Laser Specifications

The desired device is a laser oscillator stable for cw and mode-locked operation. For mode-locked operation, a pulse duration of ~20 fs is desired for use in experiments probing ultrafast phenomena. The laser should have the highest power and repetition rate feasible. Tunability of the center wavelength would be an advantage for some applications. The system should be pumped by a readily available commercial laser, be fairly compact (small “footprint” on an optical table) and have a nice Gaussian output mode with low divergence. The most important specification is the pulse duration for mode-locked operation, since this will influence the peak power and determine of the timescale of physical phenomena that can be probed.

General Laser Requirements

General requirements for a laser include a stable cavity, a gain medium, and losses that are less than the gain for each round trip through the cavity-- ideally as small as possible. The cavity stability condition is given by

\[ -1 \leq \frac{A + D}{2} \leq 1 \]

for the cavity ABCD matrix. To minimize losses, any reflective optics, with the exception of the output coupler, should be highly reflective, and transmissive optics should be inserted at Brewster’s angle if possible. Losses will reduce the efficiency of the laser and, if great enough, will prevent lasing entirely.

It is well-known that for stable mode-locked operation, a repetition rate of ~ 80 MHz is best, with rates from 70 MHz to 100 MHz possible. Lower repetition rate also means a longer cavity and larger device on the table; higher repetition rates are limited by the need to fit in all the optics including dispersion compensation. The condition on the cavity length is:

\[ \frac{c}{2nL} \sim 80 \text{MHz} \Rightarrow L \sim 1.875 \text{ m}. \]

Figure 1 Stability of cw Ti:sapphire laser as a function of d1 and d2
Requirements for Modelocking

Modelocked operation requires a large bandwidth in order to produce short pulses. So the gain medium must have a broad gain bandwidth and all the optics in the cavity must substantially transmit (reflect) the desired range of wavelengths. Finally, a short pulse requires that its constituent wavelengths have the same relative phase, so the bandwidth of the pulse is limited to the bandwidth for which the net dispersion in a cavity round-trip is zero.

While Kerr-lens modelocking will be included in this design, some of the nonlinear optical effects in the system will not be considered in detail. For example, detailed analysis of gain and loss in the cavity will not be included (we just want to “minimize” losses) and pump beam intensity and intensity required for Kerr-lens modelocking will be taken from known values.

Gain Medium

A Ti:sapphire crystal gain medium has large gain bandwidth, is extremely durable and is convenient: it consists of a single solid-state component with no messy and toxic dyes to change.

![Figure 2 Gain curve of Ti:sapphire crystal, from Moulton 1986](image)

The gain bandwidth of Ti:sapphire is more than sufficient to support 20 fs pulses. The most basic requirement for the laser is that the cavity be stable for both cw and
modelocked operation. Second, the pump laser intensity in the gain medium needs to be sufficient to give good gain over the length of the crystal or a rayleigh range. Finally, for modelocked operation, the entire desired bandwidth must be transmitted through the laser cavity with minimum net phase; i.e. the net dispersion of a round trip must be zero in order for a short pulse to be maintained. Dispersion compensation will be required for the gain crystal and any other transmissive optics in the cavity.

In general, dispersion compensation can take the form of prisms, gratings, or chirped mirrors. Need transmitted and dispersion-compensated bandwidth to support short pulses. For Ti:sapphire the central gain wavelength will be ~800 nm: 60 nm FWHM, 100 nm tail-to-tail. Repetition rate will be determined by the total cavity length: c/2nL. Lower repetition rate but will lead to longer cavity length, which may mean a larger footprint on the table. Lower limit on cavity length is given by need to fit the optics and in particular the dispersion compensation: a prism pair needs sufficient space between them to spread the colors and give good compensation.

**Dispersion Compensation**

Dispersion compensation must be internal to the cavity to keep a short pulse in the crystal, since the self-mode-locking mechanism depends on very high peak intensity. To this end we should eliminate all unnecessary transmissive optics contributing ordinary dispersion; the lenses in the laser cavity should be replaced by equivalent curved mirrors at small angles and the laser cavity “folded;” this change will also help create a more compact system, and avoid chromatic aberration.

