DIRECTLY DIODE PUMPED KERR LENS
MODE-LOCKED Ti:SAPPHIRE
OSCILLATOR

by
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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Physics).

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ABSTRACT

This document describes how 445nm laser diodes were successfully used to pump a soft aperture Kerr lens mode-locked Ti:sapphire oscillator. Measurements were taken in order to determine the mechanism behind the mode-locking bias in these oscillators. It was determined that the gain was higher for the mode-locked mode of operation even though the $1/e^2$ radius of the pump was larger than the $1/e^2$ radius of both the CW and mode-locked modes in the crystal. This indicates that the $1/e^2$ radius of the beams is not enough information to determine if mode-locking will occur and an accurate model will need to take the full beam profile into account.
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LIST OF SYMBOLS

$10^{-9} \text{ meters}$ ............................................. $\text{nm}$

Rate of absorption ............................................ $-\frac{dN_1}{dt}$

Number of electrons in ground state ......................... $N_1$

Energy density per frequency ................................ $\rho(\nu)$

Einstein coefficient for absorption .......................... $B_{12}$

Rate of spontaneous emission ............................... $-\frac{dN_2}{dt}$

Number of electrons in excited state ....................... $N_2$

Einstein coefficient for spontaneous emission ............. $A_{21}$

Rate of stimulated emission ................................ $\frac{dN_1}{dt}$

Einstein coefficient for stimulated emission .............. $B_{21}$

Stimulated emission cross section ......................... $\sigma$

Boltzmann’s constant ........................................... $h$

Electric field frequency ...................................... $\nu$

Line shape factor ............................................... $g(\nu)$

Speed of light .................................................... $c$

Intensity .......................................................... $I$

Fluorescence lifetime ......................................... $\tau_f$

Saturation Intensity ............................................ $I_{sat}$

Pump losses ....................................................... $\eta$

Pump losses from emission at pump wavelength ......... $\eta_Q$
Stokes factor (pump losses from quantum defect) \( \eta_S \)
Pump losses from poor mode-matching \( \eta_B \)
Pump light that is not absorbed \( \eta_a \)
Pump losses from scattering \( \eta_t \)
Small signal gain \( g_0 \)
Saturated gain \( g \)
Area \( A \)
Volume \( V \)
Length \( l \)
Output coupler loss \( R \)
Cavity Losses (excluding output coupler) \( \delta \)
Input Pump Power \( P_{in} \)
Output Pump Power \( P_{out} \)
Threshold Pump Power \( P_{th} \)
Slope efficiency \( S_{eff} \)
Total gain \( G \)
Vertical axis \( y \)
Horizontal axis \( x \)
Size of Gaussian beam \( w(z) \)
Waist size of Gaussian beam \( w_0 \)
Wavelength \( \lambda \)
Distance from waist \( z \)
Beam size \( w \)
Beam divergence angle \( \theta \) 

Focal length \( f \) 

Distance \( d \) 

Radius or axial distance \( r \) 

Complex transverse beam parameter \( q \) 

Index of refraction \( n \) 

Constant term in expansion of index of refraction \( n_0 \) 

Non-linear term in expansion of index of refraction \( n_2 \) 

Electric field \( E \) 

Intensity \( <E^2> \) 

10\(^{-12}\) meters \( \text{pm} \) 

Change in waist size with change in power \( \frac{dw_0}{p} \) 

Critical power \( P_{cr} \) 

Intensity dependent spot size variation at an aperture \( s \) 

Unit of frequency in one million cycles per second \( \text{MHz} \) 

Unit of energy \( \text{J} \) 

10\(^{-3}\) Joules \( \text{mJ} \) 

Unit of frequency in one thousand cycles per second \( \text{kHz} \) 

10\(^{-15}\) seconds \( \text{fs} \) 

Unit of Power \( \text{W} \) 

10\(^{-3}\) Watts \( \text{mW} \) 

Unit of angular frequency \( \text{rad} \) 

10\(^{-3}\) radians \( \text{mrad} \)
$10^{-6}$ meters \hspace{2cm} \mu m
<table>
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<th>Abbreviation</th>
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<td>Ti:sapphire</td>
</tr>
<tr>
<td>Neodimium doped vanadate</td>
<td>Nd:YVO&lt;sub&gt;4&lt;/sub&gt;</td>
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<tr>
<td>Continuous wave</td>
<td>CW</td>
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<tr>
<td>Transverse electro-magnetic</td>
<td>TEM</td>
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<td>Lowest order transverse electro-magnetic mode</td>
<td>TEM&lt;sub&gt;00&lt;/sub&gt;</td>
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<td>Cross-polarized wave</td>
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<td>Carrier envelope phase</td>
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<td>Root mean squared</td>
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<td>Pulse repetition frequency</td>
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<td>Radius of curvature</td>
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<td>High reflector</td>
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<td>Output coupler</td>
<td>OC</td>
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<td>Curved mirror furthest from pump lens</td>
<td>C2</td>
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<tr>
<td>Colorado School of Mines</td>
<td>CSM</td>
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<td>Mode-locked</td>
<td>ML</td>
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<td>Prism closest to crystal</td>
<td>P1</td>
</tr>
<tr>
<td>Prism furthest from crystal</td>
<td>P2</td>
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<td>Neutral density</td>
<td>ND</td>
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For science
CHAPTER 1
INTRODUCTION

In today’s industry and laser science as a whole, Titanium doped sapphire lasers (Ti:sapphire lasers) have a wide range of applications [1]. They possess the broadest tuning range and generate the shortest pulses of any laser [2] which makes them an ideal tool for fields ranging from spectroscopy to imaging, as well as machining[3][4][5][6]. Ti:sapphire lasers are very versatile; however, they are also one of the most expensive lasers to construct. This is primarily due to the high cost of the green lasers used to pump them [7] [8]. These green lasers, Nd:YVO$_4$ lasers, cost approximately $10,000 per Watt. Typical Ti:sapphire oscillators require three to ten Watts of pump power, bringing the cost of the pump alone to over $30,000 [9]. The other components in a Ti:sapphire oscillator generally cost under $10,000 which makes the high pump cost quite significant. In contrast, many other solid state lasers are considerably less expensive to build because they can be pumped with laser diodes, which cost tens of dollars and require only a few hundred dollars in supporting equipment. The high cost of Ti:sapphire lasers is often a barrier to those who would benefit by using them in research or for commercial purposes. If the cost of the lasers could be significantly lowered, it would open the technology up for use in many new applications.

Expense is not the only concern with Ti:sapphire lasers. Nd:YVO$_4$ pumping also adds complexity to the system. With this pumping scheme, 808nm laser diodes pump the Nd:YVO$_4$ laser which emits 1064nm light. This is then frequency doubled in a nonlinear crystal to make 532nm light which can finally be used to pump the Ti:sapphire oscillator [9]. This complex pumping scheme not only adds cost, but can also reduce reliability and stability of the pump light.

Not long ago, blue laser diodes were developed for Blu-ray in order to satisfy the constant push in the electronics industry to fit more data onto smaller devices [10]. More recently,
these diodes were pushed to higher powers which made them useful for projector technology [11][12]. These new diodes also happened to be in the absorption bandwidth of Ti:sapphire. This new technology lowered the cost per Watt of pump light from $10,000 to around $200. The cost was dramatically decreased, but new challenges came with the recently developed pump source. The rectangular, highly astigmatic pump mode made efficient energy extraction in the laser very difficult [13]. Nevertheless, a diode pumped continuous wave (CW) Ti:sapphire oscillator was built at the University of Strathclyde in Scotland in 2009 [14]. Not long after the completion of this oscillator, a mode-locked version of the laser was created by the same group [15]. This mode-locked oscillator used a saturable Bragg reflector to create a bias between the mode-locked and CW modes. Because of this, the pulse was on the order of 100fs rather than the usual 10fs obtained from Kerr lens mode-locking. This was a big step forward; however, the technology was still far from matching the performance of Nd:YVO₄ pumped oscillators, which are prized for their short pulses and resulting in high peak powers.

Current theory holds that Kerr lens mode-locking requires the radially symmetric Gaussian profile of the green pump lasers. It was therefore assumed that Kerr lens mode-locking could not be achieved with the poor pump modes of the diodes. Despite this, my colleagues and I successfully created a diode pumped, Kerr lens mode-locked Ti:sapphire oscillator in 2012 [16]. This immediately made the diode pumped oscillators useful tools rather than novel projects.

Reducing the cost of these lasers on a large scale will make them more accessible to the research and industrial groups that want to use them. Kerr lens mode-locking ensures that performance will not be hurt by the cost reduction. Eliminating complexity in the pump system especially the extremely power sensitive nonlinear process of frequency doubling, will make these lasers more stable and reliable.

Kerr lens mode-locking a directly diode pumped oscillator also raised immediate questions about how this process works since previous models of Kerr lens mode-locking predicted that it would be impossible with the pump mode of the diodes. The first directly diode pumped
Kerr lens mode-locked Ti:sapphire laser in fact showed the opposite of expected performance by having much higher mode-locking bias compared to when it was pumped with a Nd:YVO₄ laser. The goal of my project was to design and build a directly diode pumped, Kerr lens mode-locked Ti:sapphire oscillator, and then study its operational characteristics to determine if current mode-locking theory could explain the mode-locking characteristics of a diode pumped oscillator.
Laser is an acronym for light amplification by stimulated emission of radiation. In its simplest form, a laser consists of a gain medium to amplify an optical signal, a pump source to provide energy to the gain medium, and, for an oscillator, mirrors to provide feedback to the gain medium [17]. The process of stimulated emission duplicates the polarization, phase, and wavelength of the seed signal and the feedback allows the gain to overcome losses so the light emission can be self-sustaining. In an ideal continuous-wave (CW) laser, the result is a beam that is temporally and spatially coherent, meaning that the photons all have the same wavelength, polarization, and phase and the beam has a single Gaussian spatial mode. [17]. The temporal coherence makes lasers useful tools for applications that require controlled diffraction or excitation of a specific resonance in a material. Spatial coherence is important for diffraction experiments as well as tight focusing for imaging and machining since a spatially coherent beam can be focused to the diffraction limit, the smallest possible spot for the specific wavelength and lens being used.

2.1 Optical Gain

Light amplification is based on the principle that atoms and molecules can absorb energy to put them in an excited state and can emit light when they fall to a lower energy state (Figure 2.1). The excitation can come from electric fields, collisions, or absorption of a photon. In Ti:sapphire lasers, electrons are typically excited by photons from another laser. Eventually, the excited electron will drop to a lower state by emitting energy in the form of a photon in a process called spontaneous emission. The energy of the emitted photon is equivalent to the energy difference between the two energy states of the electron [18].

This process can be described using the Einstein coefficients for absorption (2.1) and emission (2.2). The rate of absorption \( \left( \frac{-dN_i}{dt} \right) \) is related to the number of electrons in the
ground state \((N_1)\), the energy density per frequency \((\rho(\nu))\) on the material, and the Einstein coefficient of absorption for that material \((B_{12})\) [19]. The rate of spontaneous emission \((-\frac{dN_2}{dt})\) is related to the population in the excited state \((N_2)\) and the Einstein coefficient for spontaneous emission for that material \((A_{21})\) [19].

\[
\frac{dN_2}{dt} = -\frac{dN_1}{dt} B_{12} N_1 \rho(\nu) \tag{2.1}
\]

\[
\frac{dN_2}{dt} = -A_{21} N_2 \tag{2.2}
\]

A third process called stimulated emission can also take place (Figure 2.2). If a photon passes by an excited atom, the electric field can stimulate the electron to drop to a lower energy state and emit a photon with the same energy and electric field phase as the original photon. When this happens, the two photons are said to be temporally coherent [17]. The second photon will also be traveling in the exact same direction as the original photon meaning that the photons are spatially coherent [17]. For this process to happen, the photon energy must be very close to the energy difference between the excited electron state and the lower electron state.

