Optics Tips and Tricks

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This appendix is meant to be a primer to working with lasers and optics, and specifically different ways of aligning laser beams with optics. These practical skills are crucial to building an atomic physics experiment, but they are taught almost exclusively in labs through direct mentoring by more experienced grad students and advisors, and honed through hours of slaving over the setup. As one of Bryce's first students, I didn't have older grad students or postdocs to ask and Bryce wasn't always around to consult. Sometimes I felt like some outside resource would have helped immensely when I was floundering around, and hopefully this will provide that resource to someone else. (The caveat, though, is that the audience of the appendix of a thesis like this is infinitesimally small, and it's very likely that this has already been done... and I couldn't find it.)

To make this section easier to explain, I'll define the axes of a laser system: **the $\hat{z}$ axis points along the direction of laser propagation**, so the $\hat{x}$-$\hat{y}$ plane is perpendicular to that (cross-section of the laser beam).

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I. LASER BASICS: DON'T LOOK AT THE BEAM

Laser safety can be summed up into one rule: **never look at a laser** (don't shine a laser into an eye). This seems like the most obvious thing, but I and other people very often accidentally skirt this number one rule, because there are so many ways eyes can contact laser beams. Some sub-rules that cover most of the safety are:

- **Wear laser goggles** (of the right wavelength/optical density).
- **Don't put optics at eye level**. **Don't put eyes at laser level**.
- **Keep track of (block) stray reflections**. Look for stray reflections (using a IR camera for near-IR beams) and block high powered ones. Build an enclosure.
- **Be careful when placing optics**. Don't angle optics when you place them. Put them straight down, so that a beam can't deflect vertically into an eye.
- **Look away from the laser/table** when bending down to pick things off the ground.

II. ALIGNING A BEAM TO A STRAIGHT LINE

This is a basic technique for steering laser beams using the core concept of laser alignment: **"near" and "far" points**. Some applications include making a beam parallel to the table as a first step for coupling into an AOM/fiber, or directing a trapping beam along an exact path through the center of a cell. This is documented pretty well by various optics companies like EdmundOptics: `https://www.edmundoptics.com/resources/application-notes/lasers/simplifying-laser-alignment/`.

A (collimated) laser beam propagating along a straight line can be steered to any angle and position with two mirrors on kinematic mounts that can tilt the mirrors vertically and horizontally (Newport Suprema is #1). The setup to steer a beam is shown in Fig. 1: a laser hits two mirrors on 2-axis mounts (labeled near and far), and we measure the position of the beam at two corresponding reference points (also labeled near and far) after the mirrors.

The near and far mirrors control the position and angle of the resultant laser beam, respectively. To best measure the angle of the beam, we look far downstream at the "far"

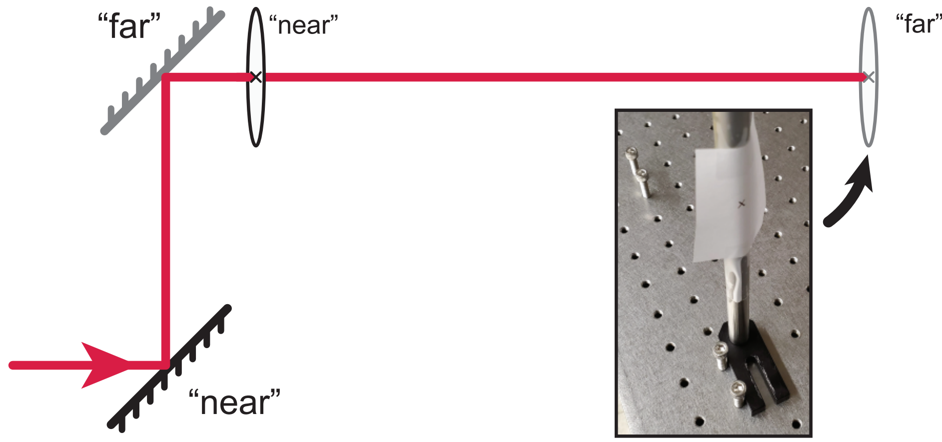

FIG. 1. Setup to align a laser. Two “near” and “far” mirrors direct the position and angle of an incident beam, which can be measured on targets placed at two “near/far” positions after the mirrors. Inset: an example of a stable laser beam target.

