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RICE UNIVERSITY

OPTICAL MANIPULATION OF He(2^3S) ATOMS
WITH A DIODE LASER

by

David Lynn Bixler

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ABSTRACT

A commercial Spectra Diode Laboratories, 1.083 µm diode laser has been used to efficiently spin polarize an atomic beam of He(2^3S) metastable atoms by optical pumping on the 2^3S_1 → 2^3P_1 (D1) transition. The diode laser is an InGaAs/GaAs strained multiquantum well with a distributed Bragg reflector to insure single longitudinal mode operation. The laser has been frequency stabilized to less than 1 MHz/hr drift.

The helium metastable atom beam is produced by electron impact and the polarization is measured using a Stern-Gerlach analyzer. Atomic polarizations exceeding 97% have been obtained with ~25 mW of power from the diode laser.

A number of experiments currently under construction may also make use of the diode laser. These include the production of a spin polarized helium ion beam by optically pumping the metastable atoms in an rf discharge, and the trapping of helium metastable atoms in a magneto-optical trap (MOT).
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Chapter 1
Introduction

Helium $^{2\text{3}\text{S}}$ atoms are of considerable interest because of their long natural lifetime ($\sim 10^4 \text{ sec}$)[1], and their large stored internal energy (19.8 eV). This energy is sufficient to cause electron ejection during interactions of a He($^{2\text{3}\text{S}}$) beam with a surface[2]. The dynamics of these processes can be studied by the use of spin-labelling techniques in which the electron spins of the He($^{2\text{3}\text{S}}$) atoms in the beam are oriented by optical pumping, and the polarization of the ejected electrons is measured[3,4]. Optical pumping can also be used to spin polarize He($^{2\text{3}\text{S}}$) atoms in an rf discharge. These atoms interact via Penning ionization to produce spin polarized helium ions which can be extracted and formed into a beam. The polarized ion beam can then be used to probe the magnetic properties of surfaces[5,6].

Optical pumping of He($^{2\text{3}\text{S}}$) atoms is performed using circularly polarized 1.083 $\mu$m $^{2\text{3}\text{S}} \rightarrow ^{2\text{3}\text{P}}$ resonant radiation. The efficiency of this process depends upon the availability of an intense source of 1.083 $\mu$m light. Early experiments were undertaken using optical pumping radiation provided by helium discharge lamps[7]; however, their low spectral brightness limited the achievable metastable atom polarization. These limitations have been largely removed by the development of a number of single-mode 1.083 $\mu$m laser sources using materials such as LNA (Lanthanum Neodymium Magnesium Hexaluminate)[8,9,10] and Ti:Sapphire[4,11]. These lasers can provide enough radiation to produce
very high beam polarizations, but are relatively complex and typically require expensive argon-ion pump lasers. Recently, single-mode semiconductor lasers operating at 1.083 μm have become commercially available[12]. In the present work the application of these lasers in optical pumping and optical manipulation of He(2^3S) atoms has been investigated. The data reveal that the diode lasers appear well suited for He(2^3S) studies.

The 1.083 μm diode lasers, developed at Spectra Diode Laboratories[13], provide single-spatial-mode output powers of ~50 mW. The diode lasers themselves are InGaAs/GaAs strained multi-quantum-well buried heterostructure devices with a built-in distributed Bragg reflector to provide single longitudinal mode output[14].

Unfortunately, the diode lasers are subject to both long-term frequency drift and short term frequency jitter. Therefore, a number of frequency stabilization techniques were developed and tested. The long-term frequency drift was eliminated by using a technique that compares the output of the diode laser to that of a stabilized HeNe, and short term frequency fluctuations were removed by using an external reference cavity. Combined, these techniques result in a stable long-term lock with a frequency drift of less than 1 MHz/hr. Two other locking schemes have also been successfully tested: locking the diode laser to an external cavity via optical feedback, and using a lock-in amplifier to lock the diode laser to an atomic transition in helium.

Using each stabilization scheme, the diode laser consistently produced He(2^3S) beam polarizations of at least 95%, proving its usefulness for He(2^3S) studies[15]. Possible future applications of diode
lasers, including production a polarized helium ion beam, and trapping of He(2^3S) atoms in a MOT, are also discussed.
Chapter 2
Diode Laser Types and Characteristics

Diode lasers operate on the same principle as all lasers: a population inversion is created in a gain medium, and optical feedback is used to induce lasing[16]. In a diode laser, the population inversion is created by passing a current through a p-n junction. Electrons are injected into a thin active region from the n-type material, and holes are injected into the region from the p-type material. Given enough current, this mechanism provides a population inversion, and optical gain. Basic diode lasers employ cleaved facets to form a Fabry-Perot cavity and provide the necessary optical feedback. The reflectivity of a cleaved facet is only 0.32, but is sufficient to support lasing. Threshold is reached when the injected current density J reaches a critical value J_{th}, at which point the gain is large enough to overcome cavity losses. Any further increase in J results in lasing action[17,18,19,20].

Despite its similarity to other types of lasers, diode lasers differ significantly from them in the details of operation[21,22,23]. In all lasers, electrons participate in three basic interactions: spontaneous emission, stimulated emission, and absorption. However, due to the nature of the energy bands in a semiconductor laser, electrons can interact with one another through intraband collisions. Thus, the electrons in a diode laser should be treated collectively. Another difference between diode lasers and other laser types is the nature of the optical mode: most lasers support TEM (transverse-electromagnetic) modes; however, in a semiconductor
laser, the optical modes are either TE (transverse electric) or TM (transverse magnetic). Finally, a characteristic unique to diode lasers is that the index of refraction is a function of the charge carrier density. This results in the longitudinal mode of the laser changing with varying current.

Diode lasers come in a variety of types, characterized by particular structures and compositions. Each type possesses properties that make them unique and affect their operation. The lasing frequency is determined by the composition of the semiconductor material and the relative concentrations of the different constituents in the active region. The active region can be classed as either a homostructure or heterostructure junction. For confinement of the spatial mode, there are gain-guided and index-guided structures. For longitudinal mode control there are additional structures such as the DFB (Distributed Feedback) and DBR (Distributed Bragg Reflector). Finally, there are the quantum well diode lasers, which exhibit improved characteristics.

2.1 The Structure of the Active Region

The geometry of the active layer is very important when considering the operating characteristics of the semiconductor laser. Figure 2.1 shows both a homostructure and a heterostructure diode laser.

Homostructure diode lasers are the simplest type, and consequently, were developed first. In a homostructure laser, the active region is not a separate material. The laser is made up of a p-n junction with the active region being at the boundary of the two layers. Homostructure diode lasers unfortunately have a very high threshold current density
Figure 2.1: Schematic illustration of (a) homostructure, and (b) heterostructure semiconductor lasers.
(J > 50 kA/cm²), which limits their ability to run continuously at room temperature, and makes them impractical for many applications.

Heterostructure diode lasers differ from homostructure lasers by the addition of a layer between the p-type material and the n-type material. This additional layer serves as the active region, and is where lasing occurs[24,25,26]. Heterostructure diode lasers with low threshold currents can be fabricated[27], and can easily be operated continuously at room temperature[28,29]. The physical reason for the reduction in $J_{th}$ is due to two effects[30]. The cladding layers on either side of the active layer have both a higher band gap and a lower refractive index than the active layer. The higher band gap serves to confine the charge carriers (electrons and holes) to the active region where they can recombine more efficiently. The lower index of refraction helps confine the optical mode to the active layer, significantly reducing internal optical losses. Because of their superior traits, heterostructure lasers dominate the market, and unless otherwise stated, all diode lasers mentioned hereafter are heterostructure lasers.

2.2 Materials

The materials from which a diode laser is constructed determines much about its operation. Most diode laser active regions are formed from GaAs-based materials (e.g. AlₓGa₁₋ₓAs or In₁₋ₓGaₓAs₁₋ₓP₁₋ₓ). However, other materials have been used to form the active region such as CdS[31] and lead salts[32,33]. The material type determines the wavelength range over which the diode laser can be made to operate. Figure 2.2 shows a number of semiconductor materials and the wavelength ranges over which they
Figure 2.2: Wavelength ranges covered by diode lasers of different materials. Lasers emitting at $\lambda > 3 \, \mu m$ usually require low temperature operation.
operate. The relative proportions of the materials in the active layer narrow the wavelength range over which the gain is sufficient to support lasing. Once the concentrations in the active layer are set, the diode laser has a very short tuning range, typically less than 20 nanometers.

Also of importance is the composition of the cladding layers. Common cladding layers are made from GaAs or InP, but other materials can also be used. The cladding layers set the lattice structure to which the active layer must conform. It should be noted that diode lasers operating in certain wavelength ranges cannot be fabricated, even if the active layer concentrations can be chosen to give that wavelength. This occurs when the lattice constant of the required active layer significantly mismatches the lattice constant of all of the materials that might be used to form the cladding layers. The only exception to this is to use a strained quantum well laser (discussed in section 2.5) in which the active layer and the cladding layers can have different lattice constants. Therefore, the materials from which a diode laser is formed must be chosen to give a similar lattice constant throughout the heterostructure, and if possible, to operate at the desired wavelength.

2.3 Diode Laser Waveguide Structures

In a heterostructure laser, the optical mode is confined to the active layer because the cladding layers have a lower index of refraction than the active layer. In order to improve the performance of a laser diode, confinement of the optical mode within the active layer is also desired. A laser without this kind of confinement is called a broad-area laser.
Lateral confinement (confinement parallel to the junction plane) can be classified into two groups: gain-guided, and index-guided. In a gain-guided laser, the optical mode is confined by the width of the optical gain region, which is determined by the width of the current-pumped region. In an index-guided device, the optical mode is confined in a central region of higher refractive index. Index guided lasers also come in two types: weakly index guided, and strongly index guided. In a weakly index guided laser, the effective change in the refractive index is achieved by varying the thickness of one of the cladding layers. Strongly index guided lasers employ what is called a buried heterostructure, in which the active region is bounded on either side by separate layers with low indices of refraction.

**Gain-guided Lasers**

Most commercial lasers have some kind of built-in structure to restrict current flow to a small area across the p-n junction plane. Primarily, this serves to lower the threshold current for continuous-wave (CW) operation. Broad-area lasers have a high threshold current since the entire active layer must be pumped at or above the threshold current density. Limits placed on the area that must be pumped significantly lower the current needed to achieve lasing. Typical threshold currents for gain-guided lasers can be as low as 100-150 mA. The low operating current has the additional advantage that the device can be operated at higher temperatures and without a severe heat-sinking requirement. Furthermore, when operating at lower currents, the lifetime of the device is increased. A
second advantage to limiting the pumped area is that the confinement allows for fundamental spatial mode operation.

The simplest of the gain-guided structures is the oxide-stripe device[34], shown in Figure 2.3(a). A number of variations of the stripe geometry exist (for example the junction stripe[35]), and are often employed in commercial laser systems. The active region in such a laser is planar and continuous, since the lateral confinement mechanism does not depend on the active layer geometry. The stripe serves as the current conductor, while the area around the stripe prevents current flow. This arrangement forces the current to flow through the active layer in only a small region directly beneath the stripe. Since optical gain can only be found in the areas of the active region in which current is flowing, the gain is also limited to a small region of the active layer. Any mode that is not confined laterally in the active area directly beneath the stripe cannot find sufficient gain to support lasing. Therefore, the width of the stripe determines the highest-order lateral mode that can be supported.

However, this view of the gain-guided device is a simplification of an exceedingly complex problem. One particular complication results from the fact that the charge carriers diffuse in the cladding layers. As a result, the current passing through the active layer falls off with distance from the stripe center, instead of exhibiting a clear cutoff. Another complication results with the consideration of the change of the index of refraction with increased charge carrier density. Known as index anti-guiding, the charge carriers lower the effective refractive index in the central area of the active region, resulting in a spreading of the optical mode.
Figure 2.3: Schematic cross section of different types of gain-guided laser structures: (a) oxide-stripe, and (b) junction stripe.
Although gain-guided devices are commonly used, they do have a number of undesirable characteristics. One of these characteristics is that the light-current (L-I) curve of gain-guided devices often exhibits a nonlinearity, or kink. This kink represents a shift in the optical mode, a transition to a higher order mode, or a shift from a TE to a TM mode. Such a shift would severely alter the amount of light coupled into an optical fiber, and would affect any application which requires precise control of the spatial mode[36]. Another problem common to gain-guided lasers is that the output power will sometimes exhibit large pulsations at frequencies of 200-500 MHz[37,38]. The pulsations are also accompanied by self-focusing (a narrowing of the optical mode when the pulse is at a maximum). Additional problems result at longer wavelengths ($\lambda>1\mu m$) where gain-guided devices exhibit increased cavity losses and severe index anti-guiding. Thus, the gain-guiding mechanism is undesirable for lasers operating beyond the visible and very near IR.

