loaded mount. The separation distance and the parallelness of the mirrors were set by three micrometers positioned 120 degrees apart. Small mirrors with 7.5mm diameter substrates were cheap but had some drawbacks. One problem was they needed to be held in an adapter to be used in most optic mounts. More importantly they allowed some bleeding around the edge of the mirror where the coating had stopped. As a result, secondary etalon effects were seen in transmission.

Figure 5. Secondary etalon
At first it was hard to believe the multiple beam effect was being supported by the side of the mirror with low reflection. This after all was simply the polished surface of the fused silica substrate with the standard 4% reflection. A quick calculation showing the ratio of the expected peak intensity to that generated by the secondary etalon gave results in very good agreement with what was observed on the scope. This led to the idea of having the mirrors anti-reflective coated.

Further testing with the smaller mirrors revealed another problem. Technicians at Research Electro Optics, the vendor of the mirrors, explained that the coating out at the edges typically is not as thick as it is towards the center and therefore cannot be as reflective in regions out at the edges as they are in the center.

Both the absorption and transmission per reflection is increased in this region of thinner coating. This problem led to the adoption of the one inch diameter substrate as finesses of better than 200 could not be achieved. The one-inch mirror is one quarter inch thick and can be coated and ground to fit most needs.
Coating and polishing is critical in this work. Fused silica is the most common substrate used. PMS or Research Electro Optics has a technique for polishing which gives surface roughness on the order of angstroms. Overall the flatness is $\lambda/10$ to $\lambda/20$. This is the number which dictates the form finesse of the instrument; however, the flatness is rated over the entire surface. When a small portion of the central region of the surface is considered then higher finesse is possible.

Typically the finesse of the cavity is around a thousand. If the mirrors are reflective enough to give a reflective finesse of fifty thousand then the form finesse will dictate the total finesse. From this the flatness is as good or better than $\lambda/1000$. Mirrors of this quality are hard to find and even harder to find off the shelf. This makes them relatively expensive. A pair of one inch mirrors can cost around $500 and will go up from there with more specialty coatings, i.e., for non standard wavelengths. Newport manufactures SuperMirrors™ with similar characteristics for roughly $500$ a piece.

Getting the mirrors parallel enough to keep beam walk-off under control proved to be a task beyond the capabilities of the modified Burleigh device. The micrometers were not sensitive enough even with forty pitch-screws. The slightest attempt at adjustment would result in a loss of the signal on the scope and usually a vain attempt to find it again with further adjustment. Sensitivity in angular adjustment is at best 2 mrad for this device. Clearly, more sensitivity and control was needed in the tuning of the mirror to ensure parallelness.
The cavity needed to support enough reflections to give a finesse of one thousand. A sensitivity of microradians was needed to keep $\alpha$ within limits such that one thousand reflections could occur before walk-off. This prompted the usage of Burleigh's piezo-electric aligner/translator, or PZAT. These are employed in Burleigh's commercial Fabry-Perots and proved to be an excellent solution to the sensitivity problem.

Figure 8 shows the design of these actuators. Three piezos arranged in a triangular configuration give translation as well as tilt adjustment. It can translate up
to two microns using Burleigh’s RC-44 Programmable Ramp Generator. Each piezo is controlled with its own bias control ranging over 0-600 V. This gives approximately three microradian resolution to the tilt adjustment.

Figure 8. PZAT-81 Aligner/Translator

Though expensive, around one thousand dollars, the PZAT is very convenient to use. Physical contact with the cavity was no longer necessary to tune the mirrors.

Early cavity designs were primitive and not so stable both thermally and vibrationally. Figure 9 is the first prototype featuring the PZAT-81. It incorporates a translation stage to facilitate the setting of the mirror spacing. This worked well as the mirrors were fully exposed to allow feeler gauges in around their edges. Unfortunately having the mirrors exposed in this fashion also left them vulnerable to any contaminants in the area. This is hazardous when the mirrors are spaced on the
order of the size of dust particles. Dust entering and depositing on the mirrors can inhibit interference in the form of scatter.

Figure 9. Early prototype with translation stage and PZAT-81

The base plate could be mounted to any commercial magnetic base or it could be bolted to another stage which offered tilt adjustments. This typically was the arrangement as the tilt stage could be vibrationally isolated from the bench with sorbathane cleats. Commercially available optic mounts were incorporated to provide easy, rough alignment of the mirrors. Though crude, the design proved successful with finesses of 1500 to 3000.

Early experiments were conducted simply to see if it would work. After the device was roughly aligned using the green beam, the mirror spacing was set, and the
source was brought in normal to the mirror, ramping and detection began. The RC-44 supplies a sawtoothed high voltage to the piezo transducers. Typically the amplitude did not exceed 400V from the bottom of the ramp to the top. A main bias controls the relative ground. The ramp cycle is also adjustable and was usually set at 50 or 100ms. This cannot be selected arbitrarily as resonances can be excited in the PZAT but this was overcome by the addition of aluminum mounting pieces to hold the mirrors. Ramping too fast resulted in lower finesses.

Detection is accomplished using New Focus's 2001 amplified detector. Amplification needed to be at maximum as the transmission intensity is typically in $\mu$W for an input intensity of 1 mW. This was a consequence of using mirrors with such high reflectivities of 99.995%. Mirrors with higher transmission characteristics will be tested in the future. Lensing onto the detector is easily accomplished using any convenient focal length lens. To ensure the spot at the detector was smaller than the photodiode, a microscope objective with a small focal length replaced the spherical lens.

The signal is conveniently monitored using a Tektronix 2230 Digital Storage Oscilloscope. With two input channels the ramp signal can be monitored simultaneously. This is important because it allows control over where the resonance peak will occur with respect to the ramp. In general the ramp behaves more linearly and with less noise in the middle 80% of the cycle as opposed to either end section.
As voltage increases the PZTs shrink in length and then relax during the sharp decrease in voltage. This accounts for the smaller resonance peaks at the relaxation portion of the ramp. The position of the main peaks is controlled by the main bias of the ramp but their relative position with respect to each other is set by the ramp amplitude, and λ. A ramp signal with a large enough amplitude can produce as many resonances during a cycle as will be permitted by the tolerances of the PZT. Remember the length of the cavity needs to change by a small λ/2 to reach the next resonance.