reference point as we adjust the “far” mirror. And to look at the beam position, we look as close as possible to the mirrors, hence the choice of the “near” mirror to align to the “near” point. Then, the alignment procedure is quite simple: **use the near mirror to align to a target at the near point, then use the far mirror to a target the far point, and iterate until the beam is aligned to both targets**.

Some notes on this procedure:

- It is important to identify the correct “near” and “far” mirrors and reference points, as if this procedure is performed with the wrong pairs of mirrors/reference points, the beam will become more and more misaligned.

- Place the mirrors at 45° to the beam to get the most range of motion.

- The near reference point should be as close to the mirrors as possible, and the far reference point as far downstream as possible.

- The **target** needs to stably define the desired position of the beam. Vertically, this is easy: just tape a piece of paper to a long post and make a dot at the desired height. Horizontally, it’s a bit more challenging, but it can be done by taping a marked paper onto a post attached to a clamp, and using the holes on the optical table to define two positions (see Fig. 1, inset).

To be a little more descriptive about the procedure, we can take the limit where the distance between the two mirrors is infinite. Then, by tilting the “near” mirror, it effectively changes only the position of the beam by the time it reaches the second mirror. And the “far” mirror changes only the angle of the resulting beam. To match these two degrees of freedom to our desired line, we look at the angle of the beam far downstream at the far reference point, and look at the position of the beam at the near reference point. In reality, though, the angle and position are coupled together so we need to continually iterate between the two mirrors and reference points.

III. ALIGNING A BEAM ON TOP OF ANOTHER BEAM

Aligning two beams on top of each other is the same as aligning a beam to a straight line, since one beam defines the line for the other. However, it may be challenging to identify the near/far points when the beams are counterpropagating. In the next section, I’ll discuss coupling a laser beam into an optical fiber, but the first step of that process is to shine a fiber pen back through the optical fiber. The incoming laser must be aligned to counter-propagate with the fiber pen output from the fiber, thus allowing the laser to enter the fiber.

As shown in Fig. 2, these setups are usually compact. Choosing the usual near/far reference points after the two mirrors (as in the previous section) would only give an inch or two of room between the points, making the alignment very tedious with lots of iteration. Instead, as shown in Fig. 2(a), we can choose reference points on either side of the mirrors.

The “near” reference point is chosen like usual, and we can align the incoming red beam to the fiber pen spot at this point (black vertical line). For the far point, however, we can instead align the orange fiber pen output to the incoming red beam in front of the “near” mirror (gray vertical line). This is like choosing the “near” point if we look at the situation in reverse (aligning the orange to the red). Iterating between these two points with their corresponding mirrors eventually overlaps the beams.