**Index-Guided Lasers**

In gain-guided lasers the lateral mode confinement is achieved through control of the optical gain along the junction plane. In contrast, index-guided lasers employ a change in the index of refraction to form a waveguide that confines the optical mode to a small region within the active layer. Two types of index guiding exist: strong index-guiding and weak index-guiding.

In the case of weak index-guiding, the laser structure is modified to produce a lateral step in the index of refraction (typical values for the step
are ~.01). The design of a weakly index-guided laser requires that the thickness of at least one layer be laterally nonuniform. Many variations of the weak index-guided laser exist[39,40]; two of these, the simple rib waveguide(a)[41] and the ridge waveguide(b)[42], are shown in figure 2.4. Weakly index-guided lasers were developed as an improvement to gain-guided lasers in which the index anti-guiding has been counteracted by the structural waveguide. The threshold current for a weakly index-guided laser, around 60-80 mA for a rib waveguide and 40-60 mA for a ridge waveguide, is considerably lower than the threshold current for a gain-guided laser. However, index-guided lasers still suffer from carrier diffusion in the active layer and in the cladding layers. The resulting lateral mode behavior is very complex since gain-guiding, carrier induced anti-guiding and structural waveguiding all interact to form the lateral modes. Numerical solutions are generally necessary to analyze the weakly index-guided device[43,44].

In a weakly index-guided device, the formation of the waveguide requires that one of the layers of the heterostructure be nonuniform along the width of junction plane. Known as the waveguide layer, the thickness of this layer relative to the size of the nonuniformity determines the effective index step. If the waveguide layer is too thick, the performance of the device becomes very similar to a gain-guided laser. Similarly, if the nonuniformity is placed in a location away from the active layer, it will not perform as an effective waveguide. The requirements for forming a weakly index-guided laser demand good control of the layer thicknesses
Figure 2.4: Schematic illustration of weakly index-guided laser structures: (a) simple rib waveguide, and (b) ridge waveguide.
during the fabrication process, thus making weakly index guided lasers difficult to make and expensive to purchase.

In a strongly index-guided laser, the active region is surrounded on all sides by a high band gap cladding material. These lasers are called buried heterostructure lasers since the active region is surrounded on four sides by cladding layers. The index step along the junction plane (~0.2) is two orders of magnitude larger than carrier induced anti-guiding. As a result, the characteristics of these lasers are determined primarily by the rectangular waveguide that confines the mode in the active region (a rectangular waveguide supports only TE and TM modes [45]). There are many types of strongly index-guiding geometry[46,47,48]; two of these, the etched mesa buried heterostructure[49] and the double channel planar buried heterostructure[50], are shown in figure 2.5 (a) and (b), respectively.

Strongly index-guided lasers possess a number of desirable characteristics. An optimized buried-heterostructure laser has a very low threshold current (~15-20 mA). These lasers can be modulated at high frequencies (~2 GHz) and operated at high powers. Furthermore, buried heterostructures are more suited for use in single frequency DFB lasers (discussed in the following section) because the waveguide modes more strongly couple to the feedback grating.

The number of lateral modes allowed in a buried heterostructure laser is controlled by the width of the active layer. If the active region is wide enough, lateral modes beyond the fundamental are allowed. The transition from the fundamental mode to a higher order mode (or
Figure 2.5: Cross sections of buried heterostructure (strongly index-guided) lasers: (a) etched mesa buried heterostructure, and (b) double channel planar buried heterostructure.
combination of modes) manifests itself as a kink in the L-I curve. The power at which a kink occurs is called the kink power, and it increases as the active layer width decreases.

Strongly index guided lasers have current blocking junctions that serve to confine the current to the active region. Unfortunately, the current confinement is not complete; a small fraction of the injection current flows around the active region. Known as the leakage current, this portion of the current does not affect the lateral mode of the device, but it does raise the threshold current. In an optimized buried heterostructure laser, the leakage current is quite small.

Strongly index-guided lasers are more difficult to fabricate than weakly index-guided or gain-guided types; however, they are much more suited for demanding applications.

2.4 Single Frequency Control Structures

A conventional semiconductor laser does not emit light in a single longitudinal mode, but supports a number of modes. The majority of the output power will be in the mode lying nearest the gain peak, with a small percentage of the output power being accounted for in the side modes. Even if a laser emits single-mode light during continuous-wave (CW) operation, it will often emit multimode light during pulsed operation. Since side modes limit optical communication rates, remove power from the primary mode, and make the laser difficult to frequency stabilize, it is
desirable to have a laser that will operate on a single longitudinal mode, even under high-speed modulation.

In a standard diode laser, the cleaved facet reflectivities remain constant for all of the longitudinal modes; the only mode discrimination in such a laser is provided by the gain profile. Usually the gain spectrum is much wider than the longitudinal mode spacing, and the resulting mode discrimination is poor. One mechanism to eliminate unwanted side modes is to introduce frequency dependent cavity losses that discriminate against the unwanted longitudinal modes. Two methods exist that are useful in achieving this effect: distributed feedback (discussed here) and coupled cavities (discussed in Appendix A).

Two types of distributed feedback laser exist: the standard distributed feedback type (DFB), and the distributed bragg reflector (DBR). Diagrams of these types of lasers are shown in Figure 2.6.

**Distributed Feedback (DFB)**

In the standard DFB laser structure, the feedback is not localized within the laser cavity, but is distributed throughout the lasing region. This is achieved through etching one of the heterostructure layers so that its thickness varies periodically along the cavity length. The resulting perturbation induces feedback from backward Bragg scattering, and the
Figure 2.6: Schematic illustration of distributed feedback (DFB) and distributed Bragg reflector (DBR) semiconductor lasers.
mode selectivity is provided by the Bragg condition for \( m^{th} \)-order coupling between the forward and backward propagating waves:

\[
\Lambda = m \lambda / 2 \mu
\]

Where \( \Lambda \) is the grating period, \( \lambda \) is the wavelength of the light in a vacuum, and \( \mu \) is the effective index of refraction of the medium\[51,52,53\].

Generally, the active layer is not directly etched, as this could produce defects that would adversely affect the operation of the device\[54\]. Instead, it is preferable to etch one of the cladding layers. However, since only the evanescent field of the transverse mode can interact with a grating located in a cladding layer, the exact location of the grating with respect to the active layer is critical. Furthermore, it is important that the corrugation depth of the grating be sufficient to affect the longitudinal mode of the laser.

Any of the various geometries of laser diodes can employ a DFB structure to improve the output longitudinal mode. However, strongly-index guided types are more suitable, and are most commonly used.

**Distributed Bragg Reflector (DBR)**

The Distributed Bragg Reflector (DBR) is an alternative scheme to providing the frequency selective feedback necessary to achieve single-mode lasing. In a DBR laser, the grating is etched in the beam path just outside the active region\[55,56\]. The grating acts as a frequency dependent
mirror, and lasing occurs for the wavelength at which the reflectivity is maximum[57].

The DBR structure has inherent losses that are minimized to achieve the best output. Originally, unpumped active material was used in the formation of the grating, but optical losses forced the use of other materials. The material chosen is almost transparent at the lasing wavelength, but optical losses still occur. Furthermore, since the DBR grating is formed of a different material, it constitutes a separate waveguide from the active region. Coupling losses between the two waveguides reduce the reflectivity of the grating.

Analysis of a DBR

To find an expression for the effective reflectivity of a DBR structure, we begin with the time-independent wave equation:

$$\nabla^2 E + \varepsilon(x, y, z)k_0^2 E = 0$$

The laser cavity is defined to be oriented along the z-axis. In the region of the grating, the dielectric constant can be written as:

$$\varepsilon(x, y, z) = \varepsilon + \Delta\varepsilon(z)$$

where $\varepsilon$ is the average value over the grating region, and $\Delta\varepsilon$ is the periodic perturbation caused by the grating.
In the case of zero perturbation (Δε=0), the solution of the wave equation takes the form:

\[ E(z) = \tilde{M}[E_e e^{ikz} + E_h e^{-ikz}] \]

Here, \( \beta \) is the mode-propagation constant, defined as:

\[ \beta = \mu k_{\alpha} + i\alpha / 2 \]

where \( \alpha \) is the mode loss coefficient, and \( \mu \) is the effective mode index.

In the presence of the dielectric perturbation, the coefficients \( E_e \) and \( E_h \) become \( z \)-dependent. Substituting the general solution into the perturbed wave equation, and allowing for slow variations of \( E_e \) and \( E_h \) yields:

\[ \frac{dE_e}{dz} e^{ikz} - \frac{dE_h}{dz} e^{-ikz} = \frac{i k_{\alpha}^2}{2\beta} \Delta \varepsilon [E_e e^{ikz} + E_h e^{-ikz}] . \]

Since \( \Delta \varepsilon \) is periodic in \( z \), with grating period \( \Lambda \), it can be expanded in a Fourier series and substituted into the above equation. Assuming the phase mismatch is smallest for the \( m^{th} \) term in the series, and collecting those phase-matched terms gives the coupled equations:
\[
\frac{dE_l}{dz} = i\kappa E_l e^{-i\Delta \beta z} \\
\frac{dE_h}{dz} = -i\kappa E_h e^{i\Delta \beta z}
\]

where \( \kappa = \frac{k_1^2}{2\beta} \Delta \epsilon_m \) and \( \Delta \epsilon_m \) is the coefficient of the m\textsuperscript{th} term in the Fourier series expansion.

A simplification can be made by setting \( A = E_f e^{i\Delta \beta z} \) and \( B = E_b e^{-i\Delta \beta z} \). Then:

\[
\frac{dA}{dz} = i\Delta \beta A + i\kappa B \\
\frac{-dB}{dz} = i\Delta \beta B + i\kappa A
\]

These equations have the general solution:

\[
A(z) = A_1 e^{iqz} + A_2 e^{-iqz} \\
B(z) = B_1 e^{iqz} + B_2 e^{-iqz}
\]

where \( q = \pm((\Delta \beta)^2 - \kappa^2)^{1/2} \).
Defining \( r(q) = (q - \Delta \beta)/\kappa \), and solving for the interdependence of the coefficients \( A_1, A_2, B_1, \) and \( B_2 \) yields:

\[
A(z) = A_1 e^{i\kappa z} + r(q) B_2 e^{-i\kappa z}
\]

\[
B(z) = B_2 e^{-i\kappa z} + r(q) A_1 e^{i\kappa z}
\]

It is evident from these equations that \( r(q) \) represents the fraction of each wave that is reflected back towards the counterpropagating wave.

Consider now a forward propagating wave incident on a DBR grating which extends from \( z = 0 \) to \( z = L \). The amplitude reflection coefficient is given by:

\[
r_e = \frac{B(0)}{A(0)} = \frac{B_2 + r(q) A_1}{A_1 + r(q) B_2}
\]

By assuming the boundary condition at the end of the reflector, \( B(L) = 0 \), we obtain:

\[
B_2 = r(q) A_1 e^{2i\kappa L}
\]

From this, the amplitude reflection coefficient for the grating is determined to be:

\[
r_e = \frac{i\kappa \sin(qL)}{q\cos(qL) - i\Delta \beta \sin(qL)}
\]
where $\Delta \beta$ can be written as $\Delta \beta = \delta + i\alpha/2$, with $\alpha$ representing the optical loss within the grating, and $\delta$ representing the detuning of the laser wavelength from the Bragg wavelength.

Figure 2.7 shows a graph of the grating reflectivity as a function of detuning from the Bragg wavelength. $\alpha L$ is chosen to be 0.1, and graphs of two different values of $\kappa L$ are shown. A similar analysis applies to DFB structures[58,59].

The characteristics of DFB and DBR laser are very similar. However, because of coupling losses between the active region and the grating in a DBR laser, threshold currents for DBR lasers tend to be higher than for DFB lasers. Other properties such as the spatial mode distribution, and the spectral purity are almost identical for both DFB and DBR lasers.

2.5 Quantum Well Semiconductor Lasers

In the average heterostructure semiconductor laser, the active layer thickness is typically in the range of 0.1-0.3 $\mu$m. Recently, lasers with an active layer thickness of $\sim 10$ nm have been constructed. In these lasers, motion normal to the active layer is restricted, and the kinetic energy of the carriers moving along that direction is quantized in a way similar to that of a one-dimensional potential well. These lasers are known as quantum well lasers[60,61].