Figure 2.2: Stimulated emission in a two level system
Stimulated emission ($\frac{dN_2}{dt}$) is effectively the opposite of absorption (2.3). It is related to the population in the excited state ($N_2$), the energy density per frequency ($\rho(\nu)$) on the material, and the Einstein coefficient for stimulated emission for that material ($B_{21}$)[19].

$$-\frac{dN_2}{dt} = \frac{dN_1}{dt} = B_{21}N_2\rho(\nu) \quad (2.3)$$

The three rate equations can be combined to get an equation for the overall signal intensity change through the gain medium,

$$\frac{dI_\nu}{dz} = \left[ A_{21} \frac{\lambda^2}{8\pi n^2} g(\nu) \right] \left( N_2 - \frac{g_2}{g_1} N_1 \right) I_\nu = \gamma(\nu)I_\nu \quad (2.4)$$

where $I_\nu$ is the intensity, $z$ is the distance through the gain medium, $\lambda$ is the wavelength, and $g(\nu)$ is the line shape factor ref:LaserElectronics. Eq. 2.4 shows that if the majority of the electrons are in the ground state, the terms on the right are less than zero, then absorption will dominate. In this case, the signal will see a net loss. When the majority of the electrons are in the excited state, a population inversion, the terms on the right will be positive. In this case, the change in intensity is positive, and the signal will see overall gain through stimulated emission [18]. Maintaining a population inversion is necessary to keep amplifying the signal, so energy must be pumped into the gain medium. If the system is continuously pumped and a population inversion is maintained, the signal will experience an overall gain through stimulated emission and lasing can occur if there is sufficient gain to overcome round trip losses (Figure 2.3).

![Figure 2.3: Net loss from relaxed system vs net gain from population inversion](image)
The dynamics in the gain medium vary depending on its composition and structure. The system pictured and described thus far is called a two level system. Two level systems consist of only an excited and ground state. The emitted and absorbed photons have the same energy in a two level system. This makes it impossible to maintain a population inversion due to a constant emission and reabsorption of light. Most lasers use a gain medium that has either a three or four level energy transfer structure in order to maintain a population inversion so that stimulated emission can be achieved.

Titanium doped sapphire is a four level system (Figure 2.4) [20]. The absorption of energy brings the electron up to the third excited state. The electron then relaxes to the second excited state, typically by emitting a phonon. The transition from the second excited state to the first excited state (the lasing transition) is achieved by emitting a photon. Finally, the electron will relax back to the ground state by emitting another phonon. The first phonon relaxation in the four level systems ensures that the pump light cannot also stimulate emission at the lasing transition. The final phonon relaxation ensures that none of the lasing light is reabsorbed [20].

![Four level system](image)

**Figure 2.4:** Four level system consisting of an upper and lower level absorbing state as well as an upper and lower level emitting state

In four level systems, it is ideal to have a long upper state lifetime for the emitting state and a short upper state lifetime for the non-emitting states [20]. The long lifetime of the emitting state ensures that spontaneous emission will not happen before stimulated emission can take place. A short lifetime of the non-emitting states ensures that the electron can drop energy levels before reabsorption can take place. Both of these conditions help to maintain a strong population inversion and maximize the gain in the laser [20]. The lifetimes and
energy differences of the various states is dependent on the type of material, therefore a gain medium with the right properties must be selected to yield the desired results.

Another consideration in selecting a gain medium and pump source is the quantum defect. This is the difference in energy between the pump photons and lasing photons. This energy difference is a result of the non-emitting transitions. A larger quantum defect causes more energy is lost to heat which decreases the efficiency of the laser.

As shown in EQ 2.4, the change in intensity can be written as a relation between the Einstein coefficients. This form is easy to understand conceptually; however, the variables involved are difficult to measure. To make these variables more applicable to real life systems, the stimulated emission coefficient can be written in the form of a stimulated emission cross-section $\sigma$, 

$$\sigma = \frac{h \nu g(\nu) B_{21}}{c} \quad (2.5)$$

where $g(\nu)$ is the line shape factor, $\nu$ is the photon frequency, $h$ is Boltzmann’s constant, and $c$ is the speed of light [20][7]. The stimulated emission cross-section corresponds to the interaction area of the atoms in the material. It is constant for each gain medium and has been accurately measured for many different gain mediums. Having units of area rather than number of atoms makes this quantity easier to use for large scale modeling.

For low intensities in the gain medium, the stimulated emission cross-section can be used to write an expression for the change in intensity. This is called the small signal gain $g_0$ [20][21][22].

$$g_0 = \frac{\sigma \tau_f \eta P_{in}}{h\nu V} \quad (2.6)$$

g_0 is written in terms of the fluorescence lifetime $\tau_f$, the pump power $P_{in}$, and the volume in the gain medium $V$. The small signal gain is expressed in terms of the pump power, spontaneous emission lifetime, pump volume, lasing frequency, and pump inefficiencies. The
pump inefficiencies can be further broken down to describe exact processes [20][23].

\[ \eta = \eta_Q \eta_S \eta_B \eta_a \eta_t \] (2.7)

\( \eta_Q \) is the loss due to emission at the pump wavelength rather than the lasing wavelength. \( \eta_S \) is the Stokes factor which accounts for the energy difference in pump photons and lasing photons. \( \eta_B \) is the inefficiency from alignment. \( \eta_a \) accounts for the percentage of pump that is not absorbed by the gain medium. \( \eta_t \) accounts for pump light that is lost on the way to the gain medium.

The small signal gain is dependent on the stored power in the gain medium. As the signal builds up, it will eventually get amplified to the point where it is comparable to the stored power. At this point, amplification of the signal will significantly deplete the stored power such that the gain will change. The intensity at which the gain is reduced to half of the small signal gain is called the saturation intensity [20] [7].

\[ I_s = \frac{h\nu}{\sigma_{\tau_f}} \] (2.8)

Since the saturation intensity is defined as the intensity where the gain drops to half of the small signal gain, the saturated gain equation can be expressed in terms of the saturation intensity [20][22].

\[ g = \frac{g_0}{1 + \left( \frac{I}{I_s} \right)} \] (2.9)

As the signal is amplified, it will build up exponentially throughout the length (l) of the gain medium. A total gain for the system can be written as [20],

\[ G = e^{gl} \] (2.10)
2.2 Optical Feedback

Gain is critically important for lasers to operate, but it is not the only aspect that must be considered. The gain medium must have a signal to amplify [24][25][26]. This signal initially comes from spontaneous emission. An atom in the excited state will spontaneously emit a photon, and that photon will stimulate other excited atoms to emit identical photons [18]. If the gain medium is the only component in the system, then once the photons leave the gain medium, the process will be over, and a new photon will have to be spontaneously emitted and amplified. In the system just described, there will be no fixed relationship between photon bunches coming out of the gain medium. For the light to be spatially and temporally coherent, feedback must be induced [17].

Feedback is generated by adding mirrors on either side of the gain medium so the photons pass through the gain medium repeatedly [24][25][26]. Through this process, a large collection of identical photons can be obtained. If the gain medium is continuously pumped to maintain a population inversion, and one mirror is made to be a partial reflector, the system will reach a steady state with coherent photons being emitted from the partial reflector, and the signal inside the cavity being replenished at the same rate that photons leak out. This is now a coherent light source called a laser (Figure 2.5).

![Figure 2.5: Schematic of a laser system containing the minimum necessary parts to achieve laser oscillation: an end mirror (left), an output coupler (right), a gain medium (pink), and a pump source (green)]
As the light circulates through the system, it experiences both gain and losses. A round trip gain (2.11) can be found by combining the gain and losses [20][27] [14].

\[ G = \delta R e^{2gl} \] \hspace{1cm} (2.11)

The signal will build up exponentially throughout the length of the gain medium, and experience losses that are proportional to the power of the signal. Losses come from scattering, absorption, transmission through mirrors, and other such sources. A major source of loss is the partially reflective output coupler where the output beam is emitted. The output coupler losses (R) are written separately from the rest of the cavity losses (δ) since the output coupling is a frequently adjusted variable [20].

EQ 2.11 shows the importance of feedback for achieving oscillation. If the round trip gain is less than one, a buildup of coherent photons will not happen. When the system is pumped until the gain is equal to the losses, the system will start to lase. The point at which the gain equals the loss is called threshold. At threshold, the round trip gain is exactly equal to 1 and EQ 2.11 can be used to find the threshold condition (2.12) [20].

\[ 2gl = \delta - \ln(R) \] \hspace{1cm} (2.12)

As the system is pumped harder, the small signal gain will increase. This increases the saturated gain so that it is higher than the losses, which causes the intensity in the laser to increase. As the intensity increases, the saturated gain will decrease until it is again equal to the losses and the system returns to a steady state operation. Combining the loss equation with the saturated gain equation gives an equation for the intensity in the cavity in terms of the small signal gain, saturation intensity, and losses [20][22].

\[ I = I_s \left[ \frac{2g_0 l}{\delta - \ln(R)} - 1 \right] \] \hspace{1cm} (2.13)
The output coupler only experiences the cavity intensity traveling in one direction. The power coming out of the output coupler will be a function of half of the cavity intensity and the output coupler reflectivity. Substituting in the power expression for the small signal gain gives the output power as a linear function of pump power \[20\][11].

\[
P_{out} = A \left( \frac{1 - R}{1 + R} \right) I_s \left( \frac{2g_0l}{\delta - \ln(R)} - 1 \right)
\] (2.14)

Setting the output power to be zero gives the pump threshold condition in terms of pump power \[20\][23].

\[
P_{th} = \left( \frac{\delta - \ln(R)}{2} \right) \left( \frac{Ah\nu}{\eta\sigma_f} \right)
\] (2.15)

The slope of EQ 2.15 gives the efficiency of converting pump power to output power. This is called the slope efficiency [20].

\[
S_{eff} = \left( \frac{-\ln(R)}{\delta - \ln(R)} \right) \eta
\] (2.16)

Using EQ 3.65 and EQ 3.64, EQ 3.56 can be simplified to [20].

\[
P_{out} = S_{eff}(P_{in} - P_{th})
\] (2.17)

It is important to note that the threshold condition is dependent on the gain and losses; however, once threshold is passed, the efficiency of converting input power to output power is dependent only on the losses.

When constructing a cavity, the ray picture is not enough to describe the beam in the resonator. The wave picture shows that only standing waves, or modes, can be supported in the cavity. This applies to both the transverse and longitudinal directions. The longitudinal modes will have wavelengths that are half integer divisions of the cavity length so that the forward and backward traveling waves interfere constructively [18]. Transverse modes will have a shape and size that is able to be duplicated after a round trip through the cavity.
This means the cavity will determine the shape, size, and wavelength of the emitted beam. In order to maximize the gain and minimize the losses, the cavity must be constructed to allow for good spatial and spectral overlap with the gain in the gain medium and the optics that provide feedback.

2.2.1 Transverse Modes

The transverse mode dictates the shape of the beam [28][29]. The transverse electromagnetic (TEM) mode can be broken into two axes and is designated as $\text{TEM}_{xy}$ [19]. The axes of a rectangular cavity like a diode are determined by the walls [30] [31]. In a free space laser, rectangular modes can still be obtained because of the adjustment axes of the mirror mounts. As shown in (Figure 2.6), transverse modes occur in each direction [28][32][33]. Numbers are added after TEM to indicate the order of each mode in the $x$ then the $y$ direction. $\text{TEM}_{00}$ is the lowest order mode in each direction with a single peak in the center of the confined area [28].