Measurement is also simplified using the 2230. Any signal can be saved and analyzed using cursors on screen. Here the Free Spectral Range is measured as the difference in time between the two main peaks, usually in ms. Upon magnification of one of the peaks the FWHM can likewise be measured as some width in time. From here the finesse can be calculated as FSR/FWHM. The scope trace is captured and
stored on a computer using a GPIB interface and programs written in basic to convert the trace into data pairs.

After the basic idea was proved successful the task of making the interferometer stable prompted further experimentation. Vibrationally the device can be isolated well enough using sorbathane between the base and the optical bench. Thermal drift then became the main thrust. The spectral characteristics of the interferometer are determined by the mirror separation. Thus any change in that separation distance will be observed as a drift in frequency. With the above design a drift of better than twice the FSR was measured per degree C.

The experimental setup to measure this thermal drift is identical to that above with the addition of a thermistor attached to the cavity to monitor the temperature and a digital volt meter, DVM, to convert the voltage drop across a resistor in the temperature monitor, see Appendix C. Here the trace on the scope is captured via GPIB and analyzed using Quick Basic code. The program records the position of the transmission peak relative to some initial value and gives the temperature at that position. This relative position can be converted to frequency and consequently a drift in frequency vs temperature plot is generated.

Most of the components in the above design are made of aluminum which has a relatively large linear thermal expansion coefficient of 24E-06/ C°. This means a 1 meter length of aluminum will expand by 24 microns for every 1 C° change in temperature. Somehow the mirrors needed to be held apart by a material with a low thermal expansion.
Figure 11 shows the most advanced design to date. It features the PZAT-81 for scanning and tilt adjustment, or tuning, and a ULE spacer to hold the mirrors apart. ULE, or Ultra Low Expansion material, is a ceramic-like substance with a thermal expansion coefficient of $10E-10 / \degree C$. In this design the aluminum sleeve is allowed to expand freely but this expansion is taken up in spring loaded screws holding the end cap fast against the ULE spacer.

Another interesting aspect to this design is the recombinant thermal expansion design of the Burleigh PZAT-81. Depending on where the body of the PZAT-81 is clamped, an amount of aluminum will expand to alter the position of the mirror attached at its end. If the clamp ring is at the right position there will be just enough aluminum expanding to cancel the expansion of the piezo material, and any other various pieces causing expansion in the opposite direction. In this case the mirror will remain still. This position is found experimentally and requires the ULE spacer length to vary as well as the length of the sleeve. With this design thermal drift was reduced to a fraction of a Free Spectral Range at 2400GHz/Deg C (FSR = 6000 Ghz).

Sacrifices included the loss of convenience in setting the mirror spacing with the translation stage and access to the mirrors. Small windows were cut into the end cap to let feeler gauges in to set the mirror separation at 20 μm. The mirrors still needed to be roughly aligned and the convenience of the commercial optic mount with its finely threaded tilt adjustments was gone.
Figure 11. Thermally stable, ULE spaced design

Here a mirror is shown mounted floating on a rubber o-ring. Three 40 pitch screws compress the mirror mount against the o-ring. The screws are easily accessed at the end cap and can be adjusted with an appropriate ball driver. The three screws cause the mirror to tilt through a large enough angle with enough resolution to give a rough adjustment to parallelness. From here the PZAT-81 is capable of tuning up the signal.

Calculations have been made regarding the frequency drift due to a change in the index of refraction of the media according to
\[ \frac{26}{n} = \frac{\Delta n}{n} = \frac{\Delta v}{v}. \]

n can change with changes in pressure as well as temperature. This effect is at the MHz level however, which is negligible in the large FSR realm of these experiments. It is a very important concern in confocal designs with larger mirror spacings\(^9\).

Up next in the series of experiments was to determine how to effectively isolate the laser source from back reflection. Back reflection, reflections of light off any optics downstream from the laser that are directed directly back into the laser, can cause the laser to change frequencies chaotically, which will show up as noise at the transmission signal of the interferometer.

A simple way to measure the back reflection is depicted in figure 12. A 50-50 beam splitter is placed in front of all other optics. This picks off any beam returning from the optics, including the interferometer and the fiber optics. The beam's magnitude is measured using Newport's model 840 optical power meter. When \( \varepsilon \) (figure 13) is zero the incident beam on the cavity is normal to the surface and back reflection is at a maximum. The cavity is held in a Newport two inch optic mount and is equipped with micrometers for tilt adjustment in pitch and yaw. A plot of tilt angle versus back-reflection power reveals the dependence on the cavity orientation. Unfortunately an order of magnitude is the limit in how well the laser is isolated using this technique.
Figure 12. Back-reflection experiment.

Figure 13. Tilt angle of cavity.
Evidently the fiber optic and its objectives were introducing a significant amount of back reflection as well as the cavity. The next phase of the experiment was to use a fiber beam splitter instead of the optic shown above.

The Gould 2X2 fiber beam splitter uses Corning Flexcor 850-5/125 single mode fiber in its inputs and outputs. The laser is launched into I1 in the usual way while I2 is directed at the Newport power meter. O1 is directed at the cavity through an appropriate objective while O2 is optically isolated using index matching grease. The tilting experiment is repeated starting at $\epsilon = 0$ and measuring the reduction in power at I2. This proved to be successful in reducing the total back reflection due to non-cavity optics.

Some experimentation was done in the isolation of the unused inputs and outputs of the beam splitter. Engineers at Gould state the back reflection due to the beam splitter itself should be 60db down from the input. We were able to measure 50db with the two outputs index matched in grease. Mandrel wrapping, wrapping the fiber around a 1/4 inch bolt, did not significantly improve results. Ideally a drop of
40db from the input intensity is considered fairly well isolated. An alternative method of isolation such as incorporating a Faraday rotator or a fiber optic isolator may be necessary to achieve this.

The remaining issues to address are the unexpectedly low transmission intensity and the asymmetry of the lineshape. Referring back to figure 2, the Airy pattern determines the expected lineshape and from the expression for the efficiency, the relative peak intensity can be determined.