The quantization of the kinetic energy normal to the active region has a number of consequences that affect the performance of the device. One result is that the density of states in a quantum well laser is
Figure 2.7: Power reflectivity of a distributed Bragg reflector as a function of detuning from the Bragg wavelength.
independant of the carrier energy. This can significantly alter the recombination rates in a quantum well laser as compared to a regular diode laser. Quantum well lasers have a lower threshold current and a higher efficiency than regular diode laser devices. They can be fabricated over a widely varying range of wavelengths by merely changing the well thickness. And quantum well lasers exhibit a threshold current that is much less temperature dependant than that of regular semiconductor lasers.

Quantum well devices come in two groups: the single-quantum well (SQW) diode laser, and the multi-quantum well (MQW) diode laser. Multi-quantum well devices have several active layers separated by barrier layers. If the band gap of the barrier layers differs from that of the cladding layers, the laser is referred to as a modified MQW diode laser. MQW diode lasers have an advantage over other laser types, including SQW diode lasers, in that MQW lasers can be operated to much higher output powers[62]. SQW and MQW laser structures are shown in figure 2.8.

A drawback of the SQW diode laser is the very small optical mode confinement factor, which can result in a higher threshold current density (when compared to MQW lasers) The confinement factor of an SQW device can be significantly increased by using a graded-index (GRIN) cladding layer (also shown in figure 2.8). This allows the advantage of a quantum well structure (high gain at low carrier density) without the drawback of a small mode confinement factor[63]. Very low threshold currents (2.5 mA) have been reported for GRIN SQW diode lasers[64].
Figure 2.8: Different single quantum-well and multiquantum-well laser structures shown schematically.
One of the greatest advantages of quantum well lasers is that they can be fabricated using an active layer in which the lattice constant differs from the lattice constant of the substrate and cladding layers. These devices are called strained quantum-well lasers[65,66,67]. In a strained quantum well device, the active layer composition can be chosen based on the wavelength desired, with little concern over the resulting lattice constant. Additionally, band structure changes induced by the lattice mismatch often improve device performance. Strained quantum-well lasers exhibit a low threshold current, and a small linewidth under both CW and pulsed operation.

2.6 Operating Characteristics of Diode Lasers

Previous sections have considered the internal structures of diode lasers and the basic concepts of their operation. Consider now the characteristics by which the performance of a diode laser is evaluated. Of particular importance are the light-current relation, spatial-mode profiles, spectral purity, and tuning characteristics.

The Light-Current Relation

As the current passing through a diode laser is varied, the power emitted from the device changes. A plot of the power emitted as a function of the device current is called a light-current (L-I) curve. A typical L-I curve is shown in figure 2.9. Notice the distinct change in output power at threshold; the current at threshold (I_{th}) is an important device characteristic. Normal operating currents are located in the linear regime
Figure 2.9: Typical light-current (L-I) curve for a semiconductor laser.
of the L-I curve, and the slope can be used to measure another important parameter, the differential quantum efficiency. A sublinear increase in power at high currents indicates the onset of saturation. Saturation occurs for a number of different reasons, including an increase in the leakage current, or an increase in the internal optical losses. It is advisable not to operate a diode laser in the saturation regime for long periods of time, since such operation could damage the facets and age the device.

Some diode lasers exhibit kinks in their L-I curve. Such a kink is an indication of a mode shift, either a spatial-mode change, or a longitudinal mode hop. Spatial mode shifts are particularly detrimental when coupling to an optic fiber, or performing any experiment sensitive to the laser's spatial distribution. Longitudinal mode hops affect the tuning characteristics of the device, and can make certain wavelengths difficult or impossible to reach. Furthermore, any mode shift, spatial or longitudinal, lowers the overall efficiency of the device. It is also important to note that the L-I curve of a diode laser is not fixed, but is strongly temperature dependant. The shape of the curve does not change much with temperature, but the threshold current and the saturation current are altered by temperature changes. As the temperature increases (decreases), the entire L-I curve shifts to higher (lower) currents. A diode laser's L-I curve can also change over time. Extensive use ages the laser and alters its characteristics, including the L-I relation.
Spatial Mode Profiles

A diode laser emits radiation in a diverging beam of elliptical cross section. Measurement of the beam profile at two locations, the near field and the far field, provides enough information about the spatial mode to evaluate the device. The spatial-intensity distribution at the output facet is known as the near-field distribution, and the angular intensity distribution far from the laser chip is called the far-field distribution.

The near-field distribution shows the shape of the mode propagating in the laser cavity. The distribution perpendicular to the junction plane (transverse distribution) depends on the thickness and composition of the layers used to make the heterostructure. Similarly, the near-field parallel to the junction plane depends primarily on the waveguiding structure in the device. In a buried heterostructure device, the parallel and perpendicular near-field distributions are very similar. A typical buried heterostructure near-field distribution is shown in figure 2.10(a)[68].

The far-field distribution indicates the angular divergence of the diode laser output. It depends primarily on the size of the active region: the far field pattern parallel to the junction plane depends on the width of the active layer, while the far field distribution perpendicular to the junction plane depends on the thickness of the active layer. Most diode lasers have large divergence angles, with the divergence perpendicular to the junction plane being the largest. However, with a few lenses and some spatial filtering, good collimated Gaussian profiles can be obtained with
Figure 2.10: Near field scan (a) along the junction plane, and far-field scans (b) perpendicular, and (c) parallel to the junction plane for a typical buried heterostructure diode laser.
minimal loss of power (~10%). Typical far-field distributions are shown in figure 2.10(b),(c)[68].

**Spectral and Tuning Characteristics**

The output spectrum, and how it changes with current and temperature, is an important characteristic of a semiconductor laser. Below threshold, the output is due to spontaneous emission and has a broad spectral width (~30nm). As the laser is brought above threshold, the spectrum narrows, and a number of peaks appear whose frequencies coincide with longitudinal modes of the laser cavity.

In a typical diode laser, many longitudinal modes oscillate simultaneously. As the current is increased, the mode nearest the peak of the gain curve continues to increase in power; however, a sizeable fraction of the total power is still carried in the side-modes. Since these side modes adversely affect many applications, it is desirable to have them reduced as much as possible. A parameter used to describe the spectral purity of a laser beam is the mode suppression ratio (MSR). The MSR is defined as the ratio of the power in the main mode to the power in the most intense side mode. MSR values in excess of 30 dB are sought for most applications. Such high MSR values can be obtained by the use of single-mode control structures, such as DFB and DBR structures (see figure 2.11 a and b).

Another important spectral characteristic of lasers is the linewidth of the main mode. Typical diode lasers have broad linewidths ranging from 10-100 MHz. Internal frequency control structures, such as DFB or DBR,
Figure 2.11: Typical output spectrum of a (a) multimode diode laser, and (b) DBR diode laser. Also shown (c) the tuning curve of a standard diode laser showing spectral gaps.
can reduce the linewidth of the laser to ~1 MHz. Similarly, quantum well semiconductor lasers have smaller linewidths than ordinary diode lasers. With the use of an external cavity (discussed in Appendix A), linewidths as small as 10 kHz have been realized[69,70].

A diode laser's operating wavelength range is primarily determined by the material from which the laser is constructed, and the geometry of the internal structures. Beyond that, the exact frequency of lasing is determined by the temperature of the device and the current passing through it. Typical tuning ranges of up to 20 nm can be achieved with temperature changes; current variations tune on a finer scale, with maximum ranges usually less than a few nanometers. A plot of wavelength as a function of temperature or current typically exhibits gaps in the tuning curve (see figure 2.11 c). As the temperature (or current) is changed, the laser may hop from one longitudinal mode to another, skipping over a small range of frequencies in the process. In some cases, careful setting of the temperature and current will allow frequencies just inside a gap to become accessible; however, frequencies deep inside a gap can only be reached with the use of an external cavity (see Appendix A). These spectral gaps encountered as the laser tunes constitute the biggest drawback to using diode lasers in atomic physics.

**Diode Laser Aging**

One of the unique characteristics of diode lasers is that their properties change over time, a process called aging. One manifestation of aging is that the tuning steps gradually move, so the current or temperature
may have to be adjusted to maintain the same lasing frequency. This poses a problem if the laser is operating near a gap in the tuning spectrum, as the desired frequency may 'age into the gap', making that frequency no longer attainable. Conversely, if the desired frequency is unreachable, aging may bring that frequency out of the gap. Eventually, a laser will exhibit other signs of aging, such as linewidth broadening, a rise in the threshold current, and eventually, multimode operation. After these signs appear, the laser will soon become no longer useful and will have to be replaced. Typical aging time scales are on the order of a couple of years with reasonable use; however, if the laser is operated at high temperatures or high currents, the aging process accelerates.

For more information on diode lasers and their operation, the following references are highly recommended: [71,72,73,74,75,76,77]

2.7 The 1.083 μm Diode Laser

Of particular interest in studies involving He(2^{3}S) metastable atoms is the production and control of intense sources of 1.083 μm radiation. A number of solid-state materials have been available that serve as the basis for lasers operating at this wavelength, but these laser systems are bulky and expensive to maintain. Recently, high power diode lasers that can operate at 1.083 μm have been developed.

These lasers employ an InGaAs/GaAs strained MQW with a DBR as the frequency selective element; they provide a maximum output power of ~50 mW. The active layer composition is In_{x}Ga_{1-x}As, where x = 0.45; and the cladding layers are AlGaAs, grown on a heavily doped GaAs substrate.
The L-I curve of the diode laser shows a threshold current of \( \sim40 \) mA, and a maximum device efficiency of \( \sim25\% \). Numerous kinks exist in the L-I curve, but they all correspond to longitudinal mode shifts. The laser output is single frequency with an MSR of \( \sim28 \) dB. The beam divergence parallel to the junction plane is \( \sim14^\circ \), and perpendicular to the junction plane is \( \sim38^\circ \). These 1.083 \( \mu \)m device characteristics are shown in figure 2.12. Higher power versions (with a maximum output power of 220 mW) of this diode laser have been tested but are not yet commercially available[14].
Figure 2.12: Characteristics of the SDL-6702-H1 diode laser operating at 1.083 μm: (a) L-I curve, (b) far-field distributions perpendicular and parallel to the junction plane, and (c) output spectrum.
Chapter 3
Stabilization and Control of a 1.083 μm Diode Laser

The utility of a laser, be it a diode laser or not, is greatly increased if its output can be tuned to different wavelengths, and its frequency precisely maintained. In particular, elimination of the long-term frequency drifts and the short-term frequency fluctuations are important. For a diode laser, the output frequency can be changed by varying either the current through the device or its temperature. However, fluctuations in these parameters result in unwanted frequency drift. Short term jitter can increase the effective bandwidth of the laser, while long term drifts jeopardize any experiment requiring the laser to remain at one frequency for an extended period of time. Furthermore, it must be noted that drifts of the current or temperature of a diode laser will also alter the output power.

3.1 Commercial Stabilization
A diode laser with no electronic or optical feedback will not maintain a stable output frequency, since both the temperature and the current will fluctuate to some extent. The temperature is the most critical because small temperature changes can alter the output frequency a large amount (~1 nm/°C). Many commercially available diode lasers (including the 1.083 μm device used in this work) are temperature stabilized using a built-in thermoelectric cooler (TEC) attached to a heatsink. However, even with the temperature of the diode laser controlled, environmental fluctuations were observed to result in significant frequency drift.
The current in a diode laser device is also monitored and held constant by the driving electronics. Unfortunately, there is some electronic noise in the current driver that is transmitted directly to the laser. Such current fluctuations tend to be faster than temperature changes, and have a less dramatic effect on the output frequency (~1 GHz/ma). In many cases, the fast current fluctuations are white noise that serve only to broaden the linewidth of the laser.

During initial testing using the commercial drive electronics, the output frequency drift of our 1.083 µm diode laser was observed to have both a slow component and a noticeably faster component. The fast component dithers the laser output frequency by ~±20 MHz about the center frequency; occasionally, the laser frequency will move as far as 50 MHz. The dither modulates the laser frequency at ~100 Hz. The slow drift, probably due to temperature fluctuations, results in a frequency walk of about 200 MHz/hr. Clearly, the size of this drift is unacceptable for experiments which depend critically on the laser frequency. Therefore, in order to eliminate both the slow and fast drift, a number of stabilization methods were devised and tested.