Figure 2.6: Lowest order Hermite-Gaussian TEM modes for a free space laser with a rectangular coordinate system
Many cavity modes can be made to overlap well with the spatial profile of the gain. These modes can lase simultaneously and can even add up to give a round shape; however, a round multimode beam will not focus as well as a TEM\textsubscript{00} beam. Because of this, most lasers are designed to operate in the lowest order transverse electromagnetic mode, the TEM\textsubscript{00} mode. A laser with a pure TEM\textsubscript{00} mode has the highest degree of spatial coherence, which means it can be focused to the diffraction limit and collimated over very long distances making it a much more precise and useful tool. Focusing to the diffraction limit means focusing as tight as the size of the optics and wavelength of the light will allow given by Eq. 2.18 \cite{20},

\[ A_m = \pi \left( \frac{\lambda f}{a} \right)^2 \tag{2.18} \]

where \( A_m \) is the diffraction limited beam area at the focus, \( \lambda \) is laser wavelength, \( f \) is focal length of lens, \( a \) is beam area at the lens.

The idea of transverse modes is slightly more obscure in free space lasers since there are no boundaries such as are to be found in fibers or laser diodes. There is a requirement, however, that the field go to zero at infinity. The Hermite-Gauss modes is the set of free-space modes that satisfy this condition in rectangular coordinates \cite{19}\cite{28}\cite{34}. Any mode is possible because the boundary is at infinity, but the gain region and mirrors select out just a few modes. The laser must be designed to use the correct pump size and the mirrors must be spaced and aligned properly to eliminate the high order modes and only lase in the TEM\textsubscript{00} mode.

The constraint on transverse modes is generally the most important in a laser design to ensure good output beam quality and power efficiency. In order to have efficient extraction of energy from the gain medium, there must be good spatial overlap between the transverse mode of the cavity and the region in the gain medium where the population inversion exists (Figure 2.7). If the transverse mode of the cavity is smaller than the gain region, then not all of the energy can be extracted from the gain medium \cite{35}\cite{22}\cite{36}. If the transverse mode is larger than the gain region, then not as many photons as is possible will travel through the
gain medium to extract energy. The optimum condition is when the cavity mode is matched in size to the gain region. This condition is called mode-matching.

Figure 2.7: Transverse mode-matching of an end pumped Ti:sapphire crystal (pink) with the pump shown in green and the transverse cavity mode shown in red.

A beam is focused by adding curvature to the wave front to change the direction the wave travels [28]. This happens because all waves travel in the direction normal to the wave front. Figure 2.8 depicts the focusing of a TEM\textsubscript{00} wave front. Far from the focus (far field) the wave front is spherical with the center at the focus and the beam behaves classically. Near to the focus (near field) the wave properties take over and the wave flattens out then diverges again. The lines indicating the propagation direction do not cross and form a point as they would in the classical picture.

Figure 2.8: a) Focusing of a Gaussian beam b) wave front curvature of focusing beam and c) cavity designed to support TEM\textsubscript{00} mode
A TEM\textsubscript{00} mode will have a flat wavefront when it is collimated. It can be turned into a purely spherical wave front that can then focused to the smallest possible spot. Higher order spatial modes will focus to a spot that is larger than the diffraction limit\cite{37}.

The TEM\textsubscript{00} mode has a Gaussian cross sectional profile and will evolve as it propagates according to the Gaussian propagation equation (2.19) \cite{28}\cite{38}. This equation expresses the size of a Gaussian beam ($w(z)$) as a function of the waist size ($w_0$), the wavelength of the light ($\lambda$) and the distance from the waist ($z$) \cite{19}. An equation can also be expressed for the wave front curvature $r(z)$ with respect to distance from the focus ($z$) (2.20) \cite{19}\cite{28}.

$$w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2}$$ \hspace{1cm} (2.19)

$$r(z) = z \left[1 + \left(\frac{\pi w_0^2}{\lambda z}\right)^2\right]$$ \hspace{1cm} (2.20)

From this, the size and divergence at any point can be calculated and the wave front curvature can be determined.

For a laser cavity to lase in a specific mode, the mode must repeat itself exactly after completing one round trip through the cavity. This means the curvature of the wave front must match the curvature of the end mirrors \cite{19}. To design a cavity that is optimized for the TEM\textsubscript{00} mode, the Gaussian propagation equations can be used to determine the proper radius of curvature for the cavity mirrors such that they are parallel to the wave front at a given distance from the waist.

Since the divergence of the wave front is dependent on the beam waist, the desired cavity waist size can be selected by changing the radius of curvature or the separation between the mirrors (Figure 2.9) \cite{39}.

There are generally more optical elements in the cavity than just the end mirrors. These must be accounted for to optimize the cavity to lase in the TEM\textsubscript{00} mode. The mode size throughout a complex cavity can be determined using ABCD matrix analysis.
Figure 2.9: Changing waist size of transverse mode by increasing separation of mirrors while holding mirror curvature constant

ABCD matrix analysis is easiest to introduce using the ray picture for propagation. A ray will have an initial displacement from the optical axis given by $r_1$ and will be traveling at an angle of $\theta_1$ with respect to the optical axis. Propagation will cause the displacement to change because of the angle with respect to the optical axis. Optical components such as lenses can cause the angle with respect to the optical axis to change. These different processes can be put into the form of an ABCD matrix. $r_1$ and $\theta_1$ can be written in the form of a vector. Multiplying the matrix and vector give a new vector that corresponds to the new angle and displacement (2.21) [19] [28].

\[
\begin{bmatrix}
  r_2 \\
  \theta_2
\end{bmatrix} =
\begin{bmatrix}
  A & B \\
  C & D
\end{bmatrix}
\begin{bmatrix}
  r_1 \\
  \theta_1
\end{bmatrix}
\]  

(2.21)

The values of A, B, C, and D are determined by properties of the component that they are modeling. Propagation changes the displacement depending on the angle with respect to the optical axis. A lens changes the angle with respect to the optical axis based on the focal length of the lens, the initial displacement from the optical axis, and the initial angle with respect to the optical axis. Using the known behavior of each component, ABCD matrices can be constructed to model the effect of the components in a laser system (Table 2.1) [19] [28].
Table 2.1: Some useful ABCD matrices

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation in a material with a constant refractive index</td>
<td>1d 0 [0 1]</td>
</tr>
<tr>
<td>Refraction at a flat surface</td>
<td>1 0 [0 \frac{n_1}{n_2} 1]</td>
</tr>
<tr>
<td>Reflection off a flat mirror</td>
<td>1 0 [0 1]</td>
</tr>
<tr>
<td>Reflection off a curved mirror</td>
<td>1 0 [-\frac{2}{R} 1]</td>
</tr>
<tr>
<td>Refraction from a thin lens</td>
<td>1 0 [-\frac{1}{f} 1]</td>
</tr>
<tr>
<td>Refracting from a right angle prism</td>
<td>[\frac{k \frac{a}{n^2 k}}{0 \frac{1}{k}}]</td>
</tr>
</tbody>
</table>

To calculate the effect on the beam propagation from many components, the ABCD matrices for all of the components are multiplied together in order of how the ray interacts with them with the matrix for the first component on the right. Equation (2.22) is an example of the transform matrix for a beam hitting a lens with focal length \(f\), propagating for some distance \(d\), hitting a flat mirror, propagating \(d\) again, reflecting off a curved mirror with radius \(R\), propagating again, then entering a material where the index changes from \(n_1\) to \(n_2\) [19].

\[
\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & \frac{n_1}{n_2} \end{bmatrix} \begin{bmatrix} 1d & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -\frac{2}{R} \end{bmatrix} \begin{bmatrix} 1d & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -\frac{1}{f} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \]  

(2.22)

These transform matrices also apply to the wave picture of beam propagation. Transform matrices can be multiplied together to get a transform matrix for a complete system. The values of A, B, C, and D can then be used in the wave ABCD equation where the \(q\) parameter contains the properties of the wave (2.23) (2.24) [19][40][28].

\[
q_2 = \frac{Aq_1 + B}{Cq_1 + D}
\]  

(2.23)
The complex beam parameter has more physical meaning when written as an inverse as it is in EQ 2.24 [28]. The ABCD equation can be rewritten to work with the inverse of $q$ (2.25) [19][28][41][42].

$$\frac{1}{q} = \frac{1}{r} - i \frac{\lambda}{\pi \omega^2} \quad (2.24)$$

$$\frac{1}{q_2} = \frac{C + D \left( \frac{1}{q_1} \right)}{A + B \left( \frac{1}{q_1} \right)} \quad (2.25)$$

A stable mode must repeat itself after one round trip through a cavity. The $q$ parameter contains all of the information about the mode. If $q_1$ is set to be equal to $q_2$ then the wave front curvature ($R$) and beam size ($w$) for a stable mode can be determined for that ABCD system [19].

2.2.2 Longitudinal Modes

For longitudinal modes in a laser, the boundaries are the end mirrors of the laser. Figure 2.10 shows a number of possible standing waves that can lie between two walls of an arbitrary cavity and the Fourier transform of the cavity modes.

For a laser to lase in a specific longitudinal mode, that mode must overlap with the emission spectrum of the gain medium, and the gain for that mode has to be above threshold. This would be a difficult constraint to work around in if the emission was truly monochromatic as is indicated by the distinct energy levels in the gain medium; however, effects from thermal vibrations and other such sources lead to broadening of the emission spectrum [19].

For a free space laser like a Ti:sapphire laser, the mode spacing in the cavity is generally around 1pm near 800nm. Ti:sapphire emits over a range of more than 400nm meaning the gain can overlap with hundreds of thousands of longitudinal modes [7] [43].
2.3 Mode-locking

The goal of mode-locking is creating controlled and repeatable spikes in output power to generate high peak powers. Power is energy per unit time; therefore, the peak power can be increased by confining all of the energy released from the laser to a short period of time. If multiple longitudinal modes lie within the emission spectrum of the gain medium, then the laser can lase in multiple longitudinal modes at the same time. In a continuous wave (CW) laser, the random amplitude and phase of the different longitudinal modes adds constructively and destructively at different times which leads to amplitude noise in the continuous output (Figure 2.11).

Occasionally, a large collection of competing modes will be in phase with each other and produce a significant spike in the power. In a CW laser, this is undesirable since it leads to noise in the output beam which affects the data collection in experiments and can even cause damage to the laser system. For a pulsed laser, these spikes are necessary to initiate mode-locking. The oscillator can be set up in a way that favors the spike in power over the continuous output by introducing an intensity dependent gain or loss to the cavity to discriminate between pulsed and non-pulsed operation. This discrimination can be done
passively with a saturable absorber or nonlinear lens, or actively with an acousto-optic modulator or electro-optic modulator. Favoring an intense spike in the radiation locks the longitudinal modes in phase with each other to create a pulsed operation called mode-locking [20]. Active elements and saturable absorbers have a slow response time which prevents these methods from making extremely short pulses. Kerr lens mode-locking is the preferred method of mode-locking for Ti:sapphire lasers since it gives the highest peak powers [44].

Figure 2.11: The signal created by adding a collection of wavelengths with random amplitude and phase together (blue), and the signal created when the same wavelengths are in phase (red) demonstrating the difference between a noisy CW signal and a mode-locked signal.

If all of the longitudinal modes in the cavity are in phase with each other, the pulse that is generated will be the Fourier transform of the longitudinal modes [45]. This pulse is described as being transform limited and is the shortest possible pulse that can be produced from that spectrum [20]. Ti:sapphire lasers, have the broadest emission spectrum of any gain medium discovered to date (Figure 2.12) [2] [7] [23]. This means they are capable of creating shorter pulses than any other gain medium [7].