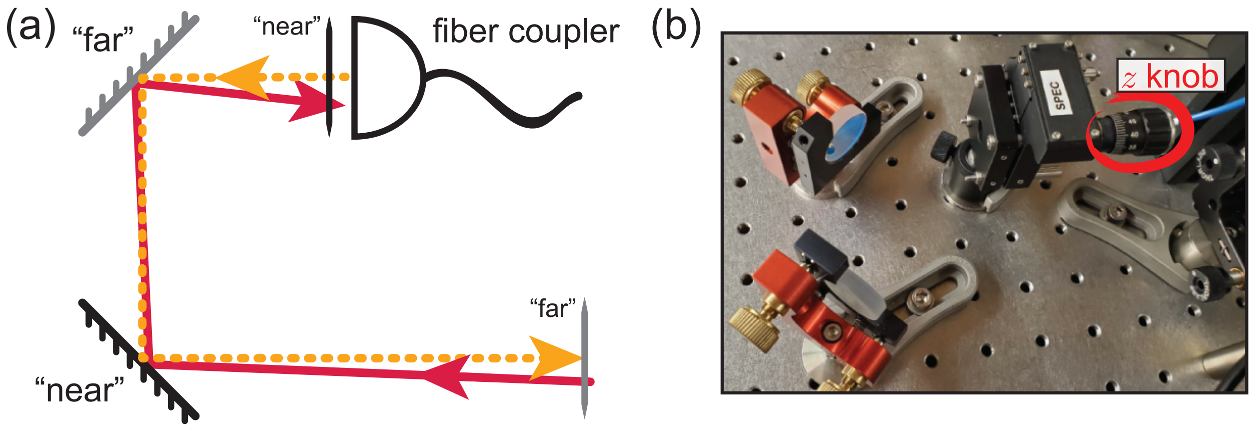

FIG. 2. Fiber coupling. (a) First step: aligning an incoming laser beam (red) to the output of a fiber pen (orange, dotted) from a fiber coupler. Two near/far mirrors (black, gray) are tuned to overlap beams at two near/far reference points (black, gray vertical lines). (b) A setup in the experiment. An aspheric lens focuses the incoming beam onto the fiber held in a z-axis mount.

IV. FIBER COUPLING

We use optical fibers extensively to split the laser system into an input beam generation side and an output science side. This way, drifts in laser alignment (due to heating up mirrors, bumping optics, etc.) on the input side do not affect the highly sensitive alignment of beams onto the atoms on the output side, only changing the overall beam power. However, this means that there is a lot of coupling laser beams into optical fibers.

To start, we need to gather the equipment. As with any beam steering, we need two mirrors on 2-axis kinematic mounts, and of course need an optical fiber. We buy (pre-clad) polarization-maintaining FC/APC to FC/APC fibers of our desired wavelength from Thorlabs (e.g., P3-780PM-FC-5). We need a fiber adapter for this (SM1FCA), an aspheric (no spherical aberrations) lens with a small focal length (A375TM), and a z-axis mount that can control the distance between the lens and fiber adapter (SM1Z). Along with some cage hardware, the typical fiber coupling setup looks like Fig. 2(b).

The idea is to match the mode of the laser beam with the mode that the fiber accepts, meaning that the angle and position of the laser must be exactly right (the two mirrors), and the asphere must be positioned exactly to focus the light into the fiber (z-axis mount). As a first pass, we roughly place the mirrors such that the laser hits the center of the fiber coupler straight on (not at a large angle).

Since our goal is to mode match, we look at the mode of the fiber by shining light back through the fiber. We hook up a "fiber pen" (visual fault locator like OVF-1), a low powered handheld laser with a fiber input, to the fiber in reverse. We roughly get the position of the asphere correct by moving the asphere and twisting the z knob on the z-axis mount until the fiber pen output is collimated. Next, we align this fiber pen output with the incoming laser beam that we want to fiber couple, as described in the previous section. This rough alignment ensures that at least some of the incoming laser is matched to the fiber mode, giving some light through the fiber.

For fine alignment, we look at the power going through the fiber as we "walk" corresponding pairs of knobs (horizontal/horizontal, vertical/vertical, z-knob/horizontal or z-knob/vertical) on the mirror mounts. We are trying to find a global maximum in the output power in the 2D parameter space of the two knobs (call them 1 and 2). In practice, this means maximizing the power with knob 1 at different values of knob 2, following the procedure:

- Maximize power by twisting knob 1.
- Twist knob 2 a little.
- Maximize power by twisting knob 1.
- If the power here is larger than at the previous knob 2 position, repeat steps 2-3. If it's smaller, twist knob 2 in the other direction and repeat step 3. Practice can make this go very quickly.

Eventually, this gets you pretty close to the maximum power with these two knobs. We do this with pairs of horizontal knobs and pairs of vertical knobs, and with the z knob and some of the other knobs. By iterating on many pairs of knobs, eventually we get to the global maximum of the 5D (!!!) parameter space.