3.2 Superlock Stabilization

Of the various methods used to reduce the long and short term frequency drift of the 1.083 µm diode laser, the first method tested was the so-called superlock stabilization system, developed earlier in this laboratory to control the long-term frequency drifts in single-mode dye lasers[78].
Superlock operates on the following principle: a laser that is ultra-stable (having a frequency drift less than 1 MHz/day), can serve as a reference for another laser system that is not stable. A diagram of the superlock system is shown in figure 3.1. To operate, superlock requires that a portion of the output from each of the two lasers, the reference laser and the unknown laser, be superimposed and directed into a confocal Fabry-Perot etalon. Usually, the laser beams are orthogonally polarized (linearly); this allows the beams to be combined, and later separated, by means of a pair of polarizing beamsplitter cubes. One mirror in the Fabry-Perot cavity is mounted to a piezoelectric translator (PZT) that is continuously ramped over a set voltage range; as the voltage changes, the length of the cavity changes. As the length of the cavity is scanned, peaks in the transmission will occur when either laser's wavelength meets the condition: \( m\lambda = 4L \), where \( m \) is an integer. The transmitted radiation is directed, based on its polarization, into one of two photodetectors. A plot of the intensity against the PZT ramp voltage shows a series of peaks from each detector, one series corresponding to each laser (see figure 3.2). Pairs of transmission peaks from different series provide a measure of the frequency difference between the lasers; furthermore, this frequency difference is expressed as a voltage difference. Since the reference laser is assumed to be ultra-stable, any change in that voltage difference will be due to a change in the frequency of the unknown laser. This allows the generation of an error signal that can be used to restore the laser to its original frequency.
Figure 3.1: Schematic diagram of the superlock stabilization system.
Figure 3.2: Illustration of the superlock detector peaks and the PZT ramp voltage.
One limitation in generating the error signal as described is that the sampling rate is limited by the PZT scan rate in the Fabry-Perot cavity (~50 Hz). This limits the speed with which superlock can respond to frequency drifts to ~20 ms. Thus, superlock cannot correct for short term fluctuations, but it can eliminate the long-term drifts in laser frequency.

In the case of a diode laser, the error signal generated by superlock can be used to control the current in the device. By connecting superlock directly to the external modulation port of the diode laser control unit, the long-term drift of the laser can be reduced to less than 2 MHz/hr. However, the short-term fluctuations remain large (~±10 MHz) and serve to effectively broaden the linewidth of the diode laser. The linewidth broadening is not critical since it may be useful in some experiments, but superlock reacts so slowly that other fluctuations are also visible. The most visible of these fluctuations is a periodic movement of the laser frequency of ~40 MHz. One result of this behavior is that if the fluctuations are sufficiently large, the laser will become unlocked. Furthermore, this noise serves to reduce the power being produced at the desired frequency.

To improve the frequency stability of the diode laser, a system was developed that could remove the faster fluctuations.

3.3 Reference Cavity Stabilization

The most effective method of diode laser stabilization developed in this laboratory to date is the use of a reference cavity in conjunction with the superlock system. This method of stabilization is shown schematically
in figure 3.3, and is based on a system used previously to stabilize a linear LNA laser[9,10]. A description of the stabilization method is as follows.

A small portion of the diode laser output is directed into a temperature stabilized Fabry-Perot reference cavity, and the power transmitted through the cavity is monitored by a photodiode. If the length of the reference cavity remains fixed, then the transmission through the cavity depends only on the laser frequency. Therefore, the diode laser can be stabilized by maintaining the power transmitted through the reference cavity at a constant level. Since a change in the output power of the diode laser would also affect the power transmitted through the cavity, a second photodiode is used to monitor the power of the laser. The ratio of the reference cavity transmission to the power reference provides a signal directly proportional to the fractional transmission through the reference cavity. Changes in this signal are used to generate an error signal that adjusts the current being sent to the diode laser. When the reference cavity is set appropriately, the transmission through the cavity increases (decreases) as the laser frequency decreases (increases), and the sign of the error signal generated indicates the direction in which the current must be adjusted to compensate.

A schematic of the circuit used to generate the error signal is shown in figure 3.4. The first section of the electronics provides the ratio of the intensities measured by the photodiodes. The error signal is created from this ratio, processed, and sent to the diode laser control unit. A functional description of the electronics is given below.
Figure 3.3: Schematic diagram of the reference cavity stabilization system.
Figure 3.4: Schematic of the electronics used to generate the error signal in the reference cavity stabilization system.
The signals from the power reference photodiode (PD1) and the reference cavity photodiode (PD2) are amplified by IC1A and IC2A, respectively; the amount of amplification is controlled by the variable resistors R1 and R2. These signals are inverted and further amplified (10x) by IC1B and IC2B. IC1 and IC2 are both LF353 dual op-amps. The output voltages from these amplifiers are then directed into the divider, which is composed of an op-amp (IC4) with a multiplier (IC3) in the feedback loop. IC4 is an OP77, chosen for its greater stability (compared to an LF356 or 741), and the multiplier chip is an MC1594. The resistors P1-P3 and R_L control the various offsets of the divider, and the amplification of the divider output. It is important that these resistors be set properly in order to guarantee linear division over the entire input voltage range (1-10 V). A discussion on how to properly set the divider offsets is given in Appendix B. The ratio signal generated by the divider is added (IC5A) to a variable constant reference voltage provided by R3. By adjusting the reference voltage, the output frequency of the diode laser can be tuned. The output from IC5A is the complete error signal.

It is necessary at this point to split the error signal into two components: a rapidly varying signal, and a slowly varying signal. The purpose of splitting the signals is to produce an error signal that can maintain a large dc offset voltage, but still allow for high speed correction. Consider a situation in which a diode laser drifts to a frequency (f_1) which is away from the desired lock frequency (f_0). The circuit responds by generating an error signal to bring the diode laser back to the proper frequency. However, as the diode laser moves back towards the desired
frequency, the error signal generated by the electronics decreases. As the error voltage decreases, the rate at which the diode laser frequency moves towards $f_0$ slows. A compromise results when the laser frequency reaches a certain point ($f_2$) where the error signal (generated because $f_2 \neq f_0$) is exactly the voltage needed to bring the diode laser from $f_1$ to $f_2$. Mathematically, $K_{\text{error}}(f_2-f_0) = K_{\text{diode}}(f_1-f_2)$, where $K_{\text{error}}$ is the error voltage generated in response to a 1 MHz drift, and $K_{\text{diode}}$ is the voltage needed to tune the diode laser by 1 MHz (assuming $f_i$ is expressed in MHz).

So the diode laser locks to a frequency between the desired lock frequency ($f_0$) and the unlocked frequency ($f_1$). The problem results when the location of $f_1$ changes, which results in the lock frequency, $f_2$, also changing, causing the ‘locked’ laser to drift. By placing an integrator in the circuit, a voltage can be stored that will eliminate the compromise situation, and hold the laser frequency at the desired lock point, $f_0$.

Unfortunately, the error signal cannot simply be sent through an integrator since that would result in the fast signals being filtered out. Thus, the error signal is split into a slowly varying voltage which is sent to the integrator, and a rapidly varying voltage which circumvents it.

After the error signal is split, one branch of it is variably amplified by IC5B, and filtered to eliminate the slowly varying components. This signal (the fast signal) is then inverted by IC6B and connected to an adder (IC7B). The amplification of the fast signal is controlled by the resistor R4. The other branch of the error signal is sent to the variable amplifier IC6A, and then directed to the integrator (IC7A). The resistor R5 controls the amplification of this signal (the slow signal). After the integrator, the
slowly varying signal is sent to IC7B, where the two signals (the fast and the slow) are added to create the final correction signal. This correction signal is then connected to the external input of the diode laser control unit. It should be noted that all of the chips mentioned above (IC5-IC7) are LF353 dual op-amps.

Some additional components of the electronics also deserve mention. Four signals must be viewed in order to set the amplifications and offsets of the circuit appropriately. Two of these are the power reference and reference cavity signals, which must be monitored to allow the proper setting of R1 and R2. The output from the divider must be monitored to set the divider offsets (P1-P3,RL) correctly. Additionally, the correction signal needs to be monitored. The LF353 dual op-amps IC8 and IC9 act as buffers between the control circuitry and the monitor outputs.

The advantage of the reference cavity stabilization system is that the correction speed is limited by the bandwidth of the electronics rather than by a mechanical component. The ~2 kHz bandwidth of the fast control system allows correction of frequency fluctuations in ~500 μs. With a correction signal that can respond this quickly, the diode laser frequency fluctuations induced by the ripple in the laser power supply can be totally removed; furthermore, the linewidth of the diode laser is slightly reduced. Unfortunately, problems do exist with this approach to stabilization. Primarily, the tunability of the locked diode laser is limited by the free spectral range (FSR) of the reference cavity. If the laser is tuned from the initial set frequency, which has a transmission coefficient of 50%, to a higher frequency with a transmission coefficient of 30%, then no problem
is evident. If, however, an attempt is made to tune the laser to a frequency for which the transmission coefficient is zero, then the slope of the transmission coefficient \( \frac{d(\text{transmission})}{d(\text{frequency})} \) vanishes. Further increasing of the laser frequency will result in the transmission coefficient increasing, and the slope becoming positive. This produces a correction signal that has the wrong sign, which causes the laser frequency to be driven away from the lock point, and the laser to come unlocked.

The use of a reference cavity also presents a long term drift problem. The transmission through the reference cavity depends on the length of the cavity; therefore, if the length is altered, the transmission coefficient changes, and a signal is sent to the diode laser to change its frequency. The most common way for the length of the cavity to be altered is through temperature fluctuations. Although the reference cavity is temperature stabilized, it is susceptible to some temperature changes that will result in laser drift. In fact, the frequency drift resulting from this can be as large as 50 MHz/hr, although typical values of drift are \( \leq 10 \) MHz/hr.

One method for correcting the changes in the reference cavity due to temperature fluctuations is to use the superlock system as part of the laser tuning mechanism. This can be done by adding the superlock correction signal directly to the correction signal generated by the reference cavity electronics. However, this method has two severe drawbacks. First, if the reference cavity drifts to a transmission minimum (or maximum), then lock will be lost due to the error signal changing sign (as described previously). A second, more subtle, problem is when the cavity
approaches a transmission minimum (or maximum). Near these points, the slope of the transmission coefficient begins to change, which alters the response of the correction electronics.

For the diode laser, a different approach, which avoids these problems, is used. The superlock system is used to stabilize the reference cavity directly. When the length of the reference cavity changes due to temperature fluctuations, superlock sends a signal to the PZT that controls the length of the cavity. When it receives the amplified superlock error signal, the PZT moves one of the mirrors in the cavity to compensate for the change. This eliminates the long-term drift and stabilizes the laser frequency to less than a few MHz of drift per day. Figure 3.5 shows the drift of the locked-superlocked laser over a period of 2 hours. As one can see, this method results in a long term drift of less than 1 MHz/hr and short term fluctuations of less than 5 MHz, which is smaller than the linewidth of the laser, estimated to be 10-15 MHz.

3.4 External Cavity Stabilization

An alternative approach to diode laser stabilization that has recently attracted much attention is the use of an external cavity. The external cavity scheme is a specific case of a group of diode laser frequency control methods known as coupled-cavity techniques (described in Appendix A).

Briefly, an external cavity is made by placing a reflective element beyond the diode laser such that a portion of the laser output is directed back into the laser active region. This external element, along with the diode laser output facet, forms a second cavity which couples to the first
Figure 3.5: Frequency drift of the diode laser (a) unlocked, and (b) locked using the reference cavity in conjunction with superlock.
cavity defined by the two cleaved facets. The interference between the
cavities results in frequency selectivity. The frequency of operation is
controlled by the exact position of the external element, and can be tuned
by a linear adjustment of that element. The output from an optimized
externally locked diode laser is single-mode, tunable over a large range
(~50 nm), and has a very small linewidth (less than 100 kHz)[76].

Tests of an external cavity stabilization scheme were performed on
the 1.083 μm DBR diode laser. The external cavity was formed by placing
a planar optical flat in the diode laser beam line parallel to the laser facets.
The flat was anti-reflection (AR) coated on the back side, so that optical
feedback was provided by the 4% reflection from the front face. The plate
was mounted on a PZT, and placed approximately 30 cm beyond the laser
diode.

Stabilization of the laser frequency was achieved by sending a
portion of the output to a reference cavity and another portion to a power
reference photodiode. In a method similar to that described previously, an
error signal was generated by taking the ratio of the reference cavity signal
to the power reference signal. This error signal was processed by a set of
electronics that were designed for the stabilization of a linear LNA laser
system [9,10].

In these electronics, the error signal is directed to a high voltage
amplifier, whose output was used to drive the PZT on which the optical flat
was mounted. As the external cavity vibrated, the PZT expanded and
contracted to compensate, and kept the length of the external cavity
constant. Unfortunately, the PZT has a limited range of motion (±1 μm).
Therefore, to compensate for larger changes in the cavity length (e.g. due to thermal expansion), an additional optical flat, ~1 mm thick, was placed at Brewster's angle in the external cavity. The Brewster plate was mounted on a galvo drive which allowed the plate to be rotated to change the optical path length in the cavity. The electronics determined when the frequency drift was too large for the PZT to compensate, and in that case, a signal was directed to a current driver which appropriately rotated the Brewster plate.