Mirrors from Research Electro Optics are highly reflective- 99.996%. Engineers specify the absorption at 4 ppm (parts per million), and the transmission is thus 35 ppm. At these values the efficiency should be 81%. That is, given an input intensity of 1 mW, the peak intensity should be roughly .81 mW. The peak intensity observed in the lab is several orders of magnitude down from this. After several weeks of head scratching, the low cavity efficiency can be attributed to the high reflectivity of the mirrors and the limited number of reflections occurring in the cavity. This is discussed in the section on Cavity Efficiency in chapter 5, Numerical Approximations.

The asymmetry of the lineshape was a real mystery. At first it was attributed to a slow response time associated with the detector in combination with some RC time delay in the connecting wires and electronics. This was proved incorrect when these factors were changed and no corresponding change in the lineshape was
Figure 15 is a plot showing the characteristic asymmetry. A slower rising “wing” to the left precedes the maximum peak which is then followed by a steep drop-off. The asymmetry always lies to the left in the principal peaks and is to the right in the relaxation cycle of the scan. This fact was critical in the first experiment to try to understand this effect.

Figure 16 shows a schematic of this experiment. Here the cavity is mounted on a translation stage along with the focusing lens and detector. This allows the cavity to be positioned at different points on the optical axis (z axis). The position of the waist is roughly known. As the center of the cavity is moved in front of and behind the waist, the lineshape is monitored on the scope. The asymmetry is seen to
increase with greater distance from the waist on either side and will be minimized when the waist is at the center of the cavity. It does not flip sides as might be expected. The cavity can be reversed so that the scanning mirror is on the incident side with no effect.

![Diagram of Gaussian beam in cavity]

Figure 16. Gaussian beam in cavity,

The above experiment essentially assumes the asymmetry is due to the Gaussian nature of the beam. The wavefronts become more and more curved with greater distance from the waist, but this curvature changes its orientation depending on which side of the waist is being used. Consequently any asymmetry generated by this should swap sides in a corresponding fashion. This is in fact what happens in a numerical simulation of the folding of a Gaussian beam in a Fabry-Perot
interferometer. This is discussed in more detail in Chapter 5, Numerical Approximations. The effect is more successfully explained assuming the beam is within the planewave approximation and one or both of the mirrors have a very slight curvature.

Figure 17 shows the Reticon array in position to detect the spot size of the beam entering the cavity. It is the same distance from the kinematic mirror as the center of the cavity is from the mirror. Removal of the mirror allows for the beam to enter the cavity to monitor the lineshape. Now a microscope objective is selected to give a relatively collimated beam with a long Rayleigh range and the planewave approximation may be adopted. The spot size is measured with the reticon array and then the kinematic mirror is removed. Smaller spot sizes correspond to shorter focal length objectives. Unfortunately the smallest spot size to give a Rayleigh range long enough is about .5mm. With this selection the asymmetry is present but not as exaggerated as it is with larger spot sizes.

In this way the amount of the mirror being used is controlled by varying the spot size. If the mirror is indeed curved on the order of one thousand meters radius, then curvature of the wavefronts is produced through the slight lensing of the beam at each reflection. The lensing will be more pronounced the further away from the optic axis, i.e. with larger spot sizes. In the limit of a perfectly plane mirror the asymmetry will disappear. With some curvature present the asymmetry will always likewise be present as long as the spot size is not zero. A numerical approximation shows this for
several spot sizes and radii of curvature. Here the asymmetry can be made to swap sides if the sign of the mirror radius is changed.

Figure 17. Using a Reticon Array to Measure the spot size

In a sense it could be argued that this is no longer a flat-plate interferometer and the asymmetry is the result of the non-mode matched state of the cavity. If the mirrors are indeed curved then higher order modes can be supported in the cavity. With such a large radius of curvature however, the spacing of the higher order modes is so small as to be unresolvable in the large FSR, low resolution limit of these cavities. The higher order modes have higher frequencies and are thus on the opposite side of the asymmetry in the line, see Appendix B.
The spectra of a diode laser running multimode provides a constant of calibration for the cavity. First the NDL 3200 is directed into a diffraction grating spectrometer to find the line spacing (figure 22). With this in hand the laser is then directed into the cavity and its spectra is displayed on the oscilloscope. The mode spacing is measured at .192nm. On the scope the mode spacing is measured at 1.56 ms. This gives the calibration constant of the cavity: .192nm/1.56ms. The FSR on the scope is 113.0 ms which translates to 13.9nm using the constant. \( \Delta \lambda / \lambda = \Delta \nu / \nu \) provides the necessary conversion from wavelength to frequency and finally, \( c/2L = \Delta \nu \) gives the cavity length \( L \) at 16 \( \mu \)m.
CHAPTER 4

EXPERIMENTAL RESULTS

The following figures are spectra of various laser sources generated from both the earlier cavity design with the translation stage and the more recent design incorporating a ULE spacer. Figure 18 is a spectrum of the HeNe gas laser at 632.8 nm. Here a Free Spectral Range of 7500 Ghz is generated from a cavity of length 20μm. The cavity length is not known precisely, i.e. it has not been calibrated yet. The finesse is a rather high 3600 giving a resolution of .003 nm, see figure 19. The data is normalized and attenuated to match what was detected with the New Focus 2001 detector. The detector was set to amplify the signal by a factor of 3000. As can be seen the transmission signal is rather weak. Here the efficiency of the cavity comes in at a very low .02% (input power = 1.75mW, output = .375μW). The dynamic range is 60db.

The translation stage design was also tested using the NDL 3200 diode laser at 670nm. Figure 21 shows the laser running multimode. Notice the multimodes appear in groups. This is the result of the convolution of the laser output with the characteristic output of the cavity. It is easy to imagine how ambiguous the spectra would be if the characteristic output of the cavity included higher order modes.
Figure 18. Spectra of the HeNe gas laser at 632.8 nm
Figure 19. Linewidth of the HeNe Gas laser at 632.8nm
Figure 20. Free Spectral Range for NDL3200 diode laser at 670nm
Figure 21. Multimode spectra of the NDL3200 diode laser at 670nm
Figure 22 shows the same spectra generated from the diffraction grating. This is the spectra used to calibrate the cavity and gives a good comparison between the two types of spectrum analyzer.