For collimated, gaussian beams, we typically get around 70-80% fiber coupling efficiency (output power from fiber/input power). For more non-ideal beams (e.g., a weird mode from a tapered amplifier), 50% is pretty good. Sometimes long-focal-length cylindrical and spherical lenses placed before the asphere can increase the efficiency with better mode matching.

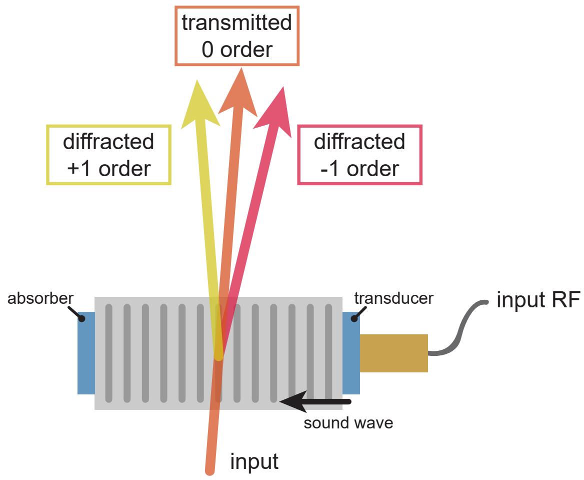

FIG. 3. AOM inner workings. A transducer shakes a crystal within the AOM at the specified radio frequency (RF), generating a sound wave. Input laser light undergoes Bragg diffraction into several orders, where the diffraction efficiency is controlled by the input beam alignment (Bragg angle) and the RF power. Tuning the frequency changes the diffraction angle. Adapted from RP Photonics [1].

V. ALIGNING AN ACOUSTO-OPTIC MODULATOR

In an acousto-optic modulator (AOM), a crystal vibrates at some input radio frequency (RF), Bragg diffracting incoming laser light. By tuning the power and frequency of the input RF (with a variable voltage attenuator), we can use AOMs to tune laser powers and frequencies to the kHz level. The output power from an AOM is primarily in a few orders (Bragg regime), and we typically choose the $+1$ (a frequency shift of $+1 \times$ input RF) or -1 order for highest diffraction efficiency.

As shown in Fig. 3, which side the RF connects to the AOM determines where the orders come out. A piezoelectric transducer inside the case converts the RF into a sound wave traveling from the RF connection to the other side of the AOM (leftwards in the figure). By momentum conservation, the diffracted order which gains a $+1$ kick must then diffract in that same direction (leftwards).

Maximizing the power in the desired diffraction order is usually straightforward:

- Mount an AOM to a 2-axis mount and fix it at the height of the incoming beam.

- Attach the AOM to some RF source, and *then*, checking the RF power against the maximum allowed power for the AOM, turn on the RF source. Tune to the desired frequency.
- Make the beam parallel to the optical table (see Section II), and direct it into the AOM. While it is better to have two mirrors in front of the AOM, we regularly only use one since the alignment is not that sensitive.
- Placing a card (Thorlabs:VRC5) behind the AOM, move the AOM around side to side (transverse to the beam), rotating it at each position, until the power in the desired order looks maximized. Clamp down the AOM.
- Adjust the input RF power to maximize the diffraction efficiency.
- (Optional) Place a half-wave plate in front of the AOM and vary its angle to maximize the diffraction efficiency.

This coarse alignment is sometimes sufficient, since our eyes are very good at measuring how bright a beam looks on a card. For fine alignment, measure the power in the desired order while adjusting the horizontal/vertical tilt of the AOM mount and the incoming beam alignment.

VI. ALIGNING A DOUBLE PASS AOM

Tuning the frequency of an AOM changes the angle of the output beams, changing the alignment of the laser downstream and ruining fiber coupling. To get around this, we can use a **double-pass** AOM setup, also called a cat's eye configuration, which allows the frequency of the resulting beam to be tuned without losing power/diffraction efficiency [2].