To compensate any remaining dispersion, we need a component with anomalous group velocity dispersion (second-order dispersion or GVD) to compensate for GVD in the crystal but low third-order effects, as these will affect ultimate pulse duration as well. High throughput is also required. Three possible sources of anomalous dispersion are a grating pair, chirped mirrors, and a prism pair. A grating pair can provide high anomalous GVD but is inefficient (~60% throughput for a pair of blazed gratings). Gratings are also expensive, easily damaged by high laser intensities and cannot be cleaned. But their broad bandwidth and the potential to compensate for third-order dispersion would make their use an intriguing problem to study. Chirped mirrors typically have to be custom-designed and coated, making them expensive and time-consuming to acquire. They also tend to suffer from resonances and are not flexible- they must be optimized for a particular center wavelength and bandwidth, leading to an oscillator that is less adjustable by the user.

Some Material Dispersion Values at 800 nm:
BK7 gives a high ratio of GVD to third order dispersion, making it a good choice for prism material. Fused silica would also be a reasonable choice.

**Paraxial Design:** ABCD matrix of laser cavity with constraints on mode in crystal.

![A general laser cavity](image)

The ABCD matrix for the cw laser cavity is given in oscillatorcw.nb, and the stability condition is shown below. The cavity is stable for d1, d2 <= f.

![Stability condition for cw operation with varying d1 and d2](image)
A commercially available cw pump laser operating at ~5W in the green, e.g. Verdi at 532, is sufficient to drive the oscillator.

A 4.75 mm thick Ti:sapphire crystal is thick enough to provide significant (~0.5 W) output power and has low enough third order dispersion to allow 20 fs output pulses. The crystal should be cut at Brewster’s angle to minimize losses.

Brewster’s angle for red light:

$$\theta_B = \tan^{-1}\left(\frac{n_i}{n_r}\right)$$

$$n_i \approx 1$$

$$n_r = 1.76 @ 800\text{nm}$$

=> $\theta_B = 60.40^\circ$.

Prism details:

For BK7, $n = 1.51078$ for 800 nm, so $\theta_B = 56.50^\circ$. For the minimum deviation condition, the apex angle $\phi$ should be

$$\phi = 180 - 2*\theta_B = 67^\circ.$$  

For BK7 prisms used at the minimum deviation angle, total group delay is minimized over the necessary bandwidth for a prism separation of 60.90 cm, measured along the optical path between the prism tips (from TisappLaserDispersion2).
To make use of the full length of the crystal as a gain region we want the rayleigh range of the pump beam to be about as long as the crystal.

Using a diode-pumped green pump laser such as a Verdi, we have a 0.5 cm input beam diameter. The desired rayleigh range is ~0.4 cm, which gives $f = 17$ cm for the focusing lens, $w_0 = 0.0829186$ cm in the crystal and peak intensity $= 2.9 \times 10^6$ W/cm$^2$ (see pump laser.nb).

For good mode matching between the green and red light, the focal length of the lenses/mirrors for the red should be as close as possible to the pump lens focal length. Changing the intercavity lenses to mirrors helps accomplish this goal: mirrors can be selected which reflect the red and transmit the green, so the pump lens can be positioned very close behind the curved mirror, allowing ~2 cm for the optical mounts and some clearance. Looking ahead, the most likely candidate lens is Newport KPA028: EFL=18 cm, BFL = 11.2 cm. This just leaves room for a $f = 10$ cm curved mirror.
The two curved mirrors for the red in the cavity should be identical for symmetry of the mode through the gain crystal: $f_1 = f_2$.

The beam passes through following components in 1 round trip:

- Output Coupler
- Curved Mirror
- Crystal
- Curved mirror
- Prism 1
- Prism 2
- High Reflector

with spaces in between each. However, the prisms do not have any focusing power, they merely change the angle of the beam, so the distances before, between, and after the prisms can be combined into one for the purposes of cavity stability analysis.

The output coupler, as shown in Figure 6, should be beyond the gain arm in order to be near the edge of the laser box. So a reasonable minimum value for $d_1$ is $\sim 20$ cm. Distance $d_4$ must be at least 61 cm (prism separation) plus enough distance ($\sim 20$ cm)
to clear the gain arm and a few cm between the second prism and the output coupler. So a reasonable minimum $d_4$ is about 85 cm. We have $d_2 \sim d_3 \sim 10$ cm, and the total cavity length = 187.5 cm. So $d_1$ can vary between about 20 cm and $187.5 - 20 - 85 = 82.5$ cm.