The favored method for mode-locking a Ti:sapphire oscillator is Kerr lens mode-locking, since this method yields the shortest pulses. This uses a nonlinear process called the optical Kerr effect to create an intensity dependent lens in a material 2.26 [46] [47][48]. The refractive index of a material \( n \) can be written in the form of a Taylor expansion as a function of intensity \( E^2 \) [46] [49].
\[ n = n_0 + n_2 < E^2 > \]  

For low intensity, \(< E^2 >\), the index of refraction is dominated by the linear term \((n_0)\). For high intensity beams, the contribution of the second order term \((n_2)\) to the total index of refraction becomes significant [49]. For beams with a radially dependent intensity like the Gaussian TEM\(_{00}\) modes used in most lasers, this nonlinear refractive index will vary radially. This has a lensing effect causing the beam to self focus [17] [28][35].

When incorporated into an optical resonator, this lens can cause the radius of the transverse mode to be dependent on the intensity of the light [20]. There are two different ways to take advantage of the change in mode size to achieve mode-locking (Figure 2.13). Hard aperture mode-locking involves blocking part of the cavity to create an intensity dependent loss [40]. Soft aperture mode-locking uses the gain profile in the gain medium to create an intensity dependent gain [20].

The loss in hard aperture Kerr lens mode-locking can come from an iris, slit, or knife edge that is placed in a part of the cavity where the intensity dependent change in mode size is large [20] [40]. The radially dependent gain in soft aperture Kerr lens mode-locking comes from the Gaussian profile of the pump laser [20]. Stable mode-locking comes from setting up the cavity in a way that the lens has a large impact on the size of the cavity.
Soft aperture Kerr lens mode-locking is generally the preferred method for Ti:sapphire lasers. Adding loss to the cavity with hard aperture mode-locking decreases the output power of the laser and makes the laser more difficult to align.

The gain in the laser produces an exponential increase of the signal, but there is only so much gain to be had. By tipping things in favor of the pulse by just a small amount, the pulse will grow a small amount each time it goes through the crystal [51]. In doing so, it leaves less for the CW mode to take up. By ensuring that the pulse wins out on gain with each trip around the cavity, eventually the CW signal will die out and the pulse will be all that is left.

Changing the curved mirror separation to alter the cavity mode size and stability can increase the impact the Kerr lens has on the cavity mode size at various points in the cavity [52][49]. A larger change in mode size will make it possible to have larger discrimination between CW and mode-locked modes. The discrimination can be described by the parameter $s$ (2.27) [20] [40].
\[ s = \left( \frac{1}{w} \right) \left( \frac{dw}{P} \left( \frac{P}{P_{cr}} \right) \right) \]  

(2.27)

s describes the relative spot size variation of the laser beam at an aperture [20] [50] and is related to the waist size \( (w_0) \) and the change in waist size per unit power \( \left( \frac{dw}{P} \right) \). Power is scaled to a critical power \( (P_{cr}) \) [52][49]. This can be used to determine the intensity dependence of the gain or loss for a given cavity configuration [? ].

Optimizing mode sizes in the cavity will allow for mode-locking, but it will not allow for a very broad spectrum of longitudinal modes to stay in phase. Material dispersion from the crystal and from the air causes the longer wavelengths of light to travel faster than the shorter wavelengths [20]. Modes that are initially locked in phase will try to drift apart. In order for a pulse to be very broad band the dispersion of the cavity must be the same for every wavelength in the pulse [45]. Prisms or chirped mirrors can be added to the cavity to add negative dispersion to offset the positive dispersion of the material [44][53]. This allows for a broader band pulse that will be shorter in time and reach higher peak powers [53].

Inserting prisms makes one of the arms of the cavity longer than the other. This mismatch in cavity arm length gives rise to two distinct stability regions which are well known in the context of Ti:sapphire lasers [20]. The outer stability region is the stable region where the curved mirror separation is greatest. In this region, the cavity mode is collimated in the prism arm which is desirable for optimal dispersion compensation and the cavity mode is focused on the output coupler. The inner stability region is the stable region where the curved mirror separation is smallest. In this region, the cavity mode is collimated in the output coupler arm and focused on the high reflector. When the mismatch in arm length is large enough, there will be a non lasing region between the two stability zones.
2.4 Diode pumping a mode-locked Ti:sapphire oscillator

Laser diodes are made up of semiconductor stacks with electrodes connected to each end. The alternating positive (p-type) and negative (n-type) doped region in the semiconductor form a band gap. When electrons are pushed from one electrode to the other, they cross over the band gap and lose an amount of energy determined by the band gap of the semiconductor structure [19]. For certain semiconductor structures, this energy is given off in the form of a photon.

The photon can travel along the facet and stimulate other electrons to emit photons that are identical to the first. The ends of the facet are cleaved to create a very smooth surface. This uniform and abrupt change in index of refraction can act as a mirror. The ends can also be coated to make them even more reflective. The result is a very small laser cavity (Figure 2.14) [19].

![Figure 2.14: Laser diode structure, cavity, and output beam](image)

The output beam will be rectangular because the cavity is short and wide, and the entire cavity is made up of a uniformly pumped gain region. The Gaussian propagation equations reveal that the output will also be highly astigmatic with the narrow direction of
the rectangular beam diverging quickly and the long direction diverging slowly [19]. The narrow and fast diverging axis is called the fast axis. The wide and slowly diverging axis is called the slow axis. Another result of the rectangular cavity is that the short direction will have a single longitudinal mode while the long direction will support multiple longitudinal modes.

A few challenges arise when trying to pump Ti:sapphire lasers with diodes. First, the only high power diodes that are currently available which emit in the absorption spectrum of Ti:sapphire lase at 445nm. This is right on the edge of the absorption spectrum which means the absorption is inefficient (Figure 2.15) [7] [14] [13]. The higher photon energy of the pump source also means the quantum defect will be higher. This leads to higher loss in the first electron relaxation when comparing to ND:YVO₄ pumps that emit 532nm light. As a result, more power goes to heat in the crystal rather than photon emissions.

![Figure 2.15: Absorption spectrum of Ti:sapphire](image)

Another problem that arises from diode pumping is that the poor beam quality of the pump source leads to a larger focus size in the crystal. This decreases the energy density and results in lower gain. It was also believed that the asymmetric profile would make soft aperture mode-locking impossible. Current theory holds that in order to achieve soft aperture mode-locking, the pump laser has to have the radially symmetric, Gaussian cross-sectional profile and tight focusing of a TEM₉₀ mode in order to achieve discrimination between...
the mode-locked and CW modes. Given that the beam from laser diodes is not radially symmetric, it was assumed soft aperture Kerr lens mode-locking could not be achieved with this pump source. However, the diodes are single mode in one direction, so tight focusing can still be achieved in that one direction. Given that hard aperture mode-locking can be accomplished using a slit rather than a round aperture, it is possible that soft aperture mode-locking can be realized in the same way by aperturing in a single direction. My goal was to construct a directly diode pumped, Kerr lens mode-locked Ti:sapphire oscillator. I then modeled and took physical measurements of the laser to determine if the soft aperture in the single direction provides enough discrimination to account for the mode-locking behavior of this laser.
CHAPTER 3
MY EXPERIENCE

During the course of my masters program I worked on many lasers at the Colorado School of Mines and at KMLabs, my current place of employment. My job at KMLabs entails designing and building lasers that meet clients unique needs. Each of these projects has provided a great experience for my occupational growth.

My final master’s project was building and investigating the blue pumped Ti:sapphire laser; however, this was not what I had intended to do when I entered the program. The original goal of my research was to build a high contrast, short pulse amplifier to be used for spatio-temporal focusing experiments. As I was nearing the end of this project, the pump laser for my oscillator failed. This was about the same time that our group was making headway with directly diode pumping an oscillator. I started working on that project thinking I could find a new pump source for my oscillator in order to finish my original project. Instead, I found myself intrigued with the blue pumping project. My advisor, Dr. Chip Durfee, and I decided to switch gears with my research and investigate how Kerr lens mode-locking is possible with this pump source.

This chapter will outline the work I performed at the Colorado School of Mines and KMLabs while I was a graduate student, and how that work provided me the knowledge and skills needed to build the second directly diode pumped, Kerr lens mode-locked oscillator. Building this oscillator was a great challenge. Although most of my previous work leading up to the amplifier that was to originally be my final project was not directly applicable to the oscillator project, I learned a considerable amount about how these systems work and how to optimize them. These experiences directly contributed to my success at building a blue pumped Ti:sapphire.
3.1 Rebuilt multi-pass amplifier senior year as undergraduate at the Colorado School of Mines

The goal of this project was to build a Ti:sapphire Chirped Pulse Amplifier system and use it to perform pump probe experiments on Quantum dots.

This was my first experience with gain and optimizing a laser system. This was an existing laser that had fallen into disrepair. The oscillator, stretcher, amplifier ring, and compressor were intact, but all of the beam steering and telescopes were missing. I worked with Dr Adams and Dr. Durfee to get the oscillator lasing and mode-locked.

Once the oscillator was working, Dr. Durfee and I checked the stretcher and determined that it was still aligned properly. My next step was to align the beam through the Pockels cell and assemble the timing circuit. The timing circuitry consisted of a fast photodiode to measure the pulses coming out of the oscillator which was used as the master clock, a dividing circuit to drop the clock signal from 80MHz to 1kHz, a delay generator to trigger each component at the correct time, a Pockels cell to pick pulses out of the oscillator beam at 1kHz, and a trigger for the amplifier pump laser. Finally, I aligned the ring with help from Dr. Durfee.

Once the beam was aligned through the ring, I repaired an old pump laser and routed it to the crystal. I then calculated the spot sizes to get a single pass gain of three. The next step was to build a telescope so the seed would focus to a size in the crystal that would yield the desired gain, and to machine a mask with the correct sized holes for the seed size. I then constructed a telescope for the pump beam so it would be mode matched to the seed.

I sent the beam into a compressor once the amplifier was optimized and built a telescope to increase the beam size on the gratings. I aligned the compressor to get rid of second and third order dispersion, and also spatial chirp.

The single pass gain of three was achieved, and the final compressed power of the laser was 300µJ at 1kHz. Unfortunately, this was the beginning of my learning curve and it took me a great amount of time to finish the pump laser repair and amplifier construction. As a
result, I did not have enough time to complete the pump probe experiments.

Ultimately, this proved to be a great experience in gain optimization, and alignment. Also, it was my first experience with aligning and mode-locking an oscillator.

3.2 Rebuilt multi-pass, second stage amplifier at Colorado School of Mines

When I began my graduate program, my initial project was to build a multi-pass ring to be used as a power amplifier for a regenerative amplifier system.

As with the previous project, I started with an old ring that had all of the steering optics and telescopes removed from it. I set the ring up to run collimated through the crystal with a beam size of roughly 2mm. I then set the pump laser to come to a gentle focus after the crystal and matched the beam size by imaging the inside of the crystal onto a camera and using the picture to mode-match the pump and seed. This amplifier was cryogenically cooled and ran with a single pass gain of two.

The final output was 8.17mJ, but because of inefficient compressor gratings, the final compressed pulse energy was only 2mJ. This was enough power to accomplish the task at hand and gratings in general are very expensive, so we decided to leave the compressor as it was.

The amplifier ran near saturation, making this a good experience in balancing gain and loss mitigation. It was also good exposure to sizing and overlapping beams in a crystal to maximize the output power.

3.3 Built 95MHz oscillator at KMLabs

This was the first oscillator I built from beginning to end, as opposed to the previous oscillator that I only aligned. This was also the first laser I assembled that was intended for sale. The specs for this laser were a power of 300mW, and a spectrum corresponding to a pulse duration of 12fs.

