Assembly and alignment guide for NicoLase - An open-source diode laser combiner, fiber launch, and sequencing controller for fluorescence microscopy

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1 Introduction

Combining multiple laser sources into a single beam then combining these beams into a single-mode fiber is not a trivial task. Of all the operations involved in constructing a fluorescence microscope, this may well be the one that takes the most patience and care.

When aligning your laser launch, do not rush. This is not something to attempt late on a Friday afternoon in a free hour before heading to the pub. This is a task involving a great amount of precision and small, careful movements. There will be very little in the way of positive results until the task is nearly complete. Set aside up to a several hours to complete the alignment, especially on your first try.

You will require the components for the laser launch and assembly tools (metric hex drivers and at least a ruler). In addition you'll need a laser power meter, fiber exit collimator, and a few extra clamps or mounts to hold these in place. The power meter can be one of many different models from Thorlabs, Newport, or other makers. It needs to be able to measure CW lasers over the visible range up to a few hundred milliwatts. A compact sensor such as the Thorlabs S130C or Newport 818 or 918 wand probes make it easy to get a reading inside the tight spaces in the NicoLase design. The exit collimator can be of any type or in the equipment the fiber exit will be coupled to as long as you have access at the exit for the power meter head. This is the only equipment used when implementing the NicoLase designs described in the manuscript, but a few optional tools can make this job easier.

An additional fiber-coupled laser is optional but very useful. This can be of any type with an FC/PC or FC/APC male terminal on the exit side of the fiber (or a female FC terminal + the SM fiber we will be using). Small pointer-type lasers made for testing fiber optics are available for ~$50 from a variety of sources. A red (~640 nm) laser is the best choice for help in aligning the beams here and assumed in the instructions here.

A spare multimode fiber will make finding the initial alignment much easier. Core size can be 25 to 250 μm. A larger-core fiber will be easier to couple but may result in more alignment time with the single-mode fiber. A 50 μm core size is a good compromise and a patch cable in this size with FC/PC connectors is available from Thorlabs for $67 (M42L02).

Finally, A spare camera or fiber-coupled photodetector is also useful in the initial stages of fiber coupling. Inexpensive sCMOS USB cameras such as the Point Grey Blackfly with Sony IMX249 chip is a good choice for this (and for routine fluorescence imaging) and list price is less than $500. The camera will be more sensitive to low signal than a power meter. When trying to get the first bit of light coupled into the fiber the camera can see the low levels at the exit before the power meter can register the signal. Once the signal is sufficient that the camera is saturated, the power meter can take over.

The diode lasers that are compatible with NicoLase design are almost always Class 3R or Class 3B. Consult the laser documentation for an indication of the safety classification for your specific units. In any case, it is recommended to have laser safety goggles on hand to prevent accident laser exposure to your or others eyes, especially those who may not have worked near lasers in the past. These lasers are sufficiently powerful to cause permanent damage to eyes and the appropriate precautions should be taken. Consult your institution's laser safety personnel if you are unsure of how to proceed with regards to laser safety.

2 Assembly

2.1 1500 assembly

Begin by securing the breadboard into its final position on the table or optical bench. The breadboard mounting holes are not immediately accessible after the lasers have been affixed to the heat sink block.

The heat sink block can now be affixed to the breadboard using M6 screws. If your heat sink was manufactured along with a shim, be sure that goes between the heat sink block and the breadboard at this step. The 1500 heat sink block can fit with one row of holes between the long side of the heat sink block and the long side of the breadboard, then with the short side of the block screwed into the first set of holes on one side (right or left is arbitrary).

Be sure that the top of the heat sink block is clean and free of extraneous dust and oil. Do the same for the bottom of the laser diode units. A Kimwipe and some ethanol is good to give a final clean-up wipe of these surfaces. This will encourage a good transfer of heat between the heat sink block and the laser diode. DO NOT apply heat transfer paste or any other compound to this interface as these are unnecessary and can off-gas onto your optics.