With the use of the external cavity stabilization scheme (shown in figure 3.6), the diode laser could be frequency stabilized for short periods of time. However, the drift in the reference cavity used to generate the error signal was substantial. Again, in a method similar to that described in section 3.2, the superlock system was used to eliminate the slow drift in the reference cavity, and improve the locking of the laser.

The use of an external cavity also reduced the output linewidth of the diode laser. A precise measurement of the linewidth could not be made, but indirect measurements indicate that the linewidth was considerably smaller than that of the unlocked diode laser (whose estimated linewidth is ~20 MHz). Measurements made using the superlock reference cavity, and studies of optical pumping rates indicate a linewidth smaller than a few MHz. However, results reported in the literature state that externally locked diode laser linewidths can be as small as 10 kHz[69,70].

One problem with the use of the external cavity is the loss of lock due to mode hops or the onset of multi-mode operation. This problem poses a serious difficulty in the use of the superlock system, as the
Figure 3.6: Illustration of the external cavity stabilization scheme.
corresponding transmission peaks change unpredictably and the system is unable to maintain the lock. The reference cavity electronic locking system is capable of recovering from mode hops; however, it is not always able to return the laser to its previous operating frequency.

The mode instabilities observed may result from a number of factors, but the primary problem is most likely the lack of feedback to the diode laser current. Since the frequency of the gain peak depends on the current and temperature of the diode laser, drifts in these parameters can result in mode hops and multi-mode operation. If a portion of the error signal is used for diode laser current control, then the current and temperature drifts could be compensated for, and the mode instability should be considerably reduced. Additionally, the lack of current feedback limits the tunability of the device, and may prevent the external cavity from recovering the original lock frequency if a mode hop occurs. Another possible source of mode instability may be unwanted optical feedback from other elements further down the beam line.

3.4 Locking to an Atomic Transistion

The final method employed to lock a 1.083 μm diode laser is the use of a lock-in amplifier to lock the laser to a He(2^3S_i)→He(2^3P_0) transition (similar to the method used in [79]). The setup is shown in figure 3.7. An rf discharge is ignited in a small glassbulb containing pure helium to create a He(2^3S) population; the diode laser beam is directed into the bulb, and a photodetector monitors the intensity transmitted through the discharge. A function generator is used to modulate the diode laser current, and a
Figure 3.7: Schematic of the system used to lock the diode laser to the $2^3S_1 \rightarrow 2^3P_0$ transition in helium.
commercial lock-in amplifier generates the error signal. This correction signal is connected into the external input of the diode laser, and used to lock the laser to the Doppler-broadened transition.

A lock-in amplifier operates on the principle of phase-sensitive detection. As the laser output frequency is modulated (at a modulation frequency $\omega_{\text{mod}}$) over the atomic transition, the intensity of the light transmitted through the discharge oscillates (see figure 3.8 (a)). If the laser frequency is exactly centered on the atomic transition, the intensity will oscillate at twice the modulation rate of the diode laser current ($2\omega_{\text{mod}}$). As the frequency of the diode laser drifts to away from the transition, the intensity oscillation becomes a linear combination of oscillations at the frequencies $2\omega_{\text{mod}}$ and $\omega_{\text{mod}}$. The lock-in amplifier filters the intensity oscillation, eliminating all frequency components except the one oscillating at the frequency $\omega_{\text{mod}}$. The magnitude of this component is used to generate an error signal that is sent to the diode laser. The sign of the error signal is determined by the phase of the intensity component oscillating at the frequency $\omega_{\text{mod}}$ relative to a reference modulation also oscillating at the frequency $\omega_{\text{mod}}$.

As the diode laser frequency is tuned over the atomic transition, the lock-in error signal maps out a dispersion curve (figure 3.8 (b)). This curve is a measure of the value of the correction signal sent to the diode laser for a given frequency shift. The size of the correction signal is determined by the sensitivity setting of the lock-in amplifier, with the bestlock being achieved at the most sensitive scales. Unfortunately, operating on a very sensitive scale introduces the risk that the lock-in
Figure 3.8: Illustrations of (a) the intensity oscillations resulting from modulation of the laser frequency across an atomic transition, and (b) the error signal generated by a lock-in amplifier as a function of frequency.
output may saturate if the laser drifts very far. Determining the best locking sensitivity is crucial to maintaining a long-term lock.

The 1.083 µm diode laser was locked to the He(2^3S₁) → He(2^3P₀) (D0) helium metastable transition using a commercial lock-in amplifier (Stanford Research Systems SR510). It was found that the best lock was achieved at the 50 µV sensitivity. Dispersion curves for various lock-in sensitivities were obtained, and the slopes of the curves at the zero-crossing point were determined. The zero-crossing slope, extrapolated to the 50 µV scale, was used to determine the error signal that would be generated for a given amount of frequency drift. Then, while the diode laser was locked, the error signal being sent to the device was monitored for ~5 hours. From this it was found that the locked laser had a maximum long-term frequency drift of less than 1 MHz/hr[80].

The applications of a diode laser locked in this way seem limited since the diode laser must remain at the transition frequency and cannot be tuned to another wavelength. There are, however, methods of tuning the laser without sacrificing this locking mechanism. One method is to lock the laser to an atomic transition that can be moved with an electric or magnetic field. Another way is to create tunable sidebands in the laser output, and lock to one of these.

Some improvements in the locking of the diode laser with the lock-in amplifier are being pursued. One improvement would be the addition of an integrator circuit between the lock-in and the diode laser external input. The integrator would eliminate the drift resulting from the compromise that forms between the diode laser and the lock-in amplifier, as in the
situation with the reference cavity electronics described in section 3.3. Another improvement under consideration is to lock the laser to a doppler-free absorption signal. To do this, the diode laser output is split into two beams, a pump beam and a low intensity probe beam. These beams are directed counterpropagating through the bulb containing the helium discharge. The absorption pattern for the probe beam shows the normal doppler broadened shape, with the addition of a peak in the middle of the pattern. This occurs when the strong pump beam saturates the transistion, which reduces the population of unexcited atoms, causing less absorption of the probe beam. However, because of the Doppler-effect, this resonance can only occur when the two lasers interact with the same velocity group of atoms. Since the two beams are counterpropagating, this situation requires that the atoms have zero velocity along the beam line. The narrow Doppler-free resonance will allow for a much tighter lock of the diode laser to be achieved with the lock-in amplifier.

If this locking mechanism proves to be ultra-stable (having a frequency drift less than 1 MHz/day), a diode laser locked in this way could serve an important purpose. Currently, the ultra-stable reference laser used in the superlock system is a helium-neon (HeNe) laser. Ultra-stable HeNe lasers unfortunately require considerable care, and are not always reliable. Furthermore, troubleshooting a malfunctioning ultra-stable HeNe laser is a formidable task. Replacement of the ultra-stable HeNe laser with a diode laser locked to an atomic transition would be a great improvement.
Chapter 4
Experiments with a 1.083 μm Diode Laser

A number of experiments involving He(23S) metastable atoms can be performed using the 1.083 μm diode laser system described in the previous chapter. These experiments, many of which are similar to those undertaken previously with more expensive laser systems, involve excitation of the He(23S)→He(23P) transition. One application that has been performed is optical pumping of a He(23S) atom beam. Two other upcoming experiments for which the diode laser may also be useful are the production of a polarized He+ ion beam, and atomic slowing of He(23S) atoms for loading into a magneto-optical trap (MOT). Since these experiments are sensitive to laser beam alignment and polarization, a discussion of the use of optical fibers to transport the 1.083 μm radiation and to improve the beam quality of the laser is also included in this chapter.

4.1 Optical Pumping

The first experiment performed with the 1.083 μm diode laser was optical pumping of a He(23S) metastable atom beam. This experiment was performed in the spin polarized metastable de-excitation spectroscopy apparatus (the SPMDS), which consists of three linked vacuum chambers (see figure 4.1)[3]. In the first chamber, a He(23S) metastable beam is produced. The second chamber is where optical pumping is performed:
Figure 4.1: Schematic diagram of the SPMDS apparatus.
and the third chamber is where the spin polarized metastable atom beam interacts with a target.

Helium gas is introduced into the source chamber through a multichannel array. The gas travels through a coaxial electron gun where it is bombarded with electrons. The collisions create a number of excited states; of these, only the He(2\(^3\)S), He(2\(^1\)S), and various high-lying Rydberg states are long-lived. A partial term diagram for helium, showing the 2\(^3\)S and 2\(^1\)S states, is shown in figure 4.2.

In order to produce a pure He(2\(^3\)S) metastable atom beam, it is necessary to remove all of the other excited states. The He(2\(^1\)S) atoms are removed from the beam by exciting the He(2\(^1\)S)→He(2\(^1\)P) transitions with 2.06 \(\mu\)m radiation. This radiation is produced by a helium discharge lamp, called the quench lamp. From the excited He(2\(^1\)P) state the atoms decay quickly to the ground state. A pair of charged plates is used to remove the electrons and ions from the beam, and ionize any highly-excited Rydberg states that may be present.

At this point the only components of the beam that can give rise to observable effects are He(2\(^3\)S) metastable atoms, fast (non-thermal) neutrals, and photons. Slow ground state helium atoms are unimportant as they are inert. The signals produced by the impurities (the fast neutrals and photons) are discriminated against by mechanically chopping the beam. As a beam pulse travels through the apparatus, these impurities spatially separate from the slower metastable atoms. Data is recorded only in that window when the He(2\(^3\)S) metastable atoms are arriving at the interaction region.
Figure 4.2: Partial term diagram for helium.
Optical pumping is performed in the second chamber where a small magnetic field (~0.5 G), applied perpendicular to the beam axis, provides a well defined quantization axis. The He(2$^3$S) atoms are optically pumped using circularly polarized radiation provided by the diode laser, tuned to the atomic resonance at 1.083 μm. The optical pumping radiation is incident parallel to the quantization axis, and transverse to the beam axis.

The He(2$^3$S) state has total angular momentum J=1 (S=1, L=0), and three magnetic sublevels with $m_j = -1, 0, +1$. Under normal conditions, all of these sublevels are populated equally. With the use of optical pumping the relative population of the $m_j = +1$ (or $m_j = -1$) sublevel can be increased[81], resulting in an electron spin polarized He(2$^3$S) beam. This process is described below.

Consider illuminating the metastable atom beam with right-hand circularly polarized (RHCP) light. This radiation excites a He(2$^3$S)→He(2$^3$P) transition subject to the selection rule $\Delta m_j = +1$. Once excited, the atoms will spontaneously decay back to the He(2$^3$S) state, this decay being governed by the selection rule $\Delta m_j = -1, 0, +1$. Figure 4.3 shows the possible excitations (straight lines) and decays (wavy arrows) for a helium metastable atom illuminated with RHCP light. From this figure it can be seen that an atom starting in the $m_j = 0$ or -1 state, after excitation by a RHCP photon, has a chance of decaying into the $m_j = +1$ state. However, for an atom starting in the $m_j = +1$ state, the only allowed excitation-decay path does not change the magnetic sublevel. Therefore, the effect after many excitation-decay cycles, is that atoms are transferred (pumped) into the $m_j = +1$ sublevel. Conversely, by using left-hand
Figure 4.3: Illustration of optical pumping with right hand circularly polarized (RHCP) light.
circularly polarized (LHCP) light, the selection rule for excitation becomes \( \Delta m_j = -1 \), and the metastable atoms are pumped into the \( m_j = -1 \) sublevel.

The third chamber of the SPMDS apparatus is the interaction chamber. Housed in this chamber is a target crystal, a retarding energy analyzer, and a Mott polarimeter. During a surface experiment, the target crystal is placed in the path of the metastable atom beam. The metastable atoms de-excite at the surface, ejecting electrons. The polarization of the ejected electrons is measured by the Mott polarimeter[82], and the energy of the electrons is determined by the retarding energy analyzer. When the ejected electron polarization is compared to the known metastable beam polarization, the de-excitation process can be determined. Once the de-excitation process is characterized, the ejected electron energy distribution can be used to gain insight into the electronic properties of the surface[83,84,85,86].