During this build, Keven Shea and Greg Taft, colleagues at KMLabs, taught me the critical steps in aligning an oscillator that I had not completed prior. This included making
sure the pump and cavity beams were level and that the angles of the curved mirrors were set to minimize astigmatism when paired with the Brewster cut crystal at the focus. I also gained knowledge on aligning prisms to the minimum deviation angle. After this was accomplished, I was able to practice optimizing the CW power. To finish, Keven and Greg taught me how to optimize the cavity for mode-locking.

This laser had a mode-locked power of 460mW with a spectrum that could support 12fs pulses.

During this project, I learned the basics behind making a Kerr lens mode-locked Ti:sapphire oscillator.

### 3.4 Built 95MHz oscillator at KMLabs

The specs for this laser were a power of 400mW, and a spectrum corresponding to a pulse duration of 10fs.

This build was very similar to the previous oscillator I built at KMLabs. I was able to get the system to lase and mode-lock without assistance from others. When it came time to broaden the spectrum to get 10fs, Greg Taft showed me how to manipulate not only the prisms, but also the separation of the optics on the rail in order to influence the spectrum to achieve the performance I needed. He also taught me that the spectrum can be manipulated further by selecting an output coupler with a specific transmission curve.

This laser had a mode-locked power of 680mW with a spectrum that could support 9.7fs pulses.

I grasped two great ideas on this project, the importance of choice of optics in an oscillator in order to attain desired performance, and how to adjust the prisms and rail to change spectrum.

### 3.5 Rebuilt 80MHz oscillator at the Colorado School of Mines

The oscillator pump laser for the first laser I built at Mines eventually gave in to its old age and broke irreparably. We had another oscillator and pump laser on a different, larger
table that had also fallen into disrepair. Another group was considering using this space for a new laser, so I set out to rebuild the oscillator so they could use it for their amplifier, and so that I could eventually build an amplifier on the table as well. The goal was to get the oscillator working again, and set it up to run with high power for the other group’s amplifier, and broad bandwidth for my amplifier.

Since all of the pump steering and focusing optics had been removed from the oscillator, I initially had to remove the crystal and curved mirrors from the oscillator cavity and align the pump laser as I had learned from building the previous oscillator. Once the pump was aligned, I put the crystal and curved mirrors back in place and adjusted them so that the fluorescence reflecting off the curved mirrors would run parallel to the table. Next, I aligned the cavity in CW and optimized it until I could achieve 320mW with 2W of pump. I then adjusted the curved mirror separation until I found a place where the laser would mode-lock with a 270mW output power and broad bandwidth when pumped with 2.3W.

The desired operation was achieved, but mode-locking was difficult to initiate and the cavity alignment was demanding to maintain. Eventually, the other group and I decided to adjust the curved mirror separation to a place where high power with narrower bandwidth, but more stable performance could be achieved.

This was a good opportunity to practice the skills that I had attained while building the preceding oscillator.

3.6 Built 40MHz oscillator at KMLabs

This was to be the seed for a 50kHz regenerative amplifier that was being built for a client.

This was good experience in cavity design because it was unlike any of the oscillators I had worked on before. The oscillator had a long output coupling arm that required relay imaging to match the characteristics of a short output coupling arm. The relay imaging had to be precise in order to not affect the focusing in the crystal. I worked with Greg Taft to come up with a design for this laser.
Stable 40MHz operation was achieved and the result was a 50 percent increase in pulse energy compared to an 80MHz oscillator of similar design.

I learned a lot about cavity stability while working on this project.

3.7 Designed and built multi-pass amplifier at the Colorado School of Mines

This was the beginning of my original thesis project. The initial goal was to build a multi-pass amplifier to get 100\(\mu\)J pulses using only 5mJ of pump energy. This could later be used to do experiments with cross-polarized wave generation (XPW).

The 80MHz oscillator I had previously rebuilt was divided down to 1kHz and used to seed the amplifier. Using the parts from the first amplifier I had built at Mines, I constructed a new amplifier that was designed to run with an unchirped seed pulse. Not stretching the pulse helped maximize the seed energy to make the amplifier more efficient. This also allowed me to use a prism compressor rather than a grating compressor, further increasing the efficiency of the system. Seeding with an unstretched pulse required a careful balance of maximizing gain while staying below the damage threshold of the gain crystal. This was done by using the damage threshold of the sapphire and the desired output pulse energy to calculate the minimum spot size possible in the crystal. That spot size was then used to calculate the required pump power and number of passes in the amplifier.

The goal of 100\(\mu\)J pulses using only 5mJ of pump power was achieved. This ended up being too much pulse energy for the XPW experiments, and the pump power was reduced so the output would only be 60\(\mu\)J.

This was a valuable experience in mode-matching to maximize efficiency.

3.8 Designed, built, and installed carrier-envelope phase (CEP) stabilized oscillator at KMLabs

The goal of this project was to design and build an oscillator that would later be used to seed a CEP stabilized amplifier. The f-2f interferometer for this system required 100mW, and the amplifier required a 300mW seed. Also, the spectrum had to stretch from 730nm to
900nm with an even energy distribution to run both the amplifier and f-2f interferometer in their ideal operating conditions. The oscillator had to be well isolated from any temperature changes or vibrations.

The oscillator was built on a vibration and temperature stabilized platform that sat on a heater pad and rubber feet. A Menlo XPS 800 f-2f interferometer was used to measure the carrier envelope phase offset. Since the photonic crystal fiber at the input side of the XPS was very alignment sensitive, this component was removed and put on the oscillator breadboard to minimize pointing changes onto the fiber. To do this, the oscillator had to be redesigned to take up 2/3 of the footprint that was initially allotted for it. The crystal was shifted out of focus to push the spectrum toward 900nm and the prisms were set near zero dispersion to broaden the spectrum to the required range. A 30 percent beam splitter was used to split off some of the output beam for the f-2f interferometer. Chirped mirrors were used to compress the pulse going to the XPS and reduce the energy needed on that beam line so more energy could be sent to the amplifier. Feedback for CEP stabilization was performed using a dual piezo mirror as the high reflector in the prism arm where the beam was spectrally dispersed.

The oscillator was able to send 300mW to the output that was to be used for the amplifier. A lock of less than 90 mrad was achieved and moving the fiber into the oscillator increased the time between re-alignments from a few hours to a few days.

During this project, I learned how to make a more robust oscillator. I also learned how to manipulate the oscillator away from normal operation to get the maximum power and desired spectrum with a minimum amount of pump power. I was able to manage heat, minimize cavity walking, and minimize effects from vibrations to make a stable laser that was less influenced by lab conditions.

3.9 Designed and built bowtie power amplifier at the Colorado School of Mines

The goal of this project was to increase the energy of the amplifier I built for XPW experiments from 60\( \mu \)J to 1mJ using the remaining 15mJ of energy from the pump laser.
A grating stretcher was built between the two stages. Initially, the second stage amplifier utilized the ring and crystal of the pre-amplifier. The passes were split into two rows. The first set of passes that made up the unchirped pre-amplifier zig-zagged vertically as the passes moved across the mirrors. The pulse was then stretched and sent back into the amplifier in an opposite zig-zag pattern that filled in the spaces between the spots from the previous amplification. This left two stacked rows of 8 spots on the mirror. The alignment of this system proved to be very difficult to maintain; and, because the mode-matching was set by the first trip through the cavity, the gain was too low to achieve the desired power.

To make the system perform as desired, the pre-amplifier was returned to its previous configuration and a second stage bowtie was constructed. This amplifier was seeded with 1\(\mu\)J and pumped with 15mJ that was split from the first stage pump. The first two passes in the amplifier were focused to increase the gain, and then the beam was collimated for the final three passes to avoid damaging the crystal. The pump light that was not absorbed was reflected back with a curved mirror and refocused into the crystal to increase the efficiency of the amplifier.

The maximum energy I ever achieved from this system was 500\(\mu\)J. This was a result of the limited number of passes I was able to take through the crystal because of the bowtie design. We decided a multi-pass ring second stage would be needed to reach 1mJ.

During this project, I acquired more practice with mode-matching.

3.10 Designed and built XPW stage between amplifiers at the Colorado School of Mines

I worked on this project with my colleague at the Colorado School of Mines, Marin Iliev. The goal of our project was to increase the bandwidth and pulse contrast of the two stage amplifier system I had been working on beforehand.

During this phase of the project, I added a prism pair compressor between the pre-amplifier and power amplifier that I had previously built to compress the pulse from the pre-amplifier. The compressed pulse was then used to make XPW which was to be used to
seed the power amplifier to achieve shorter pulses with higher pulse contrast.

The maximum conversion that Marin and I were ever able to achieve was 1 percent, so we were not able to seed the power amplifier. It was determined that more bandwidth would be needed from the oscillator to get shorter pulses and make XPW more efficiently. Since the other group using the oscillator required high power and narrow bandwidth, I would have to build a new oscillator before I could complete my project.

The need for a new oscillator to seed the amplifier is what led to my interest in the blue pumped oscillator project.

3.11 Worked on and installed CEP stabilized 10kHz amplifier and power amplifier at KMLabs

The contract specs of this laser were 2mJ at 10kHz with 21fs pulses and 300mrad RMS CEP stability over 2 hrs.

This laser used a multi-pass first stage and a bowtie second stage. A pulse shaper and gain flattening filters were used to get a 21fs pulse. Securing 21fs and maintaining the amplifiers were my main tasks while Ben Langdon worked on CEP.

The final product met all specifications and I was part of the team that installed the laser at the customers site.

During this project, I learned how to engineer a stable laser platform.

3.12 Worked on diode cages for first blue pumped, Kerr lens mode-locked oscillator for collaboration project with Colorado School of Mines and KMLabs

I assisted the building and alignment of the cage system that housed the diode and the beam shaping optics. This was to be used to pump what we hoped would become the first directly diode pumped, Kerr lens mode-locked Ti:sapphire oscillator.

The diode cages were aligned using a 1000mm focal length lens placed at the end of the cage system. An 8mm focal length asphere was placed in the cage at the diode output. The separation between the asphere and diode was then adjusted so that the fast axis of the diode was focused at 1m after the 1000mm lens. The focal point was found by partially inserting a
razor blade into the beam and finding the point where the farfield dimmed uniformly rather than to one side. A -50mm cylindrical lens was then added to the cage after the asphere to expand the beam in the slow axis, and a 150mm cylindrical lens was put in the cage 100mm from the -50mm lens to collimate the slow axis. This lens was adjusted so that the fast and slow axes focused in the same place after the 1000mm lens. This was also checked with a razor blade. The telescope was chosen so that the resulting beam was well collimated and square shaped.

The diodes generated a large amount of heat, and if their temperature was not regulated, the performance of the diodes would decrease. To help manage the heat generated by the diodes we placed them in an aluminum canister with thermal paste filling the space between the diode canister and the aluminum canister. The aluminum canister was then connected to a copper cylinder that was water cooled. A thermo-electric cooler was placed in between the aluminum canister and copper cylinder to help move heat away from the diode and into the water.

Using these diode cages, Sterling Backus was able to make the first directly diode pumped, Kerr lens mode-locked Ti:sapphire oscillator.

During this project, I learned about the output modes of the diodes, and the required beam shaping to make them into useful pumps. I also gained knowledge about the importance of heat management with these components and implementation of heat management to achieve the best performance from the diodes.

3.13 Installed 95MHz oscillator for KMLabs

The goal of this project was to install an oscillator which had been built by Kevin Shea at a customer site. The installation was successful.

Installing solo was a challenge, but it resulted in a great realization that I could complete projects on my own without constant guidance.
3.14 Worked on and installed 10kHz regenerative amplifier at KMLabs

The contracted specifications for this laser were 3.3mJ at 3kHz and 1mJ at 1kHz with a 40fs pulse width.