You can now mount the laser diodes to the heat sink block using the screws provided by the laser manufacturer. Lasers should be arranged from short to long wavelength when moving away from the fiber coupler. If you are using Vortran Stradus lasers and the 3D printed excitation filter holders you should thread the front laser mounting screws through the associated filter mount when installing a laser unit. You can install the filter itself at a later time.

Assemble the fiber coupler (Thorlabs PAFA-X-4-A) and mount (Thorlabs HCP with custom fiber launch pedestal). The mount needs to be bolted to the pedestal with an M4 screw first then the fiber coupler to the HCP mount. I prefer to mount the coupler 'backwards' on the mount as this is more compact (See manuscript Figure 1). Be sure to orient the fiber coupler so that the X and Y adjustment screws are accessible in this configuration. Position the fiber coupler and mount at the corner of the breadboard opposite the longest wavelength laser diode, roughly centered over the breadboard mounting bolt in that corner. Affix to the fiber lanch to the breadboard with a clamping fork (a Thorlabs CL8 may be easier to squeeze onto the short pedestal). The face of the mount should be as close to perpendicular to the front edge of the heat sink mount as you can get it. The axis through the center of the fiber coupler lens defines the path of the combined beam.

If you have a separate pigtailed laser, plug that into the fiber coupler now. When you switch this laser on you should get a clear collimated beam projecting straight out of the fiber coupler. This beam will propagate in the opposite direction of the beams we wish to align, but along the same path. This beam can be used to reference the central axis of the fiber coupler lens. If you do not have an additional pigtailed laser available you can leave the fiber out at this point.

The 1500 design uses a single mirror per laser diode to steer the beam into the fiber coupler. These mirrors will relay the beam into the fiber coupler while also combining the multiple wavelengths into a single beam.

Start with a standard mirror (silver front-surface mirror, Thorlabs PF10-03-P01) in a 1", 3-adjuster mount (Thorlabs POLARIS-K1) mounted on a 12.5 mm tall 25 mm diameter pedestal (Thorlabs RS05P4M). The mirror mount should be oriented such that the side with two adjusters will be on the side farthest from the laser (See manuscript Figure 1, top right). Place this mirror in front of the longest wavelength laser diode (assuming 640 nm here) such that a 90°bend in the beam path from the laser will hit the position of the fiber launch. Clamp the mirror and post to the breadboard with a 25 mm clamping fork (Thorlabs CF038 or CF125) approximately in place.

Repeat the previous step for the other mirrors, but with the appropriate long-pass 25 mm round dichroic in each mount. Take care to observe the correct orientation of the dichroic. Filter orientation can vary by manufacturer, but thankfully for Semrock and Chroma dichroics the arrow will point towards the front surface, which should point towards the laser being reflected and the fiber coupler. Place each of these mount and mirrors onto the breadboard as the 640 nm mirror was oriented. You may need to adjust all of the mirrors a bit to get them all to fit in the space available. The goal is to have each centered in front of the respective laser aperture and also the fiber coupler lens axis. Once these are all in place, clamp them all down with clamping forks and proceed to Section 3.

2.2 2400 assembly

Begin by securing the breadboard into its final position on the table or optical bench. In this model you can move the breadboard after the heat sink block has been mounted, but it is still to start with the breadboard in the final location.

The 2400 block is designed to fit in the bottom left corner, if viewed from above. There is one through hole in the 2400 block which aligns with the bottom left breadboard mounting hole. Rotating the layout 180°around the center is also possible if you want your fiber outputs to point the opposite direction. See Figure 1 of the manuscript for layout orientation. If you manufactured your heat sink block with a shim, be sure that this goes between the heat sink block and the breadboard.

Be sure that the top of the heat sink block is clean and free of extraneous dust and oil. Do the same for the bottom of the laser diode units. A Kimwipe and some ethanol is good to give a final clean-up wipe of these surfaces. This will encourage a good transfer of heat between the heat sink block and the laser diode. DO NOT apply heat transfer paste or any other compound to this interface as these are unnecessary and can off-gas onto your optics.