To measure the polarization of the metastable atom beam, the target crystal is removed from the beam path, allowing the beam to enter a Stern-Gerlach analyzer. Here the metastable beam passes through an inhomogeneous magnetic field, which spatially separates the different \( m_j \) states. Those atoms with \( m_j = -1 \) or \( m_j = +1 \) are deflected, while those with \( m_j = 0 \) pass straight through. The spatial profile of the He(2\(^3\)S) atoms emerging from the Stern-Gerlach magnet is measured by a channel electron multiplier, which can be scanned vertically. Again, time-of-flight techniques are used to discriminate against beam impurities.

Figure 4.4 shows spatial output profiles from the Stern-Gerlach analyzer taken under various conditions. In these plots, the x-axis
Figure 4.4: Stern-Gerlach profiles obtained after optical pumping with (a) RHCP light, (c) LHCP light. (b) Stern-Gerlach profile obtained in the absence of optical pumping.
represents the channeltron position, while the y-axis represents a normalized count rate. The second plot (b) shows the spatial distribution for an unpolarized beam. The first and third plots show the spatial distribution for a metastable beam that has been optically pumped with the diode laser into the $m_j = +1$ and $m_j = -1$ states, respectively. Note the clear separation of the beam into its three components (the arrows represent the expected locations of the center of each peak). The area under each peak provides a measure of the relative population of atoms in the corresponding magnetic sublevel. The beam polarization, $P_z$, is related to the area under each peak by:

$$P_z = \frac{n_+ - n_-}{n_+ + n_0 + n_-}$$

where $n_+$, $n_-$, and $n_0$ represent the number of atoms in the $m_j = +1$, $-1$, and 0 sublevels.

The data shown in figure 4.5 were obtained with the 1.083 μm diode laser operating on the $2^3S_1 \rightarrow 2^3P_1$ (D1) transition. In this case the diode laser was frequency stabilized using only the superlock system. The incident power was ~25 mW corresponding to an intensity of ~75 mW/cm² incident on the beam. This pumping was performed in a second optical pumping region, located just prior to the Stern-Gerlach. Analysis of the data indicates an atomic beam polarization in excess of 97%. Similarly, optical pumping done with the diode laser locked to the reference cavity, and with the laser locked to an external cavity produced metastable polarizations of ~95%.
Figure 4.5: Dependence of the metastable atom beam polarization on diode laser power.
One concern about optical pumping with a diode laser was the low power provided by diode lasers as compared to other laser systems (in particular a Ti:Sapphire laser). Figure 4.5 shows the dependence of the atomic beam polarization on the diode laser power. Clearly, the diode laser output power is sufficient to saturate the transition and provide very effective optical pumping. Indeed, the small remaining $m_j=0$ feature in the Stern-Gerlach plots may result from imperfect circular polarization of the laser radiation, or from inhomogeneities in the magnetic field in the optical pumping region as opposed to a shortage of laser power. This concern over the diode laser power arose since power-polarization studies done with the Ti:Sapphire laser indicated that the atomic polarization began to drop at relatively high laser powers ($\sim 20$ mW)[3]. However, a calculation of the intensity of laser light incident on the atomic beam at this power ($\sim 6.5$ mW/cm$^2$) agrees with the results obtained with the diode laser ($\sim 5$ mW/cm$^2$). This occurs because the diode laser beam was focused to match the metastable beam width, but the Ti:Sapphire beam was not focused.

Optical pumping with the diode laser was also performed in the primary optical pumping region, resulting in atomic polarizations of 80-85%. The lower atomic polarization in this case is most likely due to inhomogeneities in the magnetic field in the interaction chamber.

4.2 The Polarized Helium Ion Source

In addition to the use of spin polarized helium metastable atoms to probe surface electronic properties, the use of spin polarized helium ions is
also of interest. Spin polarized ion neutralization spectroscopy (SPINS) allows for the probing of the magnetic properties of surfaces[5], and offers the potential for imaging magnetic domains. The production and characterization of a polarized helium ion beam requires 1.083 μm radiation.

The spin polarized helium ion source under development is based on an rf-excited helium discharge (figure 4.6). Metastable atoms are produced in an rf discharge in a glass bulb containing a small pressure of helium. The application of the rf field drives free electrons in the bulb to oscillate. As they oscillate, the electrons collide with gas atoms present in the bulb. With each collision, the oscillating electron's motion is altered and it gains energy from the surrounding rf field. After acquiring 19.8 eV, the electron can excite a ground-state helium atom to the $2^3S$ metastable state[87]. An initial population of free electrons is produced by seeding the discharge with an electric spark from a Tesla coil.

Once the helium metastable atoms are produced, they survive for a few tenths of a millisecond before diffusing to the bulb walls where they are de-excited. Metastable atoms are also lost through collisions with other excited atoms in the bulb. However, in the time before a metastable atom is destroyed, it can be polarized by optical pumping (described in the previous section). To perform optical pumping, the bulb is placed in a small magnetic field that defines a quantization axis. Laser radiation, tuned to the helium $2^3S_1 \rightarrow 2^3P_1$ transition, enters the bulb along the axis defined by the magnetic field. The laser radiation is circularly polarized, and the beam is expanded by a lens to encompass the entire bulb.
Figure 4.6: Schematic diagram of the polarized helium ion source.
The measurement of the optical pumping efficiency is undertaken using a low power (intensity « saturation) probe laser tuned to the same transition as the pump laser[88]. Usually, a small portion of the laser used to optically pump the helium metastable atoms can be split off and used as the probe beam. The probe beam is colinear with the pump beam but propagating in the opposite direction, and is also circularly polarized. The polarization of the helium metastable atoms is measured by changing the sense of the circular polarization of the probe beam. If the pump beam is polarized so as to transfer atoms into the $m_j = +1$ sublevel, and the probe beam is polarized so as to also excite $\Delta m_j = +1$ transitions, then very little of the probe beam will be absorbed. This occurs because an atom with $m_j = +1$, in the presence of laser radiation tuned to the D1 transition, has no state into which it can be excited that satisfies the rule $\Delta m_j = +1$. However, if the circular polarization of the probe beam is reversed so as to excite $\Delta m_j = -1$ transitions, then the probe beam will be strongly absorbed, as there are many states into which it can be excited satisfying that selection rule. As the circular polarization of the probe beam is rotated, an oscillating absorption pattern results. The equation relating the probe absorption to the amount of atomic polarization is given by:

$$P_p = \frac{2 \cdot \ln(I_r / I_1)}{3 \cdot \ln(I_0 / I_1)}$$
where $I_r$ and $I_l$ are the transmitted probe intensities for right and left handed circularly polarized light; and $I_{0l}$ is the initial probe intensity for left handed circularly polarized light[6].

Three processes exist that produce helium ions: direct helium ionization, cumulative ionization, and Penning ionization in metastable-metastable collisions. In the case of direct helium ionization, the helium atom collides with a free electron whose energy is greater than the ionization energy of helium (24.5 eV). The electron's energy is transferred to the helium atom, producing another free electron and an unpolarized helium ion. Cumulative ionization can occur when a free electron collides with an already excited helium atom. The atom, most likely a $^2S$ or $^2P$ metastable atom, will be ionized if the colliding electron has an energy of 4.7 eV or 3.9 eV, which are their respective ionization potentials. Again, the result is the production of a free electron and an ion. The final mechanism for helium ionization is Penning ionization in metastable-metastable collisions[2]. In this case, two metastable helium atoms collide and undergo a chemi-ionization reaction which produces a ground state helium atom, a helium ion, and an electron. The rates for these three ionization processes have been estimated and show that in a weak discharge metastable-metastable collisions account for a majority of the ions produced[89].

In a metastable-metastable collision, the electronic spins of the electrons and ions produced can be predicted by applying conservation of spin angular momentum[90]. Given the polarization of the reacting metastables, the number of product ions and electrons in each spin state can
be approximated. Previous work suggests that a metastable polarization of
\(~\!20\%\) will lead to an ion polarization of \(~\!10\%\). This older work employed
a helium discharge lamp to provide the optical pumping radiation[5]. In
recent studies performed with a Coherent 899 Ti:Sapphire laser tuned to
the \(2^3S_1\rightarrow2^3P_1\) (D1) helium transition we have achieved metastable
polarizations of \(~\!70\%\). Based on this metastable atom polarization, an ion
polarization of 30-40\% should be attainable[6].

As mentioned above, a metastable atom polarization of 70\% was
achieved with the use of a commercial Ti:Sapphire laser system. The
advantage of the Ti:Sapphire system is that output powers of \(~\!300\) mW can
be achieved at 1.083 \(\mu\)m. Commercially available diode lasers that operate
at 1.083 \(\mu\)m are presently limited in output power to \(~\!50\) mW. This
presents a major limitation in the use of diode lasers to perform optical
pumping of the metastable atoms in the ion source. To operate the ion
source effectively, the entire area of the helium filled glass bulb must be
illuminated with 1.083 \(\mu\)m radiation. A diode laser does not have enough
output power to attain saturation intensity for the \(2^3S_1\rightarrow2^3P_1\) transition
over that large of an area, especially after power is lost during transport of
the beam to the apparatus, and removed for stabilization of the diode laser.

Two possible solutions exist to alleviate the diode laser power
problem. The first solution is to wait: 1.083 \(\mu\)m diode lasers have been
discussed in the literature that can produce 220 mW of output power. It is
possible, then, that high power 1.083 \(\mu\)m diode lasers may soon become
available on the commercial market. A second solution would be to
construct an array of low power diode lasers. The array could be injection
locked to a stabilized master laser (see Appendix A) to insure that all of the
diodes in the array are operating at the same frequency. The outputs from
each diode laser could then be added together to form a beam with enough
power to pump the ion source.

4.3 Slowing of He(2S) Atoms

An application of lasers that has been steadily growing is the
manipulation of the external degrees of freedom of an atom. Atoms in the
presence of electromagnetic radiation experience one type of force called
radiation pressure. Radiation pressure can be used to slow (and cool) an
atomic beam[91,92,93,94], form a magneto-optical trap (MOT)[95,96], or
achieve greater atomic beam intensities through transverse cooling[97].

Radiation pressure results from conservation of momentum during
the absorption and spontaneous emission process. Consider a moving atom
in the presence of a laser which is propagating in the opposite direction. If
the laser is tuned to the Doppler shifted resonance of the atom, the atom
will absorb a photon. The photon's momentum ($\hbar k$) is then transferred to
the atom. Since the photon and the atom were traveling in opposite
directions, the magnitudes of their momenta subtract, and the atom's total
momentum is lowered ($m v_{\text{new}} = m v_{\text{old}} - \hbar k$). Once it is in the excited state,
the atom can decay via spontaneous emission. In doing so, the atom
transfers a certain amount of momentum ($\hbar k'$) to the emitted photon.
However, spontaneously emitted photons have a spatially symmetric
distribution, so an average over many such emissions will result in a zero
net momentum change ($\Sigma \hbar k' = 0$). The absorbed photons always come
from the same direction, so the momentum transferred from each absorption will directly add ($\Sigma \hbar k = N\hbar k$). The result, after many excitation-deexcitation cycles is that the velocity component of the atom along the laser beam will be decreased.

It must be noted that, as an atom slows, the Doppler effect will shift the atomic resonance away from the laser frequency. Overcoming this problem is accomplished by either adjusting the laser frequency (frequency chirping)[92,97,98,99], or adjusting the atomic energy levels (Zeeman cooling)[93,94,100,101] as the atom slows. Only the frequency chirping method will be considered here. In most experiments, atoms emerge from an oven with a Maxwell-Boltzmann distribution of velocities centered around ~100-300 m/s. The laser frequency is initially tuned to the Doppler-shifted resonance of the atoms at the mean velocity; and is then ramped towards the unshifted atomic resonance at a rate based on the lifetime of the excited state of the atom. As the laser ramps, the slowing atoms will continue to see a Doppler-shifted laser that is on resonance. Depending on the ending frequency of the ramp, the atoms can be slowed to a complete stop (or even reversed) in one dimension[92].

The same force, radiation pressure is responsible for atomic confinement in a MOT. Consider an ideal two-level atom in the presence of two counterpropagating laser beams whose identical frequencies lie just below the atomic resonance[102]. If the atom is stationary in the radiation field, it will scatter an equal number of photons from each laser beam, and will experience no net force. However, if the atom begins moving towards
one of the lasers (laser A), the Doppler shift caused by the motion will shift that laser's frequency closer to the atomic resonance. Meanwhile, the frequency of the other laser (laser B) will be shifted farther away from resonance. Under these conditions, the atom is likely to scatter more photons from laser A than from laser B, resulting in an imbalance in the radiation pressure. As a result, the atom experiences a force that opposes the motion, and brings the atom's mean velocity in one dimension to zero. Similarly, if the atom moves in the direction of laser B, it will experience a force directed away from that laser. This situation leads to a resistance to motion in one dimension by a viscous-like force, and is called a one dimensional optical molasses. In two dimensions this type of arrangement can be used to decrease the transverse motion of atoms in an atomic beam, thus increasing the beam intensity[97].

