Multimode Fiber Optics:  
Users’ Guide for Instructors

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Abstract

In 2012, Loyola University Maryland and Rockhurst University received a grant to develop three upper-division active learning physics modules that relate physics principles to medicine. One of these modules is concerned with multimode fiber optics. The teaching materials for fiber optics are divided into two levels: Level 1 is appropriate for introductory/intermediate students and Level 2 is designed for intermediate/advanced students who may encounter optics in research or industrial settings.

This document is a users’ guide for Level 2 materials. It is designed for the instructor who wishes to teach about the physics and experimental techniques of coupling laser light into a multimode fiber. Specific instructional topics include numerical aperture, beam waist due to diffraction and spherical aberration, optical alignment techniques, overfilling and underfilling of fibers, skew rays, loss, and applications of fiber optics in medicine and other fields. This document contains step-by-step instructions for setting up the apparatus, photos, and sample data for a 200-um fiber. The users’ guide is not finished yet, but you should be able to get a good idea of issues concerning coupling of light into a fiber. The MS-Word file is available upon request.

We are currently developing Level 2 teaching materials to help students interpret the data and understand the beam at every stage of the apparatus.

If more preliminary materials on fiber optics are desired, they are available upon request. These Level 1 documents cover acceptance angle (and numerical aperture), coupling to ¼” acrylic rods and 2 mm fiber, bending, distal end, and viewing. A strong connection is made to medical applications. The teaching packets are designed for “active learning” in which students must answer questions at multiple points during the learning process.

We are interested in your feedback. Please contact us if you have comments or suggestions.

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# Multimode Fiber Optics. Level 2.

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Introductory notes

1. In a real device, the laser beam is typically focused directly into the fiber. In this users’ guide, we expand the beam first so that students can clearly see the focused cone and understand issues concerned with coupling.
2. The activities in this users’ guide are designed for the Vernier optics bench, Vernier optical components, and Thorlabs components. It is easy to adapt the activities for an optical table and industrial optical components. We have not yet completed tests with Pasco optics equipment.

Why is it important to do these exercises?

1. Obtain experience with a real, industrial fiber, optics, and optomechanics.
2. Measure the acceptance angle of a fiber at the input and beam divergence at the output ends. Develop a quantitative understanding of the experimental results and relate the results to the numerical aperture specified by the manufacturer.
3. Construct an apparatus that couples light into a fiber. Optimize the coupling. Appreciate the challenges of building effective devices.
4. Understand complexities influencing the beam profile: mode structure, skew rays, diffraction, and spherical aberration.

1. Beam shape. Expand laser beam, measure beam profile with Vernier detector, make a graph and/or see the shape and size on a piece of paper.

1.1 Apparatus

1.1.1. Optical Layout

![Diagram of beam expander, aperture, laser, and detector with labeled components: $L = f_2 - |f_1|$, $f_1$, $f_2$, Aperture, Beam Expander, Screen, Detector.]

Fig. 1.1 Optical layout for measurement of the expanded beam shape.
The apparatus includes:

- Red diode laser
- Beam expander is a Galilean telescope consisting of two lenses – defocusing lens L1 (f1= -25 mm) and collimating lens L2 (f2=300 mm). To expand collimated beam, the distance between lenses needs to be L = f2 + f1 = 300-25=275 mm. In this case the output beam is also collimated and the expansion is f2/ | f1 | = 12X.
- Aperture that cuts out the most uniform part of the beam
- Screen for visual detection
- Photodetector - for beam profile measurements only

1.1.2. Parts


Parts from Vernier:

- Combination 1.2 m dynamics track/optics bench
- Replacement Screen (SCRN-OEK)
- Red Diffraction Laser (RDL-DAK), 636 nm.
- Detector: Combination Linear Position and High Sensitivity Light Sensor

Components from Thorlabs:

- Defocusing lens L1 : Plano-Concave Lens, Ø1/2", f = -25.0 mm (LC1054) – 1 pc
- Focusing lens L2 : Plano-Convex Lens, Ø1", f = 300.0 mm (LA1484) – 1 pc
- Lens Mount for Ø1" Optics (LMR1) – 1 pc
- Lens Mount for Ø1/2" Optics (LMR05) – 1 pc
- Additional retaining ring SM1RR – 1 pc
- Mounting Base, 2” x 3” x 3/8” (BA2) – 2 pc
- Post Holder 2” in length (PH2) – 2 pc
- Optical Post Ø1/2” x 3” (TR3) – 2 pc
- (Optional) Collar for Ø1/2” post (R2) – 2 pc

Miscellaneous

- Socket head cap screw, ¼”-20, 3/8” length – 2 pc (to mount post holders to base plates) – can be purchased from Thorlabs, Newport, maybe Home Depot.

Components from McMaster Carr:

- 19-mm aperture: Gray Insulating Hard Fiber Flat Washer 1/64" Thick, 3/4" Screw Size, 1" OD (part # 90089A395) – 1 pc
- Screws and nuts to mount bases to optics bench
  - Knurled-head thumb screw, 1/4x20, 5/8” L, ½” head diam (part # 94567A540) – buy several
  - Square nut, 1/4x20 (part # 94855A247) – buy several
1.1.3. Assembly and alignment

Follow the steps below to set up the apparatus.

1. Assemble two lenses for the beam expander:
   - Attach two post holders to two base plates using socket head cap screw ¼”-20, length 3/8” as shown in the photo below. It is recommended to attach the holder to the circular hole on the side of the base.

   - Attach lens mount LMR05 and LMR1 to the 3” posts
   - Insert Ø1” focusing lens L2 (f = 300 mm) - flat side up - into the lens mount LMR1, and secure it with a retaining ring. Insert a 19-mm aperture (washer) above the ring and secure it with the second retaining ring (see figure below on the left).
2. Insert Ø1/2" defocusing lens L1 (f = -25.0 mm) - flat side down – into the lens mount LMR05 and secure it with a retaining ring (see figure above on the right).

3. Insert each assembly of post, lens mounts, and lens into post holder.

4. Install a Red Diffraction Laser on the end of the track. Secure it to the track with a mounting screw.

5. Install a Replacement Screen on the track at the distance of 600 mm from the laser. Align the red beam with the center of the screen using two adjusters on the back panel of the laser mount.

4. Install an assembly with a focusing lens (L2) at the distance of about 300 mm from the screen (Fig. 1.2). The distance in Fig. 1.2 is shown from the edge of the lens mount. Flat surface of the lens must face the laser. By horizontal and vertical positioning of the lens, align the red focused beam with the center of the screen (the center of the cross.)

5. Install an assembly with a defocusing lens L1 near the laser. Concave surface of the lens must face the laser. The distance from the edge of the lens mount L1 to the edge of the lens mount L2 is 271 mm (see Fig. 1.2.) Center the lens L1 by horizontal and vertical positioning across the beam while the expanded beam is in the center of the cross.
Verify the distances with the photo in Fig. 1.2.

**In the case of visual detection, go to section 1.2 “Measurements”**

6. Set up the detector: Combination Linear Position and High Sensitivity Light Sensor. The sensor is equipped with a wheel containing a set of slits of different width. In these measurements it is recommended to use the 1-mm slit. The