Figure 22. Spectra from diffraction grating spectrometer

At the very least the dynamic range of the flat-plate cavity far surpasses the diffraction grating as demonstrated in comparing figures 21 and 22. With the diffraction grating the modes of the laser are not quite resolved and noise from each diode in the array gives the spectra a messy appearance in contrast to the smooth
lineshape generated by the flat-plate cavity. Note the asymmetry is present in each peak in figure 21. This, once again, is a consequence of the convolution of the laser output with the cavity. The uneven spacing is a consequence of the nonuniform scanning by the piezo drivers, and noise in the laser. Any noise in the ramp or mechanical vibrations at the mirrors will appear as fluctuations in the relative wavelength.

Figure 19 shows the HeNe line centered at 632.8nm. This implies the cavity is giving wavelength information which is not true exactly. Remember these cavities provide information in the change in frequency and likewise the change in wavelength. If the cavity were to be used as a wavelength meter then a reference line of known wavelength must be launched into the cavity as well as the unknown source. Now the difference between the two lines could be measured and thus the wavelength of the unknown is found. Once the cavity is calibrated it can be used to determine mode spacing accurately.

Spectra for laser sources at 780nm are shown in figures 23-28. The cavity design used to generate these spectra is the more advanced ULE spaced cavity with the static mirror floating on an o-ring, and no translation stage is used. The lasers are standard canned packages from Sony and Toshiba. A LDC3722 Laser Diode Controller from ILX Lightwave is used to control the current and temperature of the lasers. At 115 mA and 20.02 deg C the Sony SLD201U provides 15.02 mW of power. This is launched into Newport's model F-SE fiber using a 20X objective with a 35% coupling efficiency. It is more difficult to launch a diode laser beam as it does
not have the nice Gaussian shape of the HeNe. The 40X objective at the output of the fiber gives a small spot size of .4mm at the cavity.

Figure 23. Sony SLD201U diode laser, FSR = 3300
Figure 24. Multi mode spectra of SLD201U, mode spacing = .32nm
Figure 25. Sharp LT024PD0 free spectral range
Figure 26. Sharp LT024PD0 running single mode, FSR = 3300GHz
Figure 27. Lineshape of LT024PD0 single mode
Figure 28. LT024PD0 multimode line spacing, $\Delta \lambda = 0.3$ nm
Figures 23 and 24 show the free spectral range and multimode spectra for the Sony SLD201U 20mW diode laser. The mirrors in the cavity used here were from a different vendor, Rocky Mountain Instruments, so this was the test to see if their mirrors would have an adequate form finesse. The best measured finesse was 300. A smaller free spectral range of 3300 Ghz indicates the mirrors were not as close together as they should be (L=45μm). A consequence of this smaller FSR is the overlapping of the orders of interference as seen in figure 23. The nonuniform modespacing is seen in figure 24. This effect is intensified if there is a significant amount of back reflection causing the laser to behave erratically.

Much better results are seen in figures 25 and 28 for the Sharp LT024PD0 20mW diode laser. Here the cavity is tilted 16 mrad with respect to the incoming beam. This eliminates a good deal of the back reflection reaching the laser so its operation is more consistent. The mode spacing is now much more uniform. The dynamic range was measured when the laser was running single mode at 70 db. Again a very low efficiency of .07% indicates the mirrors are not transmissive enough.

The next wavelength to be tested was at 1.523 nm. A HeNe laser from Research Electro Optics was used in a ‘free space’ experiment where no fiber is used. Here the beam is directed at the cavity with normal incidence directly from the laser. This has the disadvantage that there is no convenient control over the spot size entering the cavity. Fortunately the beam coming out of the HeNe has a small spot size of .5mm giving a Rayleigh range of 1.2 m.
At this wavelength a detector with a response curve suitable to the near IR is needed. New Focus makes a similar model to its 2001, the 2011, which can amplify the signal just as before. Another consequence of the longer wavelength is the mirrors must now be driven further to travel the $\lambda/2$ necessary to produce a free spectral range. This was accomplished easily by increasing the ramp amplitude by 100 volts relative to the amplitude used for $\lambda=633$ nm.

Figure 29. Linewidth of the HeNe at 1.523 $\mu$m
Figure 30. Free spectral range of HeNe at 1.523 μm
As can be seen the results here are similar to what was seen for other wavelengths. The mirrors used in this cavity were supplied by Newport Corporation. Their SuperMirrors™ provide similar form flatness to those supplied by Research Electro Optics with an off-the-shelf availability. Model 10CM00SR.70T features high transmission centered around 1550nm. Form flatness is rated at the usual λ/10 over the entire surface. The finesse of this cavity came in at 883 which means the mirrors have a form flatness over the size of the beam of at least λ/1760. The reflectivity is better than 99.95% giving a theoretical finesse of greater than 6000. With such a high transmission percentage of 0.02 the efficiency should be rather high at 99%. As can be seen the relative intensity, $\frac{I_L}{I}$, is at a low 0.2%. This is due to the same effect seen in the previous data where the cavity does not support enough reflections to give the expected efficiency. A numerical approximation of this effect is discussed in chapter 5. It should be noted here that the cavity spacing is estimated at 20 μm giving the 7500 Ghz FSR shown above. Calibration of the cavity was not possible at the time but could be carried out in the usual way.

As indicated above in the data presented for the diode lasers, the spectra produced by the cavity is sensitive to noise or the chaotic operation of the laser due to back-reflection. Figures 31 and 32 show the results of experiments conducted with the two types of beam splitters where the back reflection intensity is measured while the cavity is tilted through a known angle.
The beam splitter used to pick off the back-reflected beam is a simple 50-50 beam splitter positioned directly in front of the HeNe laser (633 nm), see figure 12 in previous chapter. Here a reduction in intensity of approximately 10 db is seen as the cavity is tilted through an angle of 1.1 mrad. In this configuration the additional optical surfaces introduced in the beam path prevented the reduction from reaching an acceptable level. Ideally a reduction of 40 db would leave the laser adequately isolated. To improve these results I tried using a fiber optic beam splitter from Gould. See figure 14 for the experimental setup used here.
Figure 32 shows similar results as seen above except there is now a reduction of 25 db in the back reflected intensity.