You can now mount the laser diodes to the heat sink block using the screws provided by the laser manufacturer. Lasers should be arranged from short to long wavelength when moving away from the side of the board with the fiber coupler. If you are using Vortran Stradus lasers and the 3D printed excitation filter holders you should thread the front laser mounting screws through the associated filter mount when installing a laser unit.

Assemble the fiber coupler (Thorlabs PAFA-X-4-A) and mount (Thorlabs HCP with custom fiber launch pedestal). The mount needs to be bolted to the pedestal with an M4 screw first then the fiber coupler to the HCP mount. I prefer to mount the coupler 'backwards' on the mount as this is more compact (See manuscript Figure 1). Be sure to orient the fiber coupler so that the X and Y adjustment screws are accessible in this configuration. Position the fiber coupler and mount in the corner of the breadboard opposite the longest-wavelength laser diode. To fit the rear face of the mount should be in plane with the edge of the breadboard. Affix to the fiber lanch to the breadboard with a clamping fork (a Thorlabs CL8 may be easier to squeeze onto the short pedestal). The face of the mount should be as close to perpendicular to the front edge of the heat sink mount as you can get it. The axis through the center of the fiber coupler lens defines the path of the combined beam.

If you have a separate pigtailed laser, plug that into the fiber coupler now. When you switch this laser on you should get a clear collimated beam projecting straight out of the fiber coupler. This beam can be used to reference the central axis of the fiber coupler lens. If you do not have an additional pigtailed laser available you can leave the fiber out at this point.

The 2400 design uses two mirrors to steer each beam into the fiber coupler. Four of these mirrors, referred to as the 'combining mirrors', are along one long edge of the breadboard and combine the individual beams into a single multi-color beam along the fiber coupler axis. The other four mirrors, or the 'relay mirrors', reflect one beam onto a respective combining mirror.

Start with the combining mirrors. The first is a standard mirror (silver front-surface mirror, Thorlabs PF10-03-P01) in a 1", 2- or 3-adjuster mount (Thorlabs POLARIS-K1 or POLARIS-K1-2AH) mounted on a 12.5 mm tall 25 mm diameter pedestal (Thorlabs RS05P4M). The mirror mount should be oriented such that the side with the vertical adjuster will be on the side farthest from the laser (See manuscript Figure 1, bottom right). Place this mirror in the space left by the radiused corner of the heat sink block (see manuscript Figure 1, bottom left) and at a 45°angle to the axis of the fiber coupler, pointing back in the direction of the laser diodes. Clamp the mirror and post to the breadboard with a 25 mm clamping fork (Thorlabs CF038 or CF125).

Repeat the previous step for the other combining mirrors, but with the appropriate long-pass 25 mm round dichroic in each mount. Take care to observe the correct orientation of the dichroic. Filter orientation can vary by manufacturer, but thankfully for Semrock and Chroma dichroics the arrow will point towards the front surface, which should point towards the laser being reflected and the fiber coupler. Place each of these mount and mirrors onto the breadboard at a 45°angle to the fiber axis, again pointing back towards the direction of the laser diodes. You should aim to have these mirrors be almost touching in order to have enough space for the dual port adapter (Section 7). Clamp each mirror in place with a clamping fork.

Take four more 1" 2- or 3-adjuster mounts each with standard mirror on 12.5 mm pedestal (alternatively, these can be $\frac{1}{2}$" mounts and mirrors on 25 mm tall pedestals). These will be the relay mirrors. Place each of these centered in front of both a diode lasers aperture and the respective mirror placed in the previous step. Each should be oriented at 45°to the laser beam path so that the beam is reflected off the center of the reflecting mirror onto the respective combining mirror. The relay mirrors will be placed on the breadboard in a line 45°to the front edge of the heat sink mount, running from near the fiber coupler to the far front corner of the heat sink block, immediately in front of the 640 nm laser. Once these are all in place, clamp them all down with clamping forks and proceed to Section 3.

3 Initial alignment

The goal of the initial alignment is to get some light - any light - from each of the lasers through the fiber coupler and out the far end of the fiber. This is the most difficult step of the entire process as the entry aperture of the single-mode fiber is tiny. There will be zero light through the fiber until the process is nearly complete, which may take minutes or hours.