This setup, shown in Fig. 4, bounces the diffracted +1 order back into the AOM to get twice the frequency change for a net output +2. Two passes through a quarter-wave plate ($\lambda/4$) changes the polarization of the retroreflected beam, allowing us to separate the input beam and the output beam with a polarizing beam splitter (PBS). The key here is a lens placed one focal length away from the AOM (specifically, where the RF is injected into the crystal) and one focal length away from a mirror, in a "cat's eye" configuration.

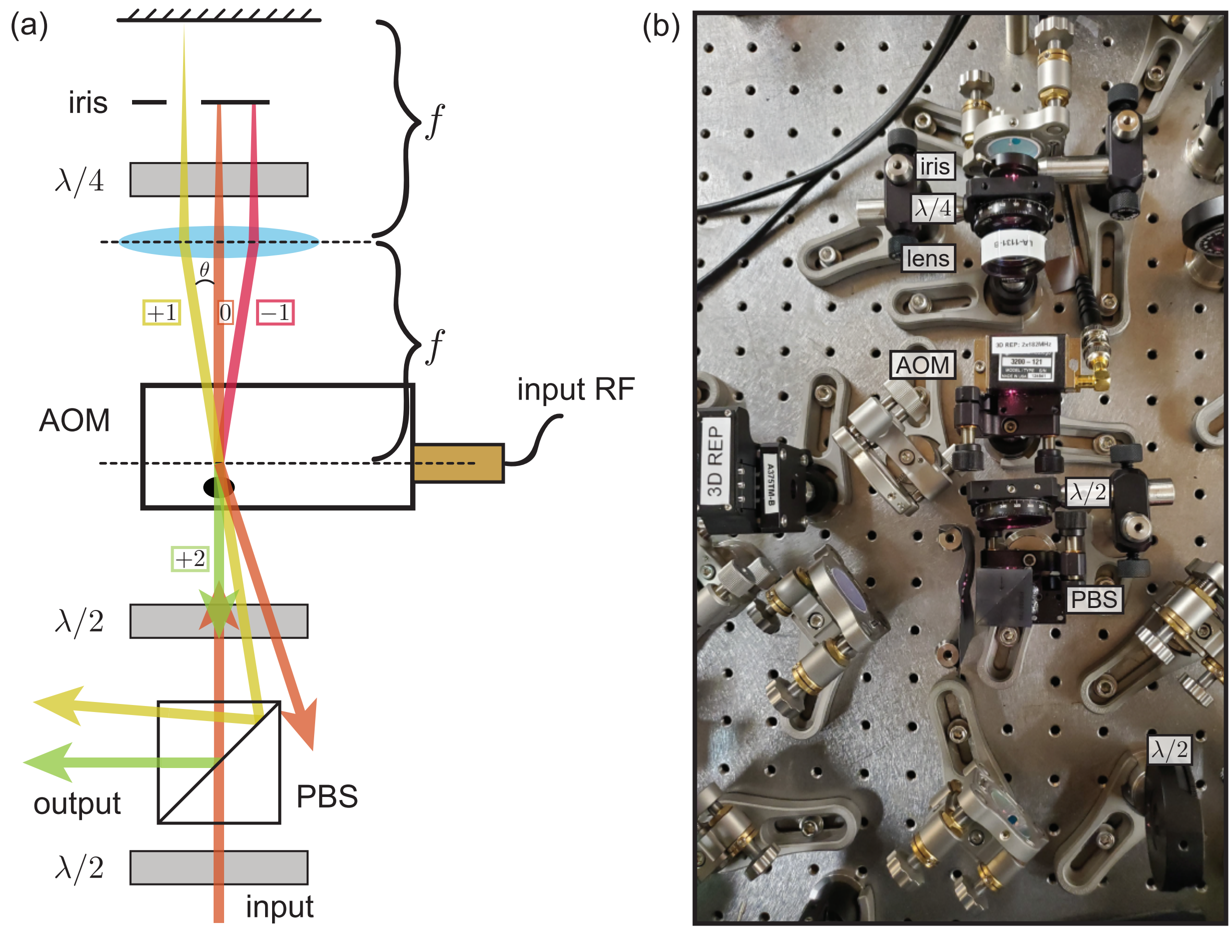

FIG. 4. Double-pass AOM for laser frequency tuning: (a) schematic and (b) real setup. An AOM is placed one focal length away from a lens, which is one focal length away from a mirror. An iris cuts off all orders except +1 (can also be −1), and a quarter-wave plate ($\lambda/4$) makes the polarization of the reflected output orthogonal to the input. Tuning the frequency changes the diffraction angle θ, but does not affect the alignment or power of the retro-reflected beam.

The diffraction orders (three are shown here: 0 and ±1) come out of the AOM at an angle θ which depends on the frequency input to the AOM. The lens placed f away catches these orders, making them go straight. We block off the undesired orders with an iris. However, because each individual order was collimated to begin with, the lens causes the beams to focus. We place a mirror at the focus of this lens (f away), such that the +1 order hitting the mirror retraces its path, expanding back to the lens where it is once again collimated. By adjusting the tilt of the mirror, we can direct the reflected beam to go back into the AOM and diffract again. I've shown again the −1, 0, and +1 orders of the second pass, where the beam that gets another +1 kick is now overall shifted by +2 orders and retraces the path of the input beam (green, downward arrow). By tuning the angle of the quarter-wave plate, we can change the polarization of the +2 output to be orthogonal to the input polarization, reflecting from the PBS towards a fiber coupling setup.