Now consider three pairs of counterpropagating laser beams entering a region along three orthogonal axes which cross at a single place. Again, the lasers are all at the same frequency, which is detuned to the red of the atomic transition. If the atom is located at the crossing point of the lasers, it will experience a radiation force which opposes motion in any direction[103]. This situation is a three-dimensional (3D) optical molasses. It must be noted that atoms in an optical molasses are not trapped; these atoms can escape by diffusion to the edge of the molasses[104].

In order to trap the atoms, it is necessary to create a position dependant force directed towards the center of the laser beam crossing region. This can be done by placing a set of anti-helmholtz coils in a position centered on the three-dimensional optical molasses. The center of
the coils \( z = 0 \) will be at zero magnetic field; a point nearby the center such that \( z > 0 \) will possess a positive magnetic field, and a point located at \( z < 0 \) will possess a negative magnetic field. The magnitude of the magnetic field near the center increases linearly with distance from the center. An atom kept at rest by the optical molasses can be located anywhere in the region where the laser beams cross. However, when the magnetic field is introduced, those atoms not at the zero-point of the magnetic field will undergo a Zeeman splitting of their magnetic sublevels. Again, we consider the atom to be a simple two-level atom with a \( J = 1 \) excited state and a \( J = 0 \) ground state (the argument given below can be generalized to more complex atoms). Due to the Zeeman splitting, the energy of one of the excited state magnetic sublevels will decrease bringing the transition from the ground state to that sublevel closer to resonance with the laser radiation. For atoms at \( z > 0 \) (\( z < 0 \)), the energy of the sublevel with \( m_j = -1 \) (\( m_j = +1 \)) decreases; therefore, for those atoms at \( z > 0 \) (\( z < 0 \)) the transition with \( \Delta m_j = -1 \) (\( \Delta m_j = +1 \)) will be closer to resonance with the laser. If the laser beams along each axis are circularly polarized so that the beam entering from the \( +z \) (\( -z \)) direction has polarization \( \sigma^- (\sigma^+) \), then the atoms will preferentially scatter photons from the laser entering nearest them. This creates an imbalance in the radiation pressure that results in the atoms experiencing a force directed towards \( z = 0 \)[95]. Since the magnetic sublevels of the atoms at \( z = 0 \) (\( B = 0 \)) are not split, these atoms scatter equal numbers of photons from each laser, and experience no net radiation force. Essentially, the magnetic
field, along with the appropriately polarized lasers, form a potential well in which the atoms are trapped[105].

In order to load a MOT, a population of atoms must be slowed to a velocity small enough to allow capture in the potential well existing around the magnetic field zero-point. Typically, atoms with a velocity less than 60 m/s will be captured. Therefore, effective loading of the MOT will occur only if a group of slow moving atoms is available. A group of slow moving atoms can be produced by slowing an atomic beam as discussed earlier. However, a drawback to this method is that a long distance is required over which to slow the atoms. Additionally, a well collimated atomic beam with enough flux to produce significant loading is necessary.

These conditions have lead to poor loading from a beam into a He($^2$S) metastable atom MOT[106]. An alternative method being developed in this laboratory involves precooling of the helium atoms to a low velocity without the use of a slowing laser[107]. In this case, helium gas is injected into a tube that has been cooled to liquid helium temperatures (~4 K). Copper baffles are placed in the tube to insure that the helium gas will be cooled by undergoing multiple collisions before emerging into a glass bulb. The helium gas in the bulb should be at a temperature near 4 K. An rf discharge, which will produce helium metastable atoms, is ignited in the glass bulb, and a small hole in the bulb allows atoms to escape into a larger chamber. Present in this chamber is an appropriate magnetic field, with the zero-point being ~3/4" below the hole in the glass bulb. The six trapping laser beams will initially be provided by
a Ti:Sapphire laser system; but the use of diode lasers to supply the necessary laser radiation is being considered.

A calculation of the mean velocity of the helium atoms at 4°K yields a value of 129 m/s. This is more than twice the velocity of atoms that can be captured, implying that only a small fraction of the atoms will be loaded into the MOT. One possible solution to this problem is to use a 1.083 µm diode laser to slow the metastable atoms as they emerge from the bulb. Figure 4.7 shows a possible arrangement of the diode laser beam within the apparatus.

For a helium atom moving at 129 m/s, the Doppler shift of the atomic resonance is 120 MHz. The sublevel splitting in helium due to the magnetic field in the trap region, under normal operating conditions (a magnetic field gradient of ~5 G/cm), would not exceed ~14 MHz. Since the linewidth of the diode laser is ~20 MHz, the splitting due to the magnetic field can be ignored. An atom moving at 129 m/s can be slowed to a speed of 60 m/s after ~750 absorption-emission cycles. The Doppler shift of the resonance at this new velocity is only 55 MHz; therefore, the diode laser must ramp from a detuning of 120 MHz to a detuning of 55 MHz. The lifetime of the He\(^{(2)}\)P state is approximately 100 ns, so under saturated conditions, 750 absorption-emission cycles would take 150 µs. During this time the helium atom would travel approximately 1/2 of an inch, bringing it to within 1/4 of an inch of the trap location.

The diode laser could be used to bring the metastable atoms to a near zero velocity. This could be done after only ~1400 absorption-emission cycles; however, doing this requires the diode laser frequency to ramp
Figure 4.7: Diagram of the trapping region in the helium metastable magneto-optical trap, showing the probable location of an atomic slowing laser.
right up to the atomic resonance. This additional laser, operating that close to resonance would perturb the MOT conditions, and lead to trap loss. It is better, therefore, to always keep the slowing laser several transition linewidths from the resonant frequency. The linewidth for the He(2³S)→He(2³P) transition is \( \sim 1.6 \) MHz. If we require that the slowing laser remain at least 10 linewidths from the atomic resonance, then the helium atoms can be slowed to a velocity of \( \sim 35 \) m/s, well within the range of the capture velocity of the trap.

### 4.4 Optical Fibers

One difficulty in operating a laser system that provides light to a number of experiments is that of efficient and reproducible transport of the laser beam to the desired apparatus. Currently, this is done with a system of lenses and mirrors that direct the beam to the appropriate location. An alternative approach is to use an optical fiber. One advantage to this method is that diode lasers can be effectively coupled into an optical fiber and, if a single-mode fiber is used, the mode quality of the beam can be improved.

Although optical fibers are just two decades old, their unique ability to carry incredible amounts of information has resulted in their widespread application. Furthermore, many advances in diode laser technology have been prompted by a need for better laser systems to keep pace with improved fiber optic systems. For example, diode lasers operating in the near infrared (particularly 1.3 µm) were developed since the first optical fibers exhibited low internal losses at that wavelength. Distributed
feedback single-mode diode lasers were developed to cut down on signal
dispersion in optic fibers. Additionally, diode lasers with good
fundamental spatial mode qualities were perfected to cut down on coupling
losses to optical fibers.

A common optical fiber is composed of high-silica glass doped with
certain impurities (e.g. germanium, fluorine, or phosphorus) that alter the
index of refraction. The simplest fiber is the step-index optic fiber, in
which the refractive index undergoes an abrupt decrease when moving
from the center to the edge of the fiber. The area of higher index of
refraction is the core; beyond that is a lower refractive index material
called the cladding layer. The transmission of light through the fiber is
accomplished by total internal reflection at the index step.

Two other types of optical fibers also exist. In the first of these, the
graded-index (GRIN) fiber, the index of refraction varies slowly with
increasing distance from the center. This serves to smooth the light path
from a sharp reflection to a rounded curve. In another type of fiber, the
single-mode optical fibers, the core is sufficiently narrow so that it
supports only one waveguide mode (HE_{11}, which is the fundamental mode
supported in a cylindrical waveguide). In this mode the light rays always
circle parallel to the central axis. Single mode fibers can be used to
 spatially filter the output from a diode laser. Figure 4.8 shows how light travels in a fiber and the intensity distribution of the HE_{11} mode.

Optical fibers possess certain characteristics that determine their
usefulness at particular wavelengths. Two characteristics of importance
are the attenuation of the light by the fiber, and the effect on the
Figure 4.8: Schematic illustrations of (a) light rays traveling in an optical fiber, and (b) the intensity distribution for the HE_{11} mode.
polarization of the beam by the fiber. A typical light attenuation range is from 5 dB/km to 0.2 dB/km, with the lowest attenuations being for the wavelengths 1.2-1.7 μm. However, the possible applications of fiber optics in this laboratory require little consideration of a fiber's attenuation, since the lengths of fiber to be used here would be so short (L < 50 m) that any power loss due to attenuation would be negligible compared to coupling losses.

Of greater consideration is the effect of the fiber on the laser polarization. In general, optical fibers exhibit some birefringence that affects the polarization of the light traveling through them. This is a drawback in the use of optical fibers, since the polarization effects are due to external stresses and are largely unpredictable. However, a particular fiber can be coiled and bent until the output beam has the desired polarization. Additionally, there do exist optical fibers that have been designed to preserve the polarization of the source laser.

More information on optical fibers and their characteristics can be found in references [108,109].

Our interest in optical fibers arises out of our need to transport laser radiation to a number of different locations. Since many of these locations lie a considerable distance from the laser, it is safer and more convenient to transport the beam through an optical fiber. Furthermore, predictable alignment of the laser to the correct location on an apparatus can be simplified with the use of an optic fiber. Once the output from a fiber is aligned appropriately into the apparatus, any drift of the laser that could result in misalignment of the beam can be corrected by adjusting the input
coupling to the fiber appropriately. Additionally, if two or more experiments use the same laser, then changing from one experiment to another requires only that the input fibers at the laser be switched.
Chapter 5
Conclusion

The development of diode lasers operating at 1.083 μm represents a significant advance in the search for a reliable source of He(2^3S)→He(2^3P) resonant radiation. The successful application of the diode laser device to optical pumping of a metastable helium atom beam has demonstrated the potential of such lasers for application to experiments involving optical manipulation of He(2^3S) atoms.

In the near future, the application of diode laser to two new experiments requiring 1.083 μm radiation will be investigated. The first of these involves the production of a polarized helium ion beam based on an optically pumped helium discharge. The polarized ion beam will be used to study the magnetic properties of surfaces, and, eventually, it may be used to map the magnetic domains on a surface. In the second experiment, use of diode lasers as an interal part of a helium metastable magneto-optical trap will be explored. This trap offers a variety of opportunities to study cold atom-atom or atom-surface collisions. Furthermore, the MOT could be used to load a magnetic trap in which the lifetime of the helium metastable state could be measured. Additionally, helium metastables in a magnetic trap provide an excellent candidate for Bose-Einstein condensation.

Although techniques have been developed that can successfully lock a diode laser, improved performance should be attainable, especially using external cavity locking schemes. The use of a glass wedge or grating
instead of an optical flat might improve stability, as would the development of an electronic system specifically designed for control of an externally locked diode laser.
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Appendix A
External Cavity Diode Lasers

As mentioned in chapter three, a diode laser can be frequency stabilized by locking the device to an external cavity[110]. An external cavity can be as uncomplicated as a single optical flat, or it can involve gratings, optical fibers, or confocal Fabry-Perot cavities. The external cavity locking system is part of a larger class of diode laser systems known as coupled-cavity devices.

Coupled-cavity devices have the advantage of stabilized single-mode operation without the limitations placed on tunability by other schemes. In a coupled cavity diode laser, there exists some form of second cavity outside the one defined by the cleaved facets of the laser. Interference caused by optical feedback from this second cavity can be modeled as a frequency dependent reflectivity from the facet nearest the external cavity. This results in different cavity losses for different Fabry-Perot modes of the primary laser cavity. In general, the loss profile caused by the optical feedback is periodic; the mode selected by the coupled-cavity device is the mode nearest the peak of the gain curve with the lowest cavity losses. Other modes with low cavity losses do also exist since the loss profile is periodic, but these modes are far from the primary mode, and are discriminated against by the gain roll-off.

Two types of coupled-cavity devices exist, the active-active and active-passive schemes. In an active-active device, there are two independently pumped laser cavities separated by an air gap. In general,
the cavities are guaranteed to be aligned since they are usually created by splitting the active region of a conventional semiconductor laser\cite{111,112}. A typical active-active device is the cleaved-coupled-cavity, or $C^3$, device (figure A.1). This laser has four facets that are mirror-like and parallel; reasonable coupling between the cavities is guaranteed provided the gap between the cavities is not too large. Longitudinal mode selection can be achieved solely by electronic means, since the current in the two cavities can be independently manipulated. Typically, one of the cavities is operated below threshold; a change in the current in that cavity significantly changes the carrier density. As a result, the refractive index, and the optical path length in the secondary cavity, changes, shifting the longitudinal mode of the laser.