The alignment will be performed with a middle-wavelength laser (the 'reference beam'). This will be the primary laser for the remainder of the alignment and while the choice is arbitrary, the chromatic nature of the optics are such that it is best for this to be one of the laser units in the middle in the wavelength range. I used the 517 nm diode on the 1500 alignment and the 488 nm diode on the 2400 unit.

For alignment a few mW of laser emission is plenty to have the beam visible. Excess power will not improve alignment and does increase the chance of an injury due to a errant exposure. For convenience you can leave all beams active and use the built-in manual shutter to switch between which ones are visible during the alignment.

Both the initial and final alignment will involve many iterations of 'walking the beam'. This translates the beam without changing the outgoing angle using at least two adjusters. On the 2400, this is accomplished by using the same adjuster on two different mirrors, turning in opposite directions. On the 1500 the third (pitch + yaw) adjuster is turned, then the pitch and yaw adjusters each moved to result in the front of the mirror, and therefore the beam position, being translated. More information on this concept can be found in many places online, including an excellent description from SUNY Stonybrook (`http://laser.physics.sunysb.edu/~simone/mini-project/`).

3.1 If you have an additional pigtailed laser

Start by ensuring the front face of the fiber port is perpendicular to the long edge of the breadboard or, equivalently, that the back edge of the fiber mount is parallel to the short edge of the breadboard. On the 2400 The rear edge of the mount should be coplanar with the edge of the breadboard; on the 1500 the center of the mount should be coaxial with the breadboard mounting hole in that corner.

Turn on the counter-propagating pigtailed laser. Adjust the orientation of the fiber port so that the exiting counter-propagating beam is traveling parallel to the long edge of the breadboard. Adjust each of the combining mirrors so that this beam passes through the center of the front face of each mirror, finally hitting the last combining mirror. From the final mirror the beam should then be directed into the 640 nm laser aperture (on the 2400 it will need to hit the middle of the relay mirror first, then onto the laser aperture).

Turn on each of the diode lasers in turn. For each you want to overlap the spot made by the counter-propagating beam on the front face of the combining mirror with that from the diode laser beam, then have the diode beam aligned into the fiber coupling lens. On the 2400 this is done by first aligning the diode beam onto the spot in the center of the relay mirror, then onto the combining mirror. Then the combining mirror is primarily rotated, with possibly a small amount of translation perpendicular to the fiber lens axis, to align the diode beam into the fiber lens aperture. On the 1500 the relay lens is not present and these first operation is performed by moving the combining mirror along the fiber lens axis. The second operation is the same on both models. Fine adjustments can be made by walking the beam using the mirror adjusters. Repeat for each additional laser until all spots overlap on the front mirror faces and are aligned into the fiber lens aperture.

Once all beams are as close to co-aligned as you can get them in this manner, remove the pigtailed laser from the fiber coupler and proceed to Subsection 3.3.

3.2 If you do not have an additional laser

Start by ensuring the front face of the fiber port is perpendicular to the long edge of the breadboard or, equivalently, that the back edge of the fiber mount is parallel to the short edge of the breadboard. On the 2400 The rear edge of the mount should be coplanar with the edge of the breadboard; on the 1500 the center of the mount should be coaxial with the breadboard mounting hole in that corner.

Turn on the longest-wavelength laser. If using the 2400, adjust the relay mirror such that the beam is hitting the center of that mirror and the reflected beam travels parallel to the breadboard surface, hitting the center of the combining mirror. For both models, then adjust the combining mirror so that the beam travels along the fiber coupling lens axis, into the center of the coupling lens aperture. You should be able to visualize the beam exiting the coupling lens on a far screen.

While leaving this laser active repeat the same steps with the other lasers. On each combining mirror the reflected laser spot should overlap on the front face of the combining mirror with the longer-wavelength transmitted beams that are upstream. The reflected beam should be steered into the coupling lens and again through the other side, projecting onto a far screen or wall. The projections of the different color laser spots may not overlap perfectly but they should be centered relative to one another.