![Graph showing back-reflection intensity vs tilt angle](image)

**Figure 32.** Back-reflection is reduced as cavity is tilted (fiber optic beam splitter)

These results indicated a reduction of 40 db could not be achieved using this type of setup. Reductions on the order of 40-50 db were seen if both ends of the fiber beam splitter were index matched in grease, i.e. the fiber ends are not directed at any optic. Further reduction will require some sort of isolation such as a Faraday rotator or perhaps a fiber isolator.
Achieving the spectra of the various lasers proved to be fairly straight forward but keeping the spectrum displayed on the scope with reasonable stability was a little more challenging. In particular thermal expansion problems can cause spectral lines to drift over several free spectral ranges. This was especially true for the cavity designs using aluminum for spacing between the mirrors. In particular, the design incorporating a translation stage was especially unstable and difficult to adjust, as the various dimensions of the materials involved in the thermal expansion were not easily determined.

Appendix C contains a section on how to calculate the expected drift for the cavities with ULE spacers. Before ULE was used an identical piece of aluminum was used to space the mirrors. The expected drift was calculated at 9100 Ghz/ C° for this cavity and then it was tested using a Sharp LT024PD0 diode laser at 780 nm. The cavity was tuned to a finesse of 300 and then placed under an incandescent bulb (60W) for a heat source. The heating was necessary as the ambient lab temperature would not change enough to see a definite thermal drift.

An AD592CN temperature transducer was in contact with the cavity using thermal grease. Its output is the voltage drop across a resistor calibrated to give temperature in Kelvin, i.e. .273 volts = 0 C°. This voltage was monitored using a Hewlett Packard 34401A multimeter linked to the computer via GPIB. As the spectral line drifts across the scope the computer records its position relative to some initial position. For each data point the temperature is received from the HP34401A
and the time is recorded. In figure 33 the cavity was calibrated to have a mirror spacing of 45 μm, FSR = 3300GHz.

Figure 33. Drift of the cavity due to thermal expansion

13,000 GHz is slightly larger than the expected 9000 but is reasonable. The difference can be attributed to not knowing the dimensions of the expanding materials precisely and more importantly, the mirror spacing could be slightly off.

Results improved significantly with the introduction of ULE as the spacer between the mirrors. The same calculation predicted a drift of 1200 GHz/°C if no aluminum was used at all. Unfortunately aluminum must be used for mirror holders
and the Burleigh PZAT-81 has an aluminum body, but proper dimensioning of the parts can compensate for this difficulty. The mirror separation is dictated by where the PZAT is clamped and the length of the ULE spacer. Figure 34 shows the drift at 2400 Ghz/ C° when the PZAT is clamped at 5 mm from the end.

![Drift due to thermal expansion of the ULE spaced cavity](image)

Figure 34. Drift due to thermal expansion of the ULE spaced cavity

With temperature controlling to .01 C° the drift could be reduced to a minuscule 24 Ghz/ C°. The experiment to determine the precise position of the clamp ring on the PZAT-81 has not been attempted yet. Segmented ULE spacers will allow different positioning to give even better thermal stability.
CHAPTER 5

NUMERICAL APPROXIMATIONS

Cavity Efficiency

Throughout these studies on flat-plate cavities an unacceptably low transmission intensity is the norm indicating a low cavity efficiency of less than 1%. From chapter 2 the efficiency is given as

\[ \eta = \left( \frac{T}{T+A} \right)^2 \]

where \( T \) is the transmission and \( A \) is the absorption of the mirrors. For Newport’s SuperMirror™ used in the above experiment the transmission is 0.02 and the absorption is 50E-06, giving an efficiency \( \eta = 99.5\% \). In figure 29 the relative intensity, which is the measured efficiency of the cavity is much lower than this at 0.2\%. This results from the cavity’s inability to support enough reflections to satisfy the very high reflectivity of the mirrors. These mirrors in particular are 99.97\% reflective which gives a reflective finesse of > 10,000.

Remember the transmission signal is characterized by the Airy function. The mathematical simplicity of this function resulted from limiting the number of reflections to infinity. If the number of reflections is not reaching infinity the drop of several orders of magnitude in transmission intensity will result. This is in fact what
is occurring. In the above example with the 1.523 \( \mu \)m laser, the finesse was 880. The finesse goes as the number of reflections occurring in the cavity. Ideally this number would approach the reflective finesse of 10,000 given above. If a finesse of 10,000 was the case then the relative intensity of the peak transmission would in fact be around 0.9995 in figure 29. A numerical approximation to this problem demonstrates this nicely.

The following program was written in Quick Basic by John Carlsten and myself to simulate the resonance condition of a flat-plate cavity. Real values for T,R, and A, as well as the number of reflections can be chosen to see the effect on the transmission line. The number of reflections determines the number of terms in the sum used to calculate the transmission of the cavity (see page 5 in chapter 2).

```
' NUMERICAL APPROXIMATION TO
' LIMIT THE NUMBER OF REFLECTIONS
' IN A FLAT-PLATE CAVITY.
'
' By Dr. John Carlsten and Mike Barrett
' 2/2/95

CLS
pi = 3.14159
r = .99996
\('r is the reflectivity. Assume both mirrors are identical.\)
t = .000035
\('t is the transmission. select according to: t+r+a=1\)
m = 78000
\('m is gives the number of reflections (goes as the finesse).\)
finish = .005
\('Select finish in multiples of 2pi.\)

steps = .00005
\('Steps will set the number of data points.\)
pairs = (finish / steps) * 2 + 1
\('pairs sets the size of the array variables.\)
DIM peaks(pairs): DIM peaki(pairs)
PRINT "s ,I","; pairs
k = 0
FOR s = -.005 TO finish STEP steps
```
k = k + 1
\[ d = s \times 2 \times \pi \]
\[ e_r = 0 \] 'The real and imaginary parts
ei = 0 'of the electric field.
FOR n = 1 TO m
\[ e_r = e_r + t \times r \times (n - 1) \times \cos((n - 1) \times d) \] 'See Hecht
\[ e_i = e_i + t \times r \times (n - 1) \times \sin((n - 1) \times d) \]
\[ i = e_r^2 + e_i^2 \] 'sum the real and imaginary parts squared.
NEXT n
peaki(k) = i 'peaki = intensity at s
peaks(k) = s 'peaks = relative width s
PRINT peaks(k); peaki(k)
NEXT s
'Open a file named trans#.dat for the data

INPUT "Enter filenumber as ##.dat to append trans##,dat"; number$
OPEN "c:\work\trans" + LTRIM$(number$) FOR OUTPUT AS #1
'OPEN "a:trans.dat" FOR OUTPUT AS #1
FOR j = 1 TO pairs
    WRITE #1, peaks(j), peaki(j)
NEXT j
CLOSE #1
END

Figure 35 shows the situation where the reflections are allowed to go to the
number specified by the reflectivity of the mirrors and the absorption is included.
Next, figure 36 gives the efficiency when the number of reflections are reduced to 880
with all other parameters identical. Here T, and R are the same as above and the
absorption, A, is set at 100E-06 for the Newport 10CM00SR.7OT SuperMirror™.
Notice how the efficiency is less than half the predicted \( \eta \) of 99\%. This is because the
number of reflections is not infinity. Figure 36 shows good agreement with what was
observed in lab (see figure 29). The factor of ten difference can be attributed to slight
differences between the actual absorption and transmission coefficients and what was used in the program.