Eric Schneider taught me how to align and optimize a regenerative amplifier. We began by using the seed to align the first cavity mirror by rotating the cavity wave plate so that the seed would be reflected back out of the cavity and aligning it back on itself. We then rotated the wave plate so that the seed would go through the cavity and walked the seed to overlap it with the pump laser. Finally, we used the last mirror in the cavity to send the seed back on top of itself. We then got the cavity lasing by blocking the seed and rotating the wave plate to 20 degrees so the polarizer would act as an output coupler. From there, we were able to maximize the power by walking the end mirrors as is conducted with an oscillator. Once this was finalized, the seed was overlapped with the amplifier output, and the pockels cell was turned on. The pockels cell window and pump delay were then adjusted to maximize the output power.

We met all of the specifications and I assisted in installing the system at the customer site.

During this project, I established the skills to build a new type of amplifier. Since regenerative amplifiers are very similar to oscillators, this was practice for cavity alignment and mode shaping.

3.15 Aligned 1W oscillator at KMLabs

The goal of this project was to make an oscillator that was initially constructed by Kevin Shea meet the quoted specifications of 800mW, 12fs, and 95MHz.

I aligned the oscillator in CW then set curved mirror separation so it would mode-lock. This laser had a mode-locked power of 880mW with a spectrum that could support 11.2fs. This project allowed me to practice maximizing oscillator efficiency.
3.16 Designed, built, and installed 30kHz regenerative amplifier and 76MHz oscillator at KMLabs

The contracted specifications for this laser were 1mJ at 10kHz, 500µJ at 30kHz, and a pulse width of 45fs.

The wide pulse repetition frequency (PRF) tuning range of this laser and high level of efficiency at each PRF made this a difficult design challenge. Initial designs avoided getting near the damage threshold on all elements in the cavity, but these designs proved to have too low of a gain to hit the power specification at 30kHz. The cavity was redesigned to have a much smaller spot size in the crystal while still having a large spot size on all of the other elements in the cavity. Initial attempts at this pushed the gain too high so that 30kHz operation was easy to achieve, but the crystal burned long before reaching 1mJ at 10kHz. The spot size in the crystal was adjusted so that the damage threshold was 1.2mJ. This made it possible to hit the high power specification at 30kHz without burning the crystal when switching to 10kHz.

The final performance of the laser was 1.1mJ at 10kHz, 520µJ at 30kHz, and a pulse width of 38fs.

I was able to manipulate a cavity to maximize its performance. I also received practice with cavity alignment.

3.17 Designed and built second blue pumped oscillator at the Colorado School of Mines

The goal of this project was to build a new oscillator to seed my amplifier with more bandwidth.

At the time pump lasers were not available and we had just successfully built the first directly diode pumped Kerr lens mode-locked Ti:sapphire, so we built a second blue pumped oscillator to use as part of my master’s project.

The final operation of the laser was 15-20mW with 250nm tip to tail bandwidth. The oscillator would have been great for our original plan, but the blue pumped oscillator deemed
to be such an interesting project that we decided to study it further rather than just using it to complete the initial project. The full details of this project are outlined in Chapter 4.

3.18 Built 1kHz regenerative amplifier at KMLabs

The contracted specifications of this laser were 4mJ at 1kHz, 2mJ at 5kHz, 1mJ at 10kHz, 45fs, and PRF locked to external source.

This was a fairly standard laser for our company, so a design was already in place. I built the laser according to the existing design and aligned it. The PRF locking was done using a piezo cavity mirror in the oscillator for fast feedback, and a stepper motor for slow feedback.

The laser had a pulse energy of 4.15mJ at 1kHz, 2.4mJ at 5kHz, and 1.5mJ at 10kHz with a pulse width of 40.1fs. It was successfully installed at the customer site.

This was great practice in cavity optimization.

3.19 Designed and built CEP stabilized oscillator and built CEP stabilized 1kHz 20mJ two stage amplifier at KMLabs

The contracted specifications of this laser were 20mJ at 1kHz with a pulse width of 25fs and $<300\text{mrad}$ RMS CEP noise.

I designed a new oscillator for this project in order to overcome some of the problems we had with the previous CEP oscillator. It incorporates the oscillator pump, the oscillator, and the Menlo XPS-800 f-2f interferometer on the same breadboard which improved power stability and CEP reliability dramatically. Water cooling was used instead of a heater pad, and the breadboard sits on a thin rubber pad instead of thick rubber feet which improved pointing stability and decreased the frequency of amplifier alignments.

The amplifier reliably generated 20mJ pulses with a pulse width of 24fs. The oscillator CEP noise is $<100\text{mrad}$ and the amplifier CEP noise is $<300\text{mrad}$. This laser has been successfully installed at the customer site.

During this project, I applied the knowledge I had gained previously in relation to stable laser platform construction and oscillator manipulation.
3.20  **Built 1kHz 12mJ two stage amplifier at KMLabs**

The contracted specifications for this laser were 12mJ at 1kHz, 8.3mJ at 3kHz, 45fs, and <1 percent power instability for 12hrs.

Because the 3kHz spec required high conversion efficiency, I knew this operation was going to be more difficult to achieve than the 1kHz operation, so I began by optimizing the laser at that pulse repetition frequency. The first stage was a regenerative amplifier. The pump mode was set to be larger than the cavity mode since the first stage had an abundance of pump power and increasing the spot size would increase the stability. 12W was extracted from the first stage. A Pockels cell was used to remove any pre-pulse, post-pulse, or amplified spontaneous emission before the second stage. This left 9.5W to seed the 5 pass, bowtie second stage. It was pumped with 100W, and had a 36W output. This gave a compressed pulse energy of 8.4mJ. 1kHz operation was easily achievable with a simple change of the timing.

The laser had a pulse energy of 12.7mJ at 1kHz and 8.4mJ at 3kHz with a pulse width of 43.6fs.

I applied knowledge of stable laser platform construction and proper mode-matching in order to build this system.

3.21  **Built 150kHz 30µJ regenerative amplifier at KMLabs**

The goal of this laser was 200µJ at 50kHz, 30µJ at 150kHz, 45fs, and a time-bandwidth product <0.6.

The final performance was 210µJ at 50kHz, 46µJ at 150kHz, 44.6fs, and a time-bandwidth product of 0.55.

I acquired practice with cavity design for low gain amplifier, and also received practice with cross pumping.
3.22 Built 100kHz 90$\mu$J regenerative amplifier at KMLabs

The goal of this laser was 90$\mu$J at 100kHz, 330$\mu$J at 30kHz, and a pulse width of 45fs. It achieved 100$\mu$J at 100kHz, with a 36fs long pulse.
CHAPTER 4
DIRECTLY DIODE PUMPED KERR LENS MODE-LOCKED Ti:SAPPHIRE LASER
CONSTRUCTION

To simplify the initial alignment of the cavity, a temporary green pump source so that the process would be similar to previous oscillators I had worked on. In order to utilize this temporary pump source, the oscillator had to be assembled on a breadboard so it could easily be moved without losing alignment. The best breadboard I had available for use was 1 foot by 3 feet. The oscillator cavity needed to fit on the breadboard, while leaving room for the diode cages.

My first design left room for the diodes to be on opposite sides of the crystal (Figure 4.1a) [39]. This was intended to mimic the cross pumping of the previous directly diode pumped laser I had worked on. A long output coupling arm was used to increase the peak power of the circulating pulse to assist in mode-locking [8]. The tip to tip separation of the prisms was 64cm which, I had learned from my previous experience, was the optimum separation to compensate for the 4.75mm thick crystal using Brewster cut fused silica prisms. The curved mirrors were switched from the 100mm radius of curvature (ROC) that I had used in the builds of my prior oscillators to a 86mm ROC. This downsize was necessary in order to get tighter focusing in the crystal and increase the intensity in the crystal to ultimately increase the gain [45]. This was implemented to offset the inefficient pumping of the diodes. ABCD traces showed that the optimum angle of incidence onto the curved mirrors to compensate astigmatism from focusing in the Brewster cut crystal was 7.5 degrees. The high reflective (HR) mirrors were 99.99 percent reflective to reduce losses, and the output coupler was 99 percent reflective to further reduce losses.

My initial design had disadvantages that immediately became apparent. First, there was little room for steering optics for the pump lasers. Second, there were too many cavity
mirrors which added a great deal of loss to the cavity.

A second design was executed that removed a cavity mirror and allowed more room for the pump steering optics (Figure 4.1 b). However, about the time this design was finished, further testing on the original directly diode pumped oscillator indicated that the diodes were sensitive to feedback from one another, and cross pumping risked damaging the diodes. Therefore, this design was abandoned as well.

A third design was created that provided room for the diodes on a single corner of the breadboard and allowed for the diodes to pump the crystal from the same side (Figure 4.1 c). This was the design that was used for the initial alignment. CW lasing was achieved using this design; however, when I attempted to mode-lock the laser, I found the 450mm long output coupling arm was too short and mode-locking was not possible.

In order to mode-lock the laser, the output coupling arm was extended by 20cm (Figure 4.1 d). This was the final design that was able to Kerr lens mode-lock while being directly pumped with diodes.

Initial alignment of the cavity was done using a Lighthouse Photonics Sprout-G-5 running at 2W (Figure 4.2) [39]. A dichroic mirror that passed green and reflected blue was placed in the beam path of the green in order for the possibility to pump with both blue and green. A 3 percent output coupler was used during the initial cavity optimization for alignment similar to the other oscillators I had worked on. Once maximum CW power was achieved, the 1 percent output coupler, which would be used for blue pumping, was put in place of the 3 percent output coupler that had been used for initial alignment. This was implemented because the blue light has lower absorption and a higher quantum defect than green light, so the pump light would be less effective at creating a population inversion. Furthermore, the pump size in the crystal created by the rectangular multimode beam produced by the diodes was large compared to what can be achieved with the Nd:YVO$_4$ pump laser which led to a lower pump energy density. Each one of these aspects contributed to a decrease in the gain. Stable mode-locking requires a specific cavity power, so the loss had to be decreased
Figure 4.1: Evolution of oscillator design starting with a) initial design b) reduction in number of mirrors and shortening of output coupling arm c) shifting rail to far end of breadboard to put diodes side by side and d) lengthening output coupling arm so laser would mode-lock

in order to offset the decrease in gain and thus maintain the same cavity power. Decreasing the pump power without also decreasing the loss would result in either Q-switching, or no mode-locking at all.

The lasing threshold was initially 0.5W of pump power with the 1 percent output coupler. The threshold was then driven down by adjusting the end mirrors of the cavity, and also adjusting the separation of the curved mirrors and the crystal position. Once the lasing threshold was down to 0.02W of green pump, blue pumping was attempted.

Initially, the diode cages were aligned using a 1000mm focal length lens (Figure 4.3) [39]. An 8mm focal length asphere was placed in the cage at the diode output. The separation between the asphere and diode was then adjusted so that the fast axis of the diode was focused at 1000mm after the 1000mm lens. The focal point was found by partially inserting
a razor blade into the beam and finding the point where the farfield dimmed uniformly rather than to one side.

The next step was to add a -50mm cylindrical lens after the asphere to expand the beam in the slow axis. A 150mm cylindrical lens was put 100mm from the -50mm lens to collimate the slow axis. This lens was then adjusted so that the fast and slow axes focused in the same place after the 1000mm lens. This was also checked with a razor blade.

Once the diode cages were aligned so that the fast and slow axes were both collimated, the diode cages were moved to the oscillator breadboard. One of the diodes was routed so that it hit the same place on the dichroic mirror where the green was passing through (Figure 4.4) [39]. The dichroic mirror was then adjusted to overlap the green and blue in the crystal. The overlapping was maximized by maximizing the output power of the oscillator since the laser was operating above threshold with just the green pump. Once the overlap was maximized, the green laser was turned off to see if the cavity would lase with only one blue diode.