To set this up, first construct a single-pass AOM setup as described in the previous section, but with a half-wave plate and PBS in front to catch the double-pass output. Next, place a *convex* lens ($f = 50$ mm is a good choice) around f away from the *RF input* of the AOM (shown in the figure with a dashed line). This is where the RF is injected and shakes the crystal, and where the diffracted orders are generated. To be more precise, we want to move the lens longitudinally until the orders stop spreading apart from each other. Place a card downstream and, looking at the separation *between the centers* of the orders, move the lens until the separation matches the separation immediately after the lens. Since the beams are not collimated, this may be challenging to measure far downstream. Make sure to center the 0 order on the lens!

Make room for the quarter-wave plate, but don't put it in yet. The iris should be very well centered on the desired order (+1 in the figure, but can also be −1), such that no light goes through if we switch off the RF power to the AOM. The mirror should be placed at the focus of the beam, and tilted until the beam goes back through the iris and through the AOM, producing diffraction on the other side. Place the quarter-wave plate in and rotate it until the output beam is fully reflected by the PBS. Determine which order is the +2 (vs. +1 or +3) by varying the frequency input to the AOM. If the lens was positioned correctly (f from the AOM), **the +2 order should be stationary**. Maximize the output power by tuning the mirror mount knobs, and the AOM mount knobs: the AOM alignment for highest single-pass diffraction efficiency may be different from the alignment for highest double-pass efficiency. Finally, a half-wave plate can be placed immediately before the AOM to improve the signal. Iterate between the angles of this half-wave plate and the quarter-wave plate.

VII. ALIGNING A TAPERED AMPLIFIER

Tapered amplifiers (TAs) house some lasing medium that, when powered, can amplify some incoming 30 mW of light into 1 W or more. These are indispensible in our laser