Figure 35. Number of reflections = 10,000

Figure 36. Number of reflections = 880
Asymmetry in Transmission Lineshape

Figure 2 shows what a typical Airy pattern line should look like in transmission from a flat-plate cavity. Experimentally an asymmetry would inevitably appear to the left as a broadened 'wing' to the peak, see figure 15. After several attempts to explain this phenomena, a model that assumes one or both of the mirrors are slightly curved rather than being perfectly flat shows good agreement with experiment.

The Gaussian beam is generating multiple reflections in the cavity. This behavior can be described as a beam propagating through a lens-like media with the lensing occurring at the reflections and in the traversing of the gap between the mirrors. A convenient way to express this lensing is via Ray Matrices. For a spherical mirror of radius $R$ the matrix is

$$\begin{bmatrix}
1 & 0 \\
-\frac{2}{R} & 1 
\end{bmatrix},$$

and for propagation through a straight section of length $d$ (assume the index of refraction is 1 throughout)

$$\begin{bmatrix}
1 & d \\
0 & 1 
\end{bmatrix}.$$

For simplicity, assume one of the mirrors is flat and the other is curved with a radius $R$, and the mirrors are separated by $d$ as in figure 37. The Ray Matrix equation for the ray $r_i, r_i$ incident on the cavity is
Figure 37. Gaussian beam as a ray propagating through the cavity

where \( r \) is the distance above the optic axis, and \( r' \) is the slope of the ray. Imagine the Gaussian beam to be a bundle of these rays with a spot size on the order of .5mm. The Rayleigh range of such a beam is 1.24 m. As the beam propagates through the cavity its wavefronts translate and are lensed by the curved mirror. After 1000 reflections the first wavefront has traversed a total distance of 2 cm. This is still well within the Rayleigh range which means the beam is fairly well collimated, and the wavefronts would remain parallel if both mirrors were flat, i.e. the Gaussian structure of the beam has little effect on the way it interferes with itself.

Notice a ray incident on the optic axis will see no lensing by the curved mirror. On the other hand, a ray further from the axis will be lensed the most; its path will deviate more. This corresponds to larger spot sized beams entering the cavity will experience this effect more than smaller beams. Now consider the resonance
condition: the mirrors are separated by $\lambda/2$. Portions of the wavefront near the axis will now undergo constructive interference and generate the expected transmission peak. Portions of the wavefront further from the axis will experience this condition earlier or later in time depending on the sign of the curvature radius, and the direction the mirror is traveling. This would look like a slow buildup in transmission intensity followed by a quick drop, or vice versa. This describes the behavior observed in the lab well and a numerical approximation written in Quick Basic gives good agreement.

This program, like the one for the transmission study, has parameters for the reflectivity, transmission and the number of wavefronts summed. The radius of curvature of the mirror and the spot size are additional parameters to be set. It uses a Gaussian distribution for the input intensity to properly attenuate the transmission peak. The main assumption is the input beam consists of plane waves which undergo a lensing as described above.

This asymmetry study assumes a plane wave is incident on a cavity with one slightly curved mirror. The spot size is $w_0$ and the output intensity is weighted by a reflectivity $r_e$, and transmission coefficient $t$. It also takes into account the Gaussian drop off in input intensity as the distance from the beam axis, $x$, is increased. It prompts for the modified data file containing the input intensity distribution (can be actual data from the reticon array or a mathematical construct. The distribution should be normalized.

Authored by Dr. John Carlsten and Mike Barrett 2/15/95.

CLS
DIM x(400), y(400)
INPUT "Enter file name to use for weighted intensity profile:"; file$
plot$ = "c:\work\" + LTRIM$(file$)  'curve file
PRINT plot$
OPEN plot$ FOR INPUT AS #2
DO WHILE NOT EOF(2)
o = o + 1
INPUT #2, x(o), y(o)
LOOP
points = o
CLOSE #2
inc = 10  'how many increments to break the spot size into
wstep = INT(points / inc)
pi = 3.14159
lambda = 6.33E-07
k0 = 2 * pi / lambda
R0 = 600  'mirror radius
w0 = .00075  'this is read off the plot of the reticon scan.
d0 = 30 * lambda
re = .99996
t = .00001
m = 1000
finish = .005
start = .005
steps = .0001
pairs = INT((finish + start) / steps) + 1
DIM peaks(pairs); DIM peaki(pairs)
DIM wtpeak(inc + 1, pairs)
g = 0
PRINT " I Ibar x/w"; pairs; points
FOR 1 = 1 TO points STEP wstep
  g = g + 1
  Ibar = y(l)
  PRINT 1; Ibar; x(l)
  k = 0
  FOR s = -start TO finish STEP steps
    k = k + 1
    d = d0 + s * lambda / 2
    er = 0
    ei = 0
    FOR n = 1 TO m
      z = 2 * d * n
      R = R0 / n
      er = er + t * re ^ (n - 1) * COS(k0 * (z + (x(l) * w0) ^ 2 / R))
      ei = ei + t * re ^ (n - 1) * SIN(k0 * (z + (x(l) * w0) ^ 2 / R))
Figure 38 gives the intensity profile of the input beam when a 20X objective is used to collimate the fiber output. The peak input intensity from the HeNe at 633 nm is 1.25 mW with a spot size of .42 mm, Rayleigh range of .87 m. The fiber is at the focal length of the objective. This position is found experimentally as the distance cannot be measured accurately. Do this by extending the beam across the lab and back to give a long path length. Now focus the beam down so that the smallest spot at the screen is diffraction limited to be as big as the waist at the output of the
objective. The beam is roughly collimated. The distance from fiber to cavity is well within the Rayleigh range (40 cm).