Lasing was not achieved, so the green was turned back on, and the second diode was aligned into the crystal. A square mirror was placed next to the beam path of the first blue diode. The beam from the second diode was steered to hit the edge of the square mirror right next to where the beam from the first diode passed by it. The square mirror was
then adjusted to make the beam from the second diode run parallel to the beam from the first diode (Figure 4.5) [39]. This would result in the beams crossing the crystal where the gain was taking place. The crossing was optimized by maximizing the output power of the oscillator. Once the power was optimized, the green was again turned off to see if lasing could be sustained using two diodes. The diodes again were unable to sustain lasing without the green pump.

To make the pumping of the crystal more symmetric around the optimum direction of the green pump beam, the pointing of the diodes was adjusted so that the beams hit the dichroic mirror with the point between them centered on where the green passed through the face of the optic so that the angle of both diodes with respect to the cavity mode would be minimized. The dichroic was adjusted for the maximization of the laser output. The green was turned off to see if lasing could be sustained with just the blue, and again it was not.

It was thought that the reason for not achieving lasing was poor diode alignment, so the diode cages were removed from the oscillator and realigned. The goal this time was to make sure the diode beams were well collimated by allowing them to propagate a long
distance. The beams were allowed to propagate for 10m (Figure 4.6) [39]. The lenses were then adjusted to make both axes as small as possible at a distance of roughly 10m from the diode cages. Using this alignment, the diodes were put back on the oscillator breadboard, and the same alignment procedure was repeated. With the diodes straddling the green on the dichroic, and crossing each other and the green beam in the center of the crystal, the green was turned off. Again, no lasing was seen with only the blue diodes pumping the laser.

The diode cages were removed and then aligned a third time. This time, the asphere was moved close to the diode so that the beam was divergent after the asphere. The cylindrical lenses were set to be 100mm apart. The beam 1m from the diode cage was a large square when the cage was aligned in this fashion. The asphere was then moved away from the diode and the square got smaller in return. It was observed that, at a certain separation between the asphere and the diode, the square began to be elongated in the horizontal direction (Figure 4.7) [39]. The asphere was pushed back toward the diode so that the smallest possible square was made 1m from the cage. Once this alignment was done on both cages, they were put back into the oscillator and aligned as before. This time, lasing was sustained with just the blue diodes pumping the oscillator.

The dichroic mirror was replaced with a high reflector for the blue to maximize the amount of light getting to the crystal. Then the diode crossing, cavity end mirror alignment, curved mirror separation, crystal position, and focusing lens position were adjusted to maximize the CW power from the oscillator. A CW power of 25mW was achieved.
The oscillator output was directed onto a power meter that had a spectrometer fiber and fast photodiode close to its surface to catch scattered light from the power meter face. This allowed for average power, spectrum, and fast power fluctuations to be measured simultaneously. The curved mirror furthest from the pump lens (C2) was moved closer to the crystal until flashes of pulses were seen on the 300MHz oscilloscope that was detecting the signal from the fast photodiode. The prism insertion was then adjusted until the height of the pulse flashes was maximized. The prism was then bumped continuously while making small adjustments to the position of C2; and, at the same time, looking for broadening of the spectrum, which would indicate a long lived pulse. Using this method, Kerr lens mode-locking was achieved.

The mode-locked power out of the oscillator varied greatly depending on where the prisms were set (Figure 4.8). The prism closest to the crystal had to be pulled out until it was clipping some of the beam in order to initiate mode-locking. Once the oscillator was mode-locked, prism 1 could be pushed in to increase the power. Prism 2 could also be inserted to increase the bandwidth. Prism 1 and prism 2 both had to be at a specific location to initiate mode-locking. The pulse repetition frequency of the oscillator was 95MHz (Figure 4.9).

Figure 4.8: Spectrum and power for different prism positions
The pulse train out of the oscillator was initially unstable. The oscillator would either double pulse, or q-switch. At 2.3W of pump power, the oscillator would bounce between these two modes of operation. Double pulsing comes from having too much cavity power. Q-switching comes from having too little cavity power. Obtaining both of these results indicated that the cavity was well aligned, but mechanical and environmental instability were causing the power to drift too high and too low.

The easiest way to dramatically improve the stability of a cavity is to eliminate air currents. An enclosure was made for the oscillator to help control the effect of air currents. Enclosing the oscillator did help stabilize the pulse train at this specific pump current. Mode-locking was stable and repeatable.
Slope efficiency measurements and spectral measurements were made on the oscillator I built at the Colorado School of Mines (CSM); however, the diodes failed before all of the desired measurements could be performed. A full set of testing was completed on a directly diode pumped oscillator at KMLabs. This laser had a slightly different pumping configuration that gave more reliable and repeatable performance for the measurements. Analysis of performance will be limited to the KMLabs laser since a full data set was not obtained for the CSM laser. The measurements on the laser I built at the Colorado School of Mines are included in Appendix A.

To start, detailed measurements of optic locations were done so that an ABCD trace of the cavity could be created. This trace gave the theoretical operating parameters of the laser (Figure 5.1) [39].

Measurements of the cavity mode were made by placing a pellicle in the cavity. The pellicle was put in two different locations and rotated so that it had a minimal effect on the output spectrum and power. The first pellicle location allowed for a measurement of the beam on the way to the output coupler, passing through the output coupler, and returning from the output coupler Figure 5.2[39].

The second pellicle location allowed for measurements of the cavity mode after it passed through the Ti:sapphire crystal Figure 5.3[39].

The first measurement was of the cavity mode profile. The cavity mode profile was measured using a pellicle in the cavity to split off some of the beam, and an M^2 machine to measure the beam profile at a measured distance from the pellicle. The M^2 machine records high resolution pictures of the beam as the camera is incrementally stepped through
Figure 5.1: ABCD trace of KMLabs oscillator and theoretical CW mode size in crystal

the focus of a lens. A fitting function is applied to the x and y axes of each picture to
determine the beam size and profile at each step. This data is used to reconstruct the beam
propagation and determine the beam profile. The lens focal length, camera pixel size, and
camera location are calibrated so that the beam size and wave front curvature are given for
the input beam. Since the distances in the cavity and on the way to the M² were known,
the wave could be theoretically back propagated using ABCD matrices to determine the size
and curvature of the wavefront at the output coupler and also in the crystal. There was
no process that should have changed the beam profile for the three measurements at the
first pellicle location; however, each measurement was taken to check the repeatability of the
measurement method. Measurements were taken for both CW and mode-locked operation
(Figure 5.4) (Table 5.1) (Figure 5.5) (Table 5.2) [39]. The M² measurements report a 4σ
diameter which was converted to $1/e^2$ radius for the spot size modeling.

The $M^2$ was then measured for the pump beams to determine the beam characteristics of the pump source in the crystal (Figure 5.6) (Table 5.3) [39].

The beam profile measurements were repeated on a Nd:YVO$_4$ pumped oscillator constructed using similar components and optic separations to allow for comparison between the two pump sources (Table 5.4).

For a cavity containing only optics that do not exhibit gain or loss, the radius of curvature of wavefront has to be zero at flat end mirrors to get standing transverse modes. Wavefront curvature at the output coupler must be a result of gain guiding. Wavefront curvature was seen in both the blue pumped and green pumped oscillator. The curvature in the Nd:YVO$_4$ pumped oscillator was the same for the x and y directions which is consistent with a round beam that has most of its power concentrated in a region smaller than the cavity mode in the crystal. The wave front curvature asymmetry in the diode pumped oscillator is consistent with an asymmetric pump beam. Gain guiding in the diode pumped oscillator indicates that this oscillator also has a majority of the pump power located in a region of the crystal that is smaller than the cavity mode.
Table 5.1: Summary of blue pumped oscillator cavity mode size measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>x wavefront curvature at OC (mm)</th>
<th>y wavefront curvature at OC (mm)</th>
<th>x spot size at OC (µm)</th>
<th>y spot size at OC (µm)</th>
<th>x focus displacement away from crystal at OC (mm)</th>
<th>y focus displacement away from crystal at OC (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW toward OC</td>
<td>-82.3</td>
<td>-38.6</td>
<td>227</td>
<td>322</td>
<td>-68</td>
<td>-38</td>
</tr>
<tr>
<td>ML toward OC</td>
<td>-102</td>
<td>-28.8</td>
<td>204</td>
<td>105</td>
<td>-66</td>
<td>-18</td>
</tr>
<tr>
<td>CW away from OC</td>
<td>-79.2</td>
<td>-36.2</td>
<td>207</td>
<td>294</td>
<td>-62</td>
<td>-35</td>
</tr>
<tr>
<td>ML away from OC</td>
<td>-93.4</td>
<td>-27.8</td>
<td>184</td>
<td>87.1</td>
<td>-58</td>
<td>-13</td>
</tr>
<tr>
<td>CW through OC</td>
<td>-80.1</td>
<td>-25.7</td>
<td>192</td>
<td>199</td>
<td>-60</td>
<td>-24</td>
</tr>
<tr>
<td>ML through OC</td>
<td>-116</td>
<td>-33.4</td>
<td>225</td>
<td>86.6</td>
<td>-81</td>
<td>-13</td>
</tr>
</tbody>
</table>

Table 5.2: Reconstructed cavity mode through crystal

<table>
<thead>
<tr>
<th>Axis</th>
<th>size leaving crystal toward OC (µm)</th>
<th>spot size returning to crystal from OC (µm)</th>
<th>spot size leaving crystal toward HR (µm)</th>
<th>spot size returning to crystal from HR (µm)</th>
<th>predicted spot size leaving crystal toward OC from HR side measurement (µm)</th>
<th>predicted spot size leaving crystal toward HR from OC side measurement (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>60</td>
<td>13</td>
<td>128</td>
<td>322</td>
<td>62</td>
<td>91.5</td>
</tr>
<tr>
<td>y</td>
<td>65</td>
<td>33</td>
<td>204</td>
<td>256.5</td>
<td>253</td>
<td>132.5</td>
</tr>
</tbody>
</table>
Table 5.3: Summary of blue pump beam measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>X spot size on crystal face near OC (µm)</th>
<th>Y spot size on crystal face near OC (µm)</th>
<th>X spot size on crystal face near prisms (µm)</th>
<th>Y spot size on crystal face near prisms (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump 1</td>
<td>128</td>
<td>287</td>
<td>113</td>
<td>123</td>
</tr>
<tr>
<td>Pump 2</td>
<td>228</td>
<td>287</td>
<td>290</td>
<td>138</td>
</tr>
<tr>
<td>Pump 3</td>
<td>191</td>
<td>317</td>
<td>239</td>
<td>161</td>
</tr>
<tr>
<td>All Pumps</td>
<td>160</td>
<td>305</td>
<td>172</td>
<td>140</td>
</tr>
</tbody>
</table>

Table 5.4: Summary of cavity mode size and pump size measurements for the green pumped oscillator

<table>
<thead>
<tr>
<th>Measurement</th>
<th>x wavefront curvature at OC (mm)</th>
<th>y wavefront curvature at OC (mm)</th>
<th>x spot size at OC (µm)</th>
<th>y spot size at OC (µm)</th>
<th>x focus displacement away from crystal at OC (mm)</th>
<th>y focus displacement away from crystal at OC (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW through OC</td>
<td>1190</td>
<td>1250</td>
<td>912</td>
<td>929</td>
<td>312</td>
<td>391</td>
</tr>
<tr>
<td>ML through OC</td>
<td>1320</td>
<td>1290</td>
<td>1130</td>
<td>1060</td>
<td>474</td>
<td>472</td>
</tr>
</tbody>
</table>
Figure 5.4: $M^2$ measurement and back propagation to determine the mode size in the crystal using the CW beam traveling toward the output coupler

A change in spot size and location is seen when comparing the CW and mode-locked measurements of both oscillators. This indicates that the nonlinear lens is keeping the beam confined to a smaller size throughout the length of the Ti:sapphire crystal. The reduction in beam size for pulsed operation was more pronounced in the y direction which indicates an astigmatic Kerr lens. This is expected for a Kerr lens in a Brewster cut crystal because the beam will be elongated in the x direction which will decrease the intensity gradient in that direction [52].