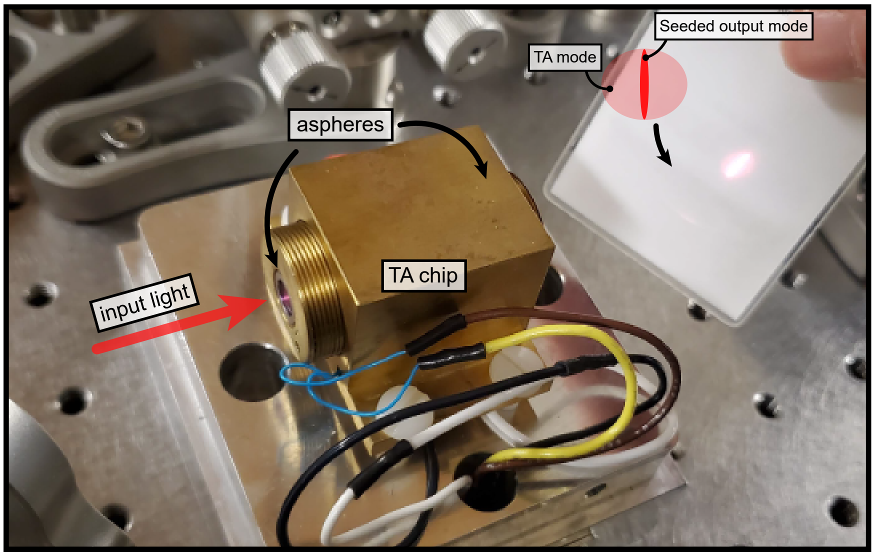

FIG. 5. A fully-aligned tapered amplifier. Two aspheric lenses focus the input seed beam and collimate the output. On the card is the desired output of a bright line inside the larger TA mode. Not shown are a half-wave plate before the TA to change the input polarization, a Faraday isolator after the output, and cylindrical lenses to shape the elliptical output.

system, but they are notoriously hard to align... and output some BAD looking modes. Aside from the few Thorlabs TAs that we bought before they were discontinued, our TAs are all designed in-house: we buy the chips online (e.g., Eagleyard 765 nm 1.5 W TA), but the housing is done by the folks down at the MRL machine shop.

Before aligning a TA, we must take great care not to destroy it. Make sure no reflections go back into the TA on the output side: use Faraday isolators and skew all optics a little (don't put them directly perpendicular to the beam). Do not drive the TA at high current without any seed light going in, and do not seed the TA without supplying some current to the chip.

So, the TA chip must be wired up to both a current and temperature controller, with the current controller set to some nonzero value (typically $\sim$500 mA). Then, let roughly 30-35 mW of input seeding light into the TA. The TA, shown in Fig. 5, has a chip/lasing medium that must be focused into with an aspheric lens, and whose output is collimated with another aspheric lens. Not shown here is a half-wave plate which adjusts the (linear) polarization of the input light. The TA outputs a mode which is low power and spatially large, even without any seeding/input light. The goal here is to see the input light "seed" the TA, appearing as a bright line/dot within this larger TA mode (Fig. 5b).

To do so, we need to very finely couple the input light into the TA with two mirrors. After roughly mounting the two lenses into the holder, we align the two mirrors to go in a straight line through the center of the two lenses (following Sec. II). This is challenging and must be done very precisely, ideally with a knife-edge card (a card cut in half). Simultaneously, we should monitor the output of the TA, looking for the telltale bright line. After the initial seeding is complete, we can iterate on the longitudinal (z) position of the input asphere and the input polarization (vs. the input beam alignment) until the output power is maximized.

To shape the output beam, we need several (3) cylindrical lenses while looking at the TA output far, far downstream. Because the TA outputs are often line-shaped (elliptical), the horizontal and vertical axes of the output spread out at different rates. The output asphere on the TA should be adjusted until the beam is collimated in one axis far downstream, while an external cylindrical lens should collimate the other axis. To make the beam look gaussian again, we then use a cylindrical telescope (two cylindrical lenses) to shrink the longer dimension of the beam to the size of the shorter dimension.

This can all be modeled using various gaussian beam propagation programs (matrices in Mathematica, Zemax, etc.) to determine exact lens focal lengths and positions, after measuring beam widths at different locations. However, the TA output may be absolutely terrible: it may look like one elliptical beam, but comprised of many, many individual "lines" which all spread at different rates. This scenario has happened when we seed one TA with the output of another TA, leading to nonsensical results when we place the expected lenses in the expected locations. In this case, we place the lenses and shape the beam along the two axes empirically.