In modelocked operation the intensity of the laser in the crystal causes Kerr lensing. Typical powers support a Kerr lens of effective focal length $\sim 1250$ cm (see pump len.nb for details).

Shown below is the stability condition of the cavity for two different ranges of $d_1$ and $d_2$ (from modelocked.nb).

**Figure 8** Stability of oscillator cavity for modelocked operation

**Figure 9** stability of cavity for modelocked operation

For modelocked operation, the laser should be operated at the edge of the stability region. This is so that the cw mode still lases but its power and stability are compromised, allowing the laser to operate preferentially in the modelocked regime. The details of
preferential gain for modelocked operation are quite complicated and will not be addressed here.

Any value of $d_1$ within the above-specified range will work, and does not affect the layout except for the value of $d_2$ that is needed to operate at the edge of the stability region, where $(A+D)/2 = 1$. The stability condition for $d_1 = 75$ cm is shown below.

![Figure 10 Stability condition for fixed $d_1=75$ as a function of $d_2$ (curved mirror to crystal spacing)](image)

**Optics to use in the system**

For the high reflector and any fold mirrors, we will use Newport 05D20-BD.2 (1/2”) or 10D20-BD.2 (1”), both lambda/10 for 800 nm.

Find or special-order BK7 prisms or substitute 2x Newport 06SB10, fused silica prisms ($365 ea$).

Output coupler: Newport 05B20-01OC.20 10% output coupler, ½” ($255$).

Pump laser lens: Newport KPA028: EFL=18 cm, BFL = 11.2 cm.

The pump laser lens leads to the condition that $d_0$, the lens-to-crystal spacing, becomes 11.2 cm. The curved mirrors for the red do not require additional consideration. The optical path length through the Ti:sapphire crystal is, to first order, $0.475 \times 1.76 = 0.836$ cm. So $d_1, d_2 \rightarrow 9.8195$ cm.

**Finite Optics**

In order to have a nice Gaussian mode out of the laser, we want the aperture stop to be the gain region in the crystal. That is, the beam waist of the red light will match that of the green pump beam in the crystal, and all other optics need to be large enough to accommodate the resulting Gaussian beam.

The beam waist size at various optics is found by tracing the waist ray and divergence ray through the system. Beam size at optics (from Excel worksheets Daisy’s \_ray \_tracer2” and “osc beam”):
<table>
<thead>
<tr>
<th>Component</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal</td>
<td>0.001173 cm</td>
</tr>
<tr>
<td>Curved mirrors</td>
<td>0.2171654 cm</td>
</tr>
<tr>
<td>Prism 1</td>
<td>0.00235 cm</td>
</tr>
<tr>
<td>Prism 1</td>
<td>0.00951 cm</td>
</tr>
<tr>
<td>High Reflector</td>
<td>0.0108 cm</td>
</tr>
<tr>
<td>Output Coupler</td>
<td>0.208375 cm</td>
</tr>
</tbody>
</table>

The beam has a waist at both the high reflector and the output coupler, as we would expect for a stable cavity. The exit pupil of the system is the beam waist at the output coupler, with a diameter of ~ 0.416 cm.

The beam is laterally dispersed by wavelength at the second prism and high reflector by an additional 0.03 cm (Excel worksheet “osc beam”). The Newport 06SB10 prisms, with their 15 mm aperture, are sufficiently large. The ½” diameter mirrors are also large enough for the beam (> 2x the beam diameter) at all points inside the cavity.

Finally, to create a more compact design, we can add a fold mirror between the gain arm and the prisms:
Final dimensions of the system:

d0, pump beam lens to center of crystal: 11.2 cm

d1, Output coupler to curved mirror: 75 cm

d2 curved mirror to center of crystal: 9.82 cm

d3: 9.82 cm

d4: 92.5

α, deviation angle of the prisms = 47.14°

prism separation = 61 cm

prism 2 to high reflector and prism 1 to curved mirror add up to 31.5 cm, exact division can be user-determined for convenience.

References
1. P.F. Moulton, Spectroscopic and laser characteristics of Ti:Al₂O₃, JOSA B 3 1, 1986.