Once all beams are as close to co-aligned as you can get them in this manner, proceed to Subsection 3.3.

3.3 Common initial alignment

Note : If you have an optional multimode fiber, you can perform the initial alignment steps here with that fiber in place. Once light is coupled into that fiber, replace with the single-mode fiber and repeat this section. The multimode fiber will let you get very close to the proper alignment, allowing you to align the single-mode fiber more quickly.

Install the single-mode fiber on the coupling mount and the exit collimator on the far end of the fiber. Clamp the exit mount so that the exiting beam can be observed. If you have an alignment camera, aim the exit collimator at that and set the camera to a live acquisition where you can watch the image on a monitor. Set the camera intensity to not autoscale so you can observe the increase in intensity more easily. If you do not have an alignment camera set the exit collimator to project into the active area of the laser power meter and set the power meter console where you can observe the readout while you manipulate the NicoLase optics.

Activate only the reference beam laser. If you've been supremely lucky, there is now light coming out of the exit of the fiber. If so, congrats! Skip to Section 4.

Much more likely is there is no light out of the fiber. The only way any light would be coupled is if the beam is both centered and straight into the coupling lens. First double-check that the beam is as close to parallel to the breadboard surface as you can measure. Sweep the beam both laterally and vertically across the coupling lens aperture by adjusting the pitch and yaw adjusters on the combining mirror, watching for signal through the fiber. When this doesn't work, return the beam to the center of the coupling lens aperture, then walk the beam a small amount in one direction with the relay and combining mirror adjusters (2400) or the three combining mirror adjusters (1500). Which direction you choose is arbitrary as we will try them all until the coupling point is found. Sweep the beam again, watching the fiber exit for any emanating light.

Repeat the translating and sweeping steps until you get some light through the fiber exit. If you feel you have lost your way, remove the fiber from the coupler and observe the light from the fiber coupling lens projected on a far screen. It should be straight and centered. Then re-set the fiber and start the sweep and translate steps again.

The amount of light that exits the fiber can be minuscule (microwatts are good!) as long as *some* light makes it through. The remaining steps focus on increasing the throughput, but we have to start with a signal to optimize. Once you have even a very small amount of light coupled into the fiber, attempt to find the maximum throughput with one last sweeping step, then proceed to Section 4

4 Fiber coupler adjustment

The FiberPort is likely not optimized for your laser wavelength and fiber out of the box. We need to make fine adjustments to the fiber coupler to improve the coupling efficiency.

There are many screws on the FiberPort that can be adjusted (see Figure 1). The cyan arrows indicate the adjustment screws for axial adjustment and tilt of the fiber core relative to the coupling lens. These will be the primary focus of the coupler adjustment. The X and Y translation screws (indicated with green arrows) can be used to do fine-tuning of the lateral fiber core position. These should be used sparingly; the coupling mirrors are a better choice to adjust the lateral position of the beam if needed. There is no need to touch any of the other screws.

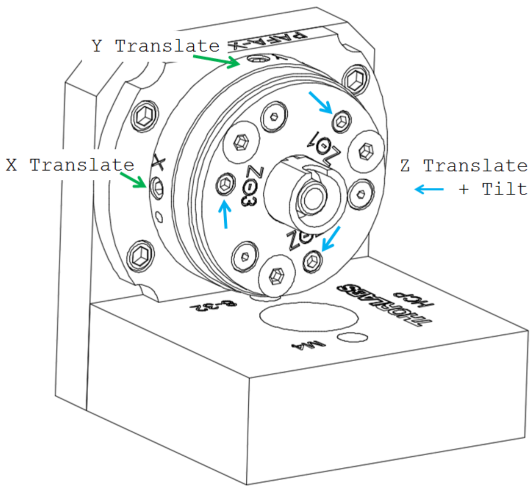

Figure 1: FiberPort adjustment screw locations. The FiberPort is installed on the HCP mount as indicated. Adjustments on the screws indicated will be used for alignment, with translation adjustments in green arrows and the axial and tilt adjustments in cyan arrows.