VIII. CLEANING OPTICS

Optics (lenses, mirrors, beam splitters...) are often covered in dust and occasional fingerprints, and it's important to keep them clean to prevent stray reflections and keep up performance. There are many techniques that are documented online through optics companies, but this is what I do:

1. FIRST, use compressed air to blow off any large debris/dust from the optic.
2. Use methanol/solvent with lens tissue to clean the optic. (Newport says 60% acetone + 40% methanol)
3. Repeat with methanol if it's still dirty.

There are different ways to use methanol to clean an optic:

1. **Drop and Drag**: Lay the lens tissue on top of the optic, put a few drops of methanol on top, and drag the wet part of the tissue across the entire optic. This works well if the optic is unmounted and the surface is flat. If any residue remains, you've put on too much methanol.
2. **Brush**: Wad up some lens tissue and grab it with forceps, without touching the part of the tissue that will contact the optic. Drop some methanol on the tissue. Wipe from the center towards the outside, and don't touch the optic twice with the same part of the tissue. This way, you don't drag dust across the entire optic and create a scratch.

Ideally, this should all be done above some lens tissue and directly above a table so the optic doesn't get dirty or damaged if you happen to drop it. Gloves are recommended, but not by me.

IX. TIGHTENING POSTS

Optics placed in mounts must be extremely secure, and failing to tighten one part of one mount can cause instability in alignment, laser power, and fiber coupling efficiency. The rule of thumb is: **tighten with an allen wrench or a long lever arm**, because a hex screwdriver can't tighten nearly enough. This should apply to all connections except thumb screws and a few other uncommon cases.

As an example, Fig. 6 shows a mirror in a mount, with many connections that should all be tightened with allen wrenches. In order, the connections to tighten are:

1. ½" post to optics holder.
2. Mirror inside optics holder. (1" retaining ring)

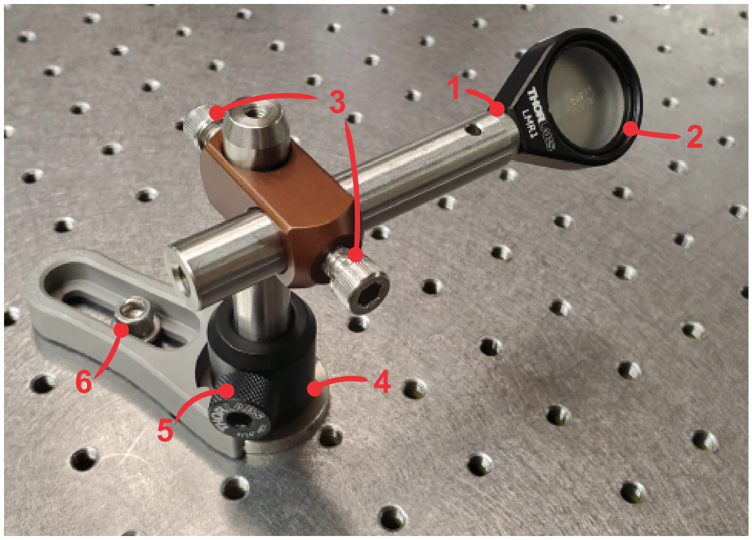

FIG. 6. An example of tightening optics mounts. Numbers indicate connections to tighten in order. See text for details.

3. 1/2” post to 90 degree angle adapter. (x2)

4. 1/2” post holder to post holder base. (try using a lever arm in the thumb screw hole for leverage)

5. 1/2” post holder to 1/2” post. (thumb screws are fragile - don’t tighten too much)

6. Post holder base to table with fork clamp.

In very small spaces, I sometimes resort to the *forbidden technique*: a vise-grip around an Allen wrench can give more leverage, but at the risk of flying apart and damaging optics.

[1] R. Paschotta, “Acousto-optic modulators,” (2019), accessed: 2019-09-29.

[2] E. A. Donley, T. P. Heavner, F. Levi, M. O. Tataw, and S. R. Jefferts, Review of Scientific Instruments **76**, 063112 (2005), https://doi.org/10.1063/1.1930095.