Figure 38. Reticon array scan of beam spot size entering the cavity

Figure 39. Asymmetry when spot size is .425mm
Now the parameters for this cavity are entered in the program and the input intensity profile of figure 38 is used to attenuate the reflected wavefronts. The parameters are $T = 1 \times 10^{-5}$, $R = 99.996\%$, $w_0 = .425$ m, mirror radius = 400 m, number of reflections $m = 1000$. The asymmetry generated by this numerical simulation is shown in figure 40 and the radius of curvature is modified to fit the actual data of figure 39. This radius is 400 m.

![Figure 40. Numerical simulation of transmission peak](image-url)
Figure 41. Asymmetry increases with smaller radius of curvature, $R_m=400m$

Figure 42. Asymmetry of peak vs. theory
CHAPTER 6

CONCLUSION

Spectral analysis of laser light with single and multimode wavelengths can be done using high-finesse flat-plate cavities. The cavities can be used in conjunction with a fiber optic or they can be used in a free space application. Finesse is usually greater than 1000 without the need to mode-match the cavity. Several wavelengths in the visible and near infrared have been successfully displayed.

The free spectral range of the cavity is variable according to the cavity length. This is set at 15-45 μm to give a FSR range of 10,000 GHz down to 3300 GHz with resolution better than .01 nm. The cavity is thermally stable to at least 2400 GHz/ C° and can be improved using temperature controlling.

An asymmetry in the transmission peak will result from a slight curvature of one or both of the mirrors. Curvatures as slight as 600 m⁻¹ can produce significant asymmetries but do not confuse the information in the spectra. The asymmetry will be more pronounced for larger spot sizes on the order of .4 mm or greater.

Cavity efficiency is usually a fraction of one percent and is a result of the inability of the cavity to support enough reflections, dictated by the mirror reflectivity, to satisfy the theoretical efficiency of 99% or better. This difficulty is resolved by
using amplified detectors such as the New Focus 2001 and 2011 photo diode packages with gain at 30,000.

The output of the cavity is sensitive to feedback in the form of back-reflected light returning to the laser and causing it to run chaotically. This produces nonuniform spacing in the multi-mode spectra of a diode laser and can be seen as additional peaks in transmission. This effect can be reduced up to 25 db by tilting the cavity but requires isolation for better reduction.
APPENDICES
APPENDIX A

LAUNCHING A LASER INTO A SINGLE MODE FIBER
When working with high-finesse cavities it is important to have a nice clean Gaussian beam. Furthermore, it is nice to be able to control the spot size and position of the waist, etc. This is accomplished easily using single-mode fiber. For an excellent introduction to fiber optics see Newport’s catalog which includes an excellent section on the subject\textsuperscript{11}.

To gain the benefits of the fiber it is necessary to launch the laser source efficiently into the fiber using some sort of positioning device to hold the fiber and a lensing arrangement. Figure 43 gives the basic picture.

![Figure 43. Using a lens to launch a laser](image)

For successful launching, or mode matching, the lens must focus the light such that the incident rays on the core of the fiber with diameter \(d\) do not have an incident angle larger than that specified by the Numerical Aperture of the fiber. The Numerical Aperture, \(NA\), is defined as the sine of the largest angle an incident ray can have before it excites radiation modes in the fiber. A simple relation gives the desired focal length: \(D = \frac{4\lambda f}{\pi \omega}\).
The beam diameter $D$ is conveniently measured by a scale and $\omega$ is prescribed by the core diameter such that $\omega = 1.28 \, d$. For the F-SV fiber used in most of the experiments here the core diameter is 3.8$\mu$m and the beam diameter of the HeNe laser is 1mm. Thus the fiber must be positioned at a focal length of 6mm to get a waist of 6.48$\mu$m from the objective (lens). Newport has several objectives to choose from which are identified by their power: 10x, 20x, 40x, etc. The focal length of the 20x objective is 8.3 mm whereas the focal length of the 40x is 4.3 mm. Using the 20x objective, a good coupling efficiency of 50% is observed.

Before the light can enter the fiber efficiently the fiber must be cleaved properly. This is accomplished using Newport’s F-BK2 fiber cleaver. This leaves the end of the fiber with a clean endface that has a very small angular deviation from perpendicular. After cleaving it is a good idea to check the quality of the cleave with a microscope. Another good check for cleave quality is to observe the spot at the output of the fiber. It should have a nice circular shape with a Gaussian intensity profile. Once the fiber is satisfactorily cleaved it can be conveniently positioned in front of the objective using a fiber chuck/coupler combination such as the Newport F915.

The source then needs to be directed such that the beam enters the aperture of the chuck mount. A good check to see how true the beam has entered the device is to watch the back-reflected spot on the laser. It should go right back into the laser aperture when the beam is true. Now monitor the output of the fiber with a white
index card or power meter as the various adjustments to the position of the chuck with respect to the objective are made.

Rough in the position of the chuck by adjusting the x and y translation screws and by sliding the chuck in until it is at the working distance from the objective. The working distance is specified in the catalog for the 20x objective at 1.9mm. Now tighten the set screw which prevents further slippage of the chuck and fine tune the positioning using the pitch and ‘z-ring’ adjustments. The ‘z-ring’ is a convenient name for the finely threaded ring which moves the chuck closer or further from the objective.
APPENDIX B

MODE MATCHING
Though mode matching was not necessary in these experiments it is important to explain further why a flat-plate configuration might be chosen over a spherical or confocal cavity. Remember mode matching means fitting the Gaussian beam wavefronts to the curvature of the mirrors in the cavity. This can be difficult as there are five degrees of freedom to adjust: the translation of the cavity in the x, y, and z directions and the pitch and yaw, or tilt with respect to the input beam.

Figure 44. Positioning of the waist

Figure 44 illustrates the procedure for positioning the beam in the cavity. $z_o$ is the Rayleigh range of the output from the microscope objective. If $z_o = z_{oc}$, where $z_{oc}$ is the Rayleigh range of the cavity

$$z_{oc} = \frac{1}{2} \sqrt{L(2R_m - L)}$$

$L$ is the length of the cavity, and $R_m$ is the radius of curvature of the mirrors, then the cavity is mode matched. It is easy to see the difficulty of satisfying these conditions when the waist needs to be positioned with such care. The relevant expressions relating the quantities in figure 44 are
Larry Watson includes some excellent tips on how to position the cavity correctly in his paper$^{14}$.