Begin by noting the power meter reading at the fiber exit (or intensity signal on the observing camera). Adjust one of the FiberPort Z tilt screws in an arbitrary direction about half a turn (it is best to always start and stop with the same screw for consistency). The power reading should go down. Adjust the next Z tilt screw the same magnitude in the same direction. Now turn the final Z tilt screw in the same direction while observing the power meter reading and adjust the screw to maximize. Work around the Z tilt screws again, giving fine adjustments to the first and second screws to further maximize the power meter reading.

Now - is this new level higher or lower than the starting level? If higher, proceed with another turn of the first screw in the same direction. If lower, proceed but with a turn in the opposite direction. Repeat the steps in the previous paragraph until you can no longer increase the reading at the fiber exit.

You can occasionally add in small adjustments to the lateral beam position. One option is the X and Y translate screws on the fiber coupler. These should be used carefully as they are very sensitive. Inserting or removing the hex key can be sufficient to alter the alignment. Otherwise you can try small adjustments of walking the beam at the coupling (and, if necessary, relay) mirrors. These will also be quite sensitive at this point, but the adjusters themselves are more stable.

At this point the power through the fiber should be higher than before. With any luck, you have aligned the coupling lens to the center of the optical fiber and have a reasonable coupling efficiency and hundreds of microwatts to milliwatts through the fiber. Once you are satisfied with the coupling efficiency of the reference beam (aim for $> 50\%$), you can proceed to Section 5.

There is the danger that the alignment thus far has been on a side lobe of the focused spot in the coupling lens rather than to the central beam. If you have optimized both the Z tilt screws and the lateral beam position but still cannot get more than a percent or so coupling efficiency you may have focused on one of these side lobes. If you are not sure, you probably have focused on a side lobe. Coupling the central portion of the beam is definitely a 'you'll know it when you see it' situation with a dramatic increase in fiber throughput in a small range of alignment adjustment.

Even focusing on a side lobe means that you are close to the proper alignment. The solution is to translate the beam to find the central lobe. Using the coupling mirror (and on the 2400, the relay mirror) walk the beam in an arbitrary direction to see if you can find the central portion of the beam. Most likely the adjustment will need to be laterally, rather than vertical. Once it is found, repeat this Section before moving on.

5 Align remaining beams

With the reference beam aligned and FiberPort adjusted, coupling the remaining beams should be more straightforward. Leave the reference beam active and then activate another one of the beams (here I will assume have chosen the 640 nm beam, but this is an arbitrary selection). Ensure that the 640 nm beam overlaps with the reference beam at the front face of every coupling mirror starting with the reference beam coupling mirror and moving downstream. If not, adjust the position of the 640 nm beam using the coupling mirror (and, on the 2400, the relay mirror) of the 640 nm beam ONLY. Do not adjust any of the downstream mirrors or any of the screws on the FiberPort.

You should again aim for some, if small, amount of light through the fiber with this new beam. You can watch the fiber exit for the new color coming through or toggle the reference beam and see if the second beam is coming through. Once you have a signal from the 640 nm beam through the fiber, turn off the reference beam. Change the wavelength setting on the power meter, if necessary, and optimize the coupling efficiency of the 640 nm beam using the mirror or mirrors for that beam only.

Repeat these steps for all of the lasers on your fiber launch. I find it best at this point to work from longest wavelength to shortest as the longest-wavelength laser can act as the reference for positioning all of the others. Once aligning all beams is complete, you should have a reasonable signal for each laser coming through the fiber. Proceed to Section 6

6 Final alignment adjustment

Prior to final adjustment of the beam path, install any desired excitation filters. Depending on the spectral quality of the beam from your lasers, this may or may not be required for all lines. We find that the 488-490 nm beams are particularly troublesome. If you choose to install excitation filters at a later date there may be a small amount of touch-up alignment required for that beam, equivalent to repeating the following steps.