The active-active devices are classified based on the relative optical path lengths of the two cavities. If $\mu_1 L_1 = \mu_2 L_2$ then the device is said to have long-long geometry; otherwise, the device has long-short geometry. Long-long devices have the difficulty that they are subject to frequent mode hopping. However, long-short devices usually require large temperature or current changes to achieve reasonable tunability. Obviously, the choice as to which device is preferable depends on the application.

In an active-passive coupled cavity laser, an external cavity is formed by placing a reflective surface just beyond one, or both, of the laser facets\cite{113,114}. This is called an external cavity semiconductor laser, with the second cavity being formed by the external mirror and the facing laser facet. In these external cavity devices, wavelength tunability and
Figure A.1: Schematic illustration of a C³ laser.
stabilization can be achieved by changing the secondary cavity length, either thermally[115], or with a PZT[116]. Additional mode-selectivity can be achieved if the external reflector is dispersive, i.e. if its reflectivity is wavelength dependent. This can be accomplished by using a grating[69,70], or a frequency selective filter[117]. The use of a grating has an advantage in that rotation of the grating allows a considerable tuning range (~50 nm).

Externally locked diode lasers do not tune continuously, but experience mode hops between ranges of smooth tuning. However, the tuning range of an external cavity diode laser does not exhibit tuning gaps like those exhibited by a regular diode laser. In many cases, an externally locked diode laser can be forced to operate at a frequency that was located in a gap of the unlocked laser's tuning range.

Another characteristic of external cavity diode lasers is their small linewidth compared to conventional semiconductor laser devices. The linewidth of a standard diode laser is typically 10-100 MHz, but can be ≤10 MHz for DBR, DFB, or C^3 devices[118,119]. However, in the case of an external cavity, the linewidth is further reduced by the increased length of the secondary cavity. Physically speaking, as the cavity length increases, the photon lifetime increases. Therefore, there will be a larger number of intracavity photons for a given output power, and the linewidth of the longitudinal mode will decrease. Linewidths as small as 10 kHz have been observed using a few-centimeter-long external cavities[69,70].

One method of making an external cavity diode laser is to AR coat both the front and back facets of the laser chip, and place the device in a
conventional linear resonator. One problem with this is that both facets of a diode laser are not usually accessible given typical packaging of the devices. Additionally, AR coating of the laser chip is a nontrivial and potentially expensive task. It is easier to form an external cavity on only one side of the diode laser, particularly since many high power diode lasers already have low reflectance coatings on their output facets. Diagrams of these two methods of forming an external cavity are shown in figure A.2.

Another method of diode laser control related to the use of an external cavity is injection locking (optical amplification)[120,121,122]. In this method, the output from a stabilized single-mode master laser is used to lock the diode laser by sending a very small portion of the master laser's output power into the diode laser chip. This power must be very small to avoid damaging the diode laser, and if the master laser is also a semiconductor device, care must be taken that light from the slave laser does not enter the master laser. The amount of gain provided by the slave laser depends on its current, and on the wavelength of the master laser; the gain is especially high if the master laser frequency matches a longitudinal mode of the slave laser. When locked in this way, the output of the slave laser will match the master laser in wavelength, linewidth, and stability.

Unfortunately, a diode laser's performance is sensitive to spurious optical feedback. An external cavity can be formed with very little laser radiation being coupled back into the laser diode (e.g. only a 4% reflection of the light from the 1.083 μm diode laser was sufficient optical feedback to lock the laser). Since the diode laser cavity is so short, and the finesse of the diode cavity is so low, there are relatively few photons in the internal
Figure A.2: Schematic diagram of two types of external cavity systems.
cavity; therefore, the lasing wavelength is easily perturbed by the smallest amount of optical feedback. With all of the reference cavities and the monitoring photodiodes necessary to stabilize a conventional diode laser, it is possible that one of these elements will reflect light back into the laser. Even AR coatings on the optics are often insufficient in preventing enough optical feedback from occurring to affect a laser's operation. Optical feedback can also occur from windows on the vacuum chambers employed in the experiments; although, effective coupling to the diode laser is less likely if the distance to the apparatus is large.

Uncontrolled optical feedback inevitably results in mode instabilities in the diode laser output. To limit this it is advantageous to slightly misalign every optic that has a chance of coupling back to the diode laser; if misalignment is not possible then some form of optical isolator must be used. Misalignment of the optics does pose problems since elements such as reference cavities must be carefully aligned to operate properly. Therefore, a compromise must be made between perfect alignment and minimization of the optical feedback.

For more on external cavities and optical feedback see references [72,76].
Appendix B
Optical and Electronic Alignment of the 1.083 μm Diode Laser Locking System

The most successful frequency stabilization of the diode laser was achieved using a reference cavity in conjunction with the superlock system. In this scheme, electronic feedback from the reference cavity is used to stabilize the diode laser frequency, and the reference cavity itself is stabilized by superlock. A complete description of the methods used to set up and lock the diode laser follows.

The output from a diode laser is extremely divergent, and must be collimated before it can be used. Typically, a collection lens is placed very close to the diode laser output facet to gather as much of the laser radiation as possible. The collection lens must be AR coated and carefully aligned to avoid unwanted optical feedback into the diode laser cavity. A second lens, appropriately placed beyond the focus of the collection lens, is used for collimation; relatively good beam profiles can be achieved (if this lens is placed before the collection lens focus, its output has a ringed appearance, and much of the laser power is lost in the outer, uncollimated, rings).

After the lens positions are optimized, the stabilization optical elements are installed. A beamsplitter (typically a glass plate) is used to pick off a small fraction of the laser output and direct it to the reference cavity. Another beamsplitter is used to pick off a fraction of the reference cavity beam to be sent to the power reference photodiode. The reference cavity and the power reference photodiode are the same elements as used to
stabilize a linear LNA laser system described elsewhere. The signals from the reference cavity photodiode and the power reference photodiode are directed to the electronic system described in section 3.3.

Alignment of the reference cavity requires that the cavity length be continuously ramped using a PZT which is operated over a voltage range 0-1 kV. As the reference cavity is ramped, the transmitted signal is monitored by an oscilloscope connected to the reference cavity signal monitor of the locking electronics. If the cavity is properly aligned, a symmetric, periodic series of transmission peaks is observed. The reference cavity location, and the steering beamsplitter are adjusted until alignment is achieved. Unfortunately, perfect alignment of the reference cavity will result in unwanted optical feedback to the diode laser that can cause signal drop-outs and instability. After near perfect alignment is achieved, a slight misalignment of the reference cavity must be performed; a lower signal, and some asymmetry is acceptable. When the cavity is sufficiently misaligned, the signal pattern will be stable and continuous.

After the reference cavity is properly aligned, the next step is to align the power reference photodiode. First, the electronics are used to monitor the signal generated by the power reference photodiode. The reference photodiode, placed in the beam that is split off of the reference cavity beam, is adjusted until the power reference signal is maximized. The steering beamsplitter should not be moved significantly since that could result in misalignment of the reference cavity; however, small adjustments of the steering beamsplitter are usually sufficient to maximize
the power reference signal. Optical feedback from the power reference photodiode is not generally a problem.

After the two monitoring systems are in place, the reference cavity PZT should be disconnected from its directing ramp and connected to a variable high-voltage dc source. The transmitted signal from the reference cavity is monitored as the voltage is slowly varied. The voltage is set so that the reference cavity signal is maximized, and trimpot R1 is adjusted until the maximum signal is ~8 V. The reference cavity voltage is then adjusted until the minimum signal is reached. In general, the minimum signal will not be zero volts, but a minimum signal greater than ~2 volts is unacceptable. If the minimum signal is too large, the reference cavity must be realigned. When the minimum reference cavity signal is acceptable, the cavity PZT drive voltage is set so that the reference cavity signal is approximately halfway between the maximum and minimum values (~4 V). Furthermore, the voltage should be set so that an increase in the voltage results in an increase in the reference cavity signal. The best locking results are obtained for PZT supply voltages in the range of 300-700 volts.

After the reference cavity voltage is properly chosen, the power reference signal is set. The power reference voltage amplification can be changed by adjusting trimpot R2. This signal should be amplified to ~8 V, or equal to the maximum reference cavity signal. If the desired signal level from either the reference cavity or the power reference is beyond the range of the trimpot, then the element in question must be realigned, and the voltage setting process described above must be repeated. When both elements are properly set, the two signals can be input to the divider.
Proper operation of the divider circuit depends on the settings of the divider offsets (P1-P3, R_L). Once set, these offsets do not need to be changed; however, the divider should be checked after any adjustments are made to the circuit. The divider is properly adjusted through a sequence of steps that require control of the input voltages. The input voltages can be controlled by removing the op-amps IC1 and IC2, and placing an external dc voltage source on the inputs to the divider. To begin, the reference cavity voltage (V_r) is set at zero volts. The offset trimpot P3 is adjusted until the divider output voltage (V_o) remains fixed (not necessarily at zero volts) while the power reference voltage (V_p) is changed over the range +1 V to ±10 V. With V_r set at zero volts, and V_p adjusted to +10 V, the trimpot P1 is rotated until the output voltage, V_o, is zero. At this point, the inputs, V_r and V_p, are connected together so that they are equal. The trimpot P2 is adjusted until the divider output voltage remains constant as the input voltages are varied from +1 V to +10 V. With V_r = V_p, the amplification R_L is set such that the average value of V_o is -10 V as the inputs are varied over +1 V to ±10 V. To optimize the performance of the divider, it is necessary to repeat the adjustment procedure a number of times, until all of the criteria are simultaneously satisfied. The circuit is designed to operate over a range of input voltages from +1 to ±10 volts, with the best operation occurring for the higher voltages. It is crucial that the power reference signal not drop below +1 V.

Once the circuit adjustments are complete, the output from the circuit is connected to the external modulation input of the diode laser controller. To minimize electronic noise the diode laser controller was
modified from its commercial design. As a result, the input port on the
front panel no longer functions; therefore, an isolated BNC connector
(installed on the left side of the controller) is used for external inputs. This
modification was necessary because of problems encountered with ground
loops in the laser diode control unit.

To lock the diode laser, the error signal output is monitored, and the
reference voltage (tuning potentiometer) is adjusted so that the error signal
averages around zero. The lock switch is used to engage the locking
system. If the diode laser current displayed on the controller jumps when
the lock is engaged, then the error signal may be incorrectly zeroed. The
laser must be unlocked, the error signal re-zeroed, and the locking system
again engaged. If the laser continues to resist locking, then the reference
cavity may have drifted away from its original setting and must be checked
(the reference cavity drifts quite rapidly for the first hour after turn-on).
If it has drifted, the reference cavity must be reset by adjusting the supply
voltage to the PZT. When the reference cavity is properly set, the laser
locks without difficulty. The tuning potentiometer allows the laser
frequency to be changed, but tuning too far can result in the loss of lock.
To tune beyond the range allowed, the lock is broken and the laser current
is adjusted with the diode laser controller, then lock is re-established at the
new frequency.

The stability of the lock can be controlled by changing the
amplifications applied to the fast and slow components of the error signal.
The fast signal amplification should be adjusted to produce the smoothest
frequency profile. Ripples or spikes in the output frequency profile of the
laser indicate that the fast signal is either undercompensating, or overcompensating. The slow signal amplification controls the tuning range, and is, in general, kept small, since higher amplifications often cause the laser frequency to oscillate (ring). However, the slow signal amplification must be large enough to allow a reasonable tuning range, and to allow the electronics to recover from longitudinal mode hops.

When the laser is locked to the reference cavity, it will still drift in response to long-term changes in the reference cavity (due to temperature fluctuations). This long-term drift is removed by the superlock system; the correction signal is generated as described in section 3.2. This signal is sent through a variable amplifier and a long-time-constant integrator to the external input of the high voltage source supplying the reference cavity. Inside the high voltage supply, the correction signal is amplified and added to the DC voltage that is supplied to the PZT in the reference cavity. Since the reference cavity is temperature stabilized, the length variations due to temperature fluctuations are small enough to be compensated for by the PZT. The amplification of the superlock signal must be adjusted to give sufficient correction to maintain the lock; however, too much amplification will again result in a slow ringing in the output frequency.

A diagram of the complete locking system is shown in figure B.1. If the optical elements and the electronics are set properly, the diode laser will remain within a few MHz of the lock frequency for periods of many hours.
Figure B.1: Complete diagram showing the locations of the components for the superlocked reference cavity diode laser locking system.