The duplicated measurements at measurement location 1 agreed well with each other showing that the results were accurate.
Figure 5.5: Beam sizes in the crystal of the blue pumped oscillator with CW in red, ML in green, and pumps in blue. Beam sizes were determined using ABCD analysis to propagate M² measurements back to crystal. Measurements are broken down into x (horizontal) and y (vertical) axes. Column a shows the measurements taken at position 1 with the beam traveling toward the OC. Column b shows the measurements taken at position 1 with the beam traveling through the OC. Column c shows the measurements taken at position 1 with the beam traveling away from the OC. Column d shows the measurements taken at position 2 with the beam traveling away from the crystal, toward the first prism. Units are in µm.

All measurements showed that the 1/e² radius of the CW and ML modes were smaller than the 1/e² radius of the diode pump beam in the crystal. This was consistent for both the x and y axes.

Next, spectral measurements were taken at the four different sampling locations (Figure 5.7) (Figure 5.8). The spectrum out of the output coupler was the same for each of the measurements. The pellicle gave a well known reflectivity so that the actual spectrum in the cavity could be determined.

The spectrum inside the cavity shows a large dip in the center while the output spectrum does not. This could indicate a spectrally dependant reflectivity for the output coupler.
Figure 5.6: M² measurement and back propagation to determine the beam size of pump 1 in crystal

The lower reflectivity near the center will cause higher losses for the CW mode than the mode-locked mode [54]. This would have the same effect as a hard aperture and would lead to a bias toward mode-locked operation.

To check if the features in the spectrum were from the pellicle or from the output coupler, reflectivity measurements were performed for the pellicle (Figure 5.9) and transmission measurements were performed for the output coupler (Figure 5.10). Measurements were performed using the output of a broadband Ti:sapphire oscillator. The amount of light reflected from the pellicle was too small to be measured with a power meter, so the reflectivity could not be calibrated to a percentage. The measurements for the output coupler were calibrated by measuring the power of the incoming beam and the transmitted beam.
Figure 5.7: Normalized mode-locked spectra for measurement position 1 in the diode pumped oscillator

The pellicle showed a dip in reflectivity that went nearly to zero. The location of the dip was tunable by rotating the pellicle. The transmission of the output coupler showed a minimum in the center of the spectrum. This indicates that the dip in the measured cavity spectra was from the pellicle and that the output coupler has the opposite of the desired reflectivity spectrum for creating a modelocking bias.

The pellicle was aligned near Brewsters angle to have a minimal effect on the output power and spectrum of the oscillator. This centered the dip in reflectivity on the spectrum of the oscillator causing the dip seen in the spectra. Measurements could have been improved by using a pellicle with a different thickness, or by aligning the pellicle at a different angle.

Next, the output power of the blue pump source was measured for multiple pump currents Figure 5.11.

Using the pump power data, output power as a function of input power was measured for CW and mode-locked modes of operation using two different spectra (Figure 5.12) (Figure 5.13).

These measurements were repeated on the Nd:YVO$_4$ pumped oscillator to allow for comparison between the two pump sources Figure 5.14 Figure 5.15.
A linear fit was applied to the output curves to determine the slope efficiency and threshold for each oscillator (Table 5.5) (Table 5.6).

Table 5.5: Slope efficiency for blue pumped oscillator

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Slope efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML1</td>
<td>0.0867</td>
</tr>
<tr>
<td>CW1</td>
<td>0.1819</td>
</tr>
<tr>
<td>ML2</td>
<td>0.1667</td>
</tr>
<tr>
<td>CW2</td>
<td>0.1935</td>
</tr>
</tbody>
</table>

The slope efficiency can not be directly compared for the green and blue pumped oscillators because the blue pumped oscillator required a different output coupler than the green pumped oscillator. Since the output coupler reflectivity will impact both the slope efficiency and the threshold, it is expected that the data from the blue pumped and green pumped oscillators would be different. The slope efficiency for the blue pumped oscillator can, however, be interpreted without comparison to the green pumped oscillator because of the unique characteristics of the curves.
Figure 5.9: reflectivity measurement for pellicle as a function of wavelength. Reflection units are arbitrary.

Slope efficiency is only related to losses in the pump and cavity, while threshold is related to both loss and gain. The slope will decrease for increasing losses. Threshold will decrease with decreasing losses of increasing gain. For the diode pumped oscillator, the threshold is much lower for ML operation, but the slope efficiency is also lower. The decrease in threshold has to come from an increase in gain since the slope efficiency shows that the losses are increasing rather than decreasing. This indicates that the pump overlap is improved for the ML operation which points to a soft aperture being the mechanism for creating the

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Slope efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML1</td>
<td>0.59556</td>
</tr>
<tr>
<td>CW1</td>
<td>0.48417</td>
</tr>
<tr>
<td>ML2</td>
<td>0.55707</td>
</tr>
<tr>
<td>CW2</td>
<td>0.48224</td>
</tr>
</tbody>
</table>
Figure 5.10: Percent transmission through output coupler as a function of wavelength.

mode-locking bias.
Figure 5.11: Blue diode pump power vs current

Figure 5.12: ML output spectra for blue pumped oscillator slope efficiency measurements

Figure 5.13: Blue pumped oscillator output power curves
Figure 5.14: ML output spectra for the Nd:YVO₄ pumped oscillator slope efficiency measurements

Figure 5.15: Output power curves for green pumped oscillator
The pumping scheme of the two different diode pumped oscillators was significantly different, so performance from the two oscillators differed greatly. The oscillator at CSM was too difficult to maintain and as a result, a full set of measurements was impossible to obtain with this laser. Though the performance of this laser hints at a mode-locking mechanism, more measurements would be necessary for any conclusive results. A full set of data was obtained with the oscillator at KMLabs.

6.1 CSM oscillator

Initial alignment of the diodes and cavity was more difficult for the directly diode pumped oscillator; however, alignment and long term performance was very robust. The system was able to run for months without requiring realignment.

A camera was set up to image the crystal so that alignment of the diode cages could be fixed easily should a misalignment occur. It was found that simply minimizing the spot size of the pumps at a consistent distance from the pump lens was enough to fix any misalignments in the diode cages.

The cavity alignment was also very robust, but very difficult to align. CW lasing was easy to recover in the event of a misalignment, but optimizing for mode-locking was always difficult. The cavity mode had to hit a specific spot on the first prism which was difficult to find. This spot was very close to the tip of the prism. This seems to indicate that some hard aperturing was necessary in order to initiate mode-locking. Once the oscillator was mode-locked, the first prism could be pushed further into the cavity mode indicating that soft aperturing was enough to maintain mode-locking.
6.2 KMLabs oscillator

Beam profile measurements on this oscillator showed a decrease in spot size in the crystal for the mode-locked mode compared to the CW mode. This shows that a Kerr lens was present; however, the CW and mode-locked modes were both smaller than the pump in the x and y direction. These results were consistent for the green and blue pumping. Beam size measurements examined the $1/e^2$ radius of the beams. It is likely that these measurements did not account for hot spots in the beam that could lead to higher gain for a smaller cavity mode size.

The beam profile measurements also showed a large wave-front curvature at the output coupler. This wave-front curvature would only be possible if gain guiding had a significant influence on the cavity mode. This indicates that the majority of the pump power was in a region of the crystal that was smaller than the cavity modes.

Reflectivity measurements on the output coupler showed a minimum transmission at the center of the oscillator spectrum. This is the opposite of the desired reflectivity curve for an output coupler that supports broad band pulses. This shows that the output coupler is not the source of the mode-locking bias.

The slope efficiency for CW and mode-locked modes was lower for the blue pumped oscillator which would be expected because of the lower absorption, higher quantum defect, and poor mode-matching. The slope efficiency was lower for ML which means the losses are higher for ML operation compared to CW operation. Threshold decreased for ML operation compared to CW operation. Since threshold is inversely proportional to losses and proportional to the gain, a decrease in threshold means that the gain increased more than the losses. Soft aperture mode-locking is defined by having higher gain for the ML mode of operation. This means a soft aperture was the mechanism that created a mode-locking bias in the diode pumped oscillator.

The decreased mode volume in the crystal for mode-locked operation shows that a Kerr lens was present in the diode pumped oscillator. The decrease in threshold paired with a
decrease in slope efficiency for mode-locked operation demonstrates that there is an increase
gain for pulses. It is clear that soft aperture Kerr lens mode-locking is taking place in these
directly diode pumped Ti:sapphire oscillators. Since the $1/e^2$ pump beam size was larger
that the $1/e^2$ cavity mode size for both CW and ML operation in both the diode pumped
and Nd:YVO$_4$, it can be concluded that the $1/e^2$ radius does not give enough information
to determine if the soft aperture effect will be present. Hot spots in the multi-mode beam
may be the cause for the mode-locking bias that was observed. An accurate model for soft
aperture mode-locking will need to take the full pump beam profile into account.
REFERENCES CITED


APPENDIX - DIRECTLY DIODE PUMPED OSCILLATOR MEASUREMENTS ON COLORADO SCHOOL OF MINES OSCILLATOR

The slope efficiency for the mode-locked (ML) and continuous wave (CW) modes of operation was measured for multiple pulse widths. The pump output was first measured at multiple currents to get a power curve to use for the slope efficiency measurements (Figure A.1).

![Figure A.1: Pump power vs pump current](image)

\[
\gamma = -17.683x^4 + 147.84x^3 - 583.51x^2 + 2076.8x - 935.68
\]

The CW and ML slope efficiencies were then measured for four different prism positions giving four different pulse widths in the crystal (Figure A.2)(Figure A.3)(Figure A.4).

From these measurements, an average continuous wave and mode-locked slope efficiency were calculated (Table A.1).

Next, spectral measurements were taken at different points in the cavity. This was done to try to determine the spectral shaping from the various components. The measurements were of the spectrum transmitted through the output coupler, and the reflections off both crystal faces and both prisms (Figure A.5).
Figure A.2: Test spectra

Figure A.3: Continuous wave power curves

Figure A.4: Mode-locked power curves
Table A.1: Slope efficiency comparison

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>CW Slope</th>
<th>ML Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0088</td>
<td>0.012</td>
</tr>
<tr>
<td>2</td>
<td>0.0091</td>
<td>0.0134</td>
</tr>
<tr>
<td>3</td>
<td>0.0095</td>
<td>0.0183</td>
</tr>
<tr>
<td>4</td>
<td>0.0089</td>
<td>0.0145</td>
</tr>
<tr>
<td>Average</td>
<td>0.009075</td>
<td>0.01455</td>
</tr>
</tbody>
</table>

Figure A.5: Spectrum out of oscillator. Spectrum off the crystal on the way to the output coupler. Spectrum off the crystal on the way from the OC. Spectrum off Prism 1 (P1). Spectrum off Prism 2 (P2).
Finally, the pump profile in the crystal was measured. This was done by removing the crystal and placing a camera on a translation stage where the crystal was positioned. The diodes were run at full power, and the power was cut down with a reflective ND5 filter, and absorptive ND 3 filter, and an absorptive ND 5 filter to keep the camera from saturating (Figure A.6).

Figure A.6: Diode crossing in crystal (translation in microns)