Turn on the shortest-wavelength laser only and, if possible with your meter, measure the laser power entering the fiber coupling lens (*i.e.* between the last coupling lens and the FiberPort). Note this power. For easy calculation later you may choose to set it to a easy-to-divide value such as 10 mW.

Move the power meter to the exit of the fiber. Note the power at the fiber exit. Walk the beam in a chosen direction by using the tip+tilt adjuster on the coupling or adjuster pair on the relay lens and coupling lens, if on the 1500 or 2400, respectively. The best method here is to turn one adjuster maybe a quarter turn in one direction, then the compensating adjuster(s) to maximize the signal out of the fiber. If the power out of the fiber has increased, repeat this step. Otherwise, turn the first adjuster back in the other direction the same amount, then the compensating adjuster(s). Repeat for all axes until you are satisfied with the coupling for the first laser. Reference coupling efficiencies are given in the mansucript, but a throughput of at least 20% should be attainable.

Repeat these steps for the remaining laser lines, working from shortest to longest wavelength. We work in this direction because the minor tilt adjustments of the dichroic mirrors in the downstream coupling mirrors can affect the alignment of the upstream beams. By working from shortest to longest wavelength in this final alignment we ensure that downstream mirrors are not going to be adjusted later.

Once you are finished with these steps, note the final coupling efficiencies for all lines. Periodically check the power at either end of the fiber and compare efficiencies to the recorded values to monitor long-term drift of the optics. We find that a minor re-adjustment every few months is necessary to keep the system at top performance.

7 Dual port adapter

To couple a second fiber exit to the 2400 model, begin by assembling the dual-port adapter. See manuscript Figure 2 for reference in these steps. The 6 mm cage rods can be press-fit into the 3D printed mount. The 12.5 mm polarizing beamsplitter cube can be affixed to the 3D printed mount by double-sided tape. Observe the orientation of the cube in the mount, ensuring that the reflected beam will travel in the desired direction. The half-wave plate is then inserted into the rotational mount and that mount affixed to the installed cage rods. If you wish to include the optional linear polarizer as well, this is installed in the same way as the half-wave plate and rotation mount.

The assembled mount is then placed at the position between the final coupling lens and the FiberPort on the 2400 breadboard and affixed with a clamping fork (see manuscript Figure 2). Turn on the reference laser beam and rotate the half-wave plate so that the light from this beam is roughly evenly divided between the two polarization paths. Adjust the translation and rotation of the mount so that the transmitted beam through the beamsplitter cube is centered and straight and at the same time the reflected beam travels through the center of the exiting face and parallel to the short edge of the breadboard.

Assemble the two dual-port steering mirrors. These can be 1" mounts and standard mirrors on 12.5 mm pedestals or $\frac{1}{2}$" mounts and mirrors on 25 mm pedestals. Also assemble the additional fiber coupler and mount on the custom pedestal as we did with the primary coupler. Mount the fiber coupler to the breadboard with the back edge of the mount parallel to the long edge of the breadboard. An appropriate lateral position is roughly in line with the 488 nm relay mirror (see manuscript Figure 1, lower right) but you can adjust to fit on your system. Roughly place the two relay mirrors such that the beam hits the center of both mirrors and travels into the fiber port coupling lens aperture. If you have the additional pigtailed laser, you can install that into the fiber coupler and use the counter-propagating beam as a guide to place the relay mirrors, overlapping the reference and counter-propagating beams.

With the two relay mirrors, repeat the steps from Section 3.3 to couple the reference beam into the fiber coupler. Then repeat Section 4 to optimize the FiberPort. Aligning the additional beams should not take any work, as this was taken care of when coupling into the first fiber. Final adjustment follows the plan of Section 6, but only with the reference laser and only by adjusting the two dual port relay mirrors.

Once this alignment is complete, note the incoming and outgoing laser powers at either end of the fiber and record the coupling efficiencies. You should also measure the extinction ratio achieved on this system when the half-wave plate is rotated. See manuscript Table 2 for reference values achieved on one implementation of this design. Monitor these values periodically as an indication when re-alignment may be required.