When the cavity is mode matched the fundamental $TEM_{00}$ mode is excited in the cavity at resonance. If for some reason the cavity is not mode matched then off-axis, higher order modes are excited. In transmission they appear as additional peaks with smaller intensities than the fundamental. See figure 45.

The mode spacing is given by$^{15}$

$$(\Delta \nu)_{\text{ms}} = \frac{c}{2\pi L} \cos^{-1} \left[ 1 - \frac{L}{R_m} \right].$$
If the cavity is used to display the spectra of a diode laser running multi-mode, and the cavity is not mode matched well then the off-axis modes might be confused with the modes of the laser. Notice the Mode spacing goes to zero for very high radii of curvature in the mirrors. This is the essence of why the flat-plate regime is preferred.
APPENDIX C

ALIGNMENT AND EQUIPMENT
i. Alignment

Alignment of the cavity is the same for all the designs mentioned above. The basic procedure is to get the mirrors roughly parallel using some coarse adjustment while adjusting the mirror spacing to the desired length. For the ULE spaced cavities the rough tilt adjustment is done using a ball driver to turn the three 4-40 screws that compress the mirror holder against the o-ring in the end cap of the cavity. The screws are adjusted while the interference pattern is monitored on a card placed in the green (543 nm) beam. This beam is combined to overlap the beam being analyzed using a beam splitter.

The green beam is allowed to pass through a hole in the card and then returns to the card after entering the cavity. Multiple spots are seen when the mirrors are not parallel. As the mirror is adjusted these spots combine to one spot and then the Airy pattern is present. Once the mirrors are nearly parallel the rings of the pattern will be spaced far apart and the pattern is centered on the hole in the card. The same technique can be used in transmission where a hole in the card is not necessary. The pattern will consist of broad dark rings and narrow bright rings which is opposite of what is seen in reflection.

ii. Connections

The various pieces of equipment are connected as seen in figure 46. Burleigh’s RC-44 Programmable Ramp Generator has an output/100 bnc jack for monitoring on channel 1 of the scope. Channel 2 is used to monitor the signal from
the New Focus 2001 (or 2011) detector. The cavity’s PZAT-81 plugs into the back of the ramp with a special connector.

Figure 46. Connections

When doing thermal drift experiments the AD592CN temperature transducer is taped to the cavity and is wired to a switch box containing the calibration resistor (1Kohm). This is connected via coax to the HP34401A Multimeter. The Multimeter and the Tektronics 2230 Digital Storage Oscilloscope are connected via GPIB to the computer. Pictures from the scope are stored and manipulated with a program written in Quick Basic by Gregg Switzer called TEK2230.BAS. Thermal drift data was
acquired via a similar program called THERMAL6.BAS, which was also authored by Gregg and modified by myself to run the HP34401A.

iii. Diode Control

When diode lasers were used a controller was needed to provide a constant current to the diode and to control the temperature. The ILX LDC3722 Laser Diode Controller was used for operation of the 780 nm diode lasers. Connections are simple: one lead each for the temperature control and current supply. ILX also provides a convenient diode mount that accepts these connections. Constants for calibration needed to be set to operate the thermistor in the mount correctly. The constants were set at C1 = 1.104, C2 = 2.397, C3 = .559. It is a good idea to limit the current to a value close to the maximum allowable for the diode being used. This was set at 80 mA.

For the NDL3200 diode at 670 nm a constant current supply from Wavelength Electronics was used. This is a compact circuit contained in a small package that is easy to adapt to many applications. The model number is LDD200-APC-3M and was fitted to a model LDDPCB-M accessory circuit board. This does not monitor or control temperature but simply supplies current to the diode.

iv. Temperature Drift Calculation

Calculating the expected thermal drift of a cavity is a relatively simple and straightforward procedure. The basic assumption is that the materials involved will expand in a linear fashion according to their characteristic expansion coefficient $\alpha$:

$$\alpha = \frac{\Delta L}{L} / C^\circ.$$
Some expansion coefficients of the materials involved in these cavities are:

<table>
<thead>
<tr>
<th>Material</th>
<th>Coefficient /Deg C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>24E-06</td>
</tr>
<tr>
<td>Piezo</td>
<td>4E-06</td>
</tr>
<tr>
<td>Steel</td>
<td>15E-06</td>
</tr>
<tr>
<td>Fused Silica</td>
<td>.5E-06</td>
</tr>
<tr>
<td>ULE</td>
<td>10E-10</td>
</tr>
</tbody>
</table>

A listing of the various components which either push the mirrors together or pull them apart helps to determine the net expansion:

**Expanding- Pulling the mirrors apart:**

- PZAT-81 Aligner-Translator
- Sleeve
- Cup

Total: 9.51cm AL

**Expanding- Pushing the mirrors together:**

- Substrates 1.27cm Fused Silica
- Mirror holders 3.44cm AL
- Screws 1.27cm Steel
- Piezo 4.60cm Ceramic

Net expansion:

\[
[(9.51-3.44cm)(24)-(.5+15cm)(1.27cm)-(4.6cm)(4)](1E-06) = 1076nm
\]

One free spectral range corresponds to a change in mirror spacing of \( \lambda/2 = 390 \text{ nm} \).

For the cavity calibrated at \( L=45 \mu\text{m}, \) FSR = 3300 Ghz. Thus a drift of 1076 nm corresponds to a drift in frequency of 9100GHz/\(^\circ\text{C}\).

2 ibid.

3 Watson, Larry, Carlsten, J.L., "High Finesse Cavities", Montana State University, Department of Physics, Bozeman, MT.

4 Hecht. pg. 367

5 ibid pg. 372


9 Repasky, K.S., Wessel, J.G., Carlsten, J.L., "Frequency Stability of High Finesse Interferometers". Bozeman, MT, Department of Physics, Montana State University.


12 Watson, L., Carlsten, J.L., "High Finesse Cavities". Bozeman, MT, Department of Physics, Montana State University.


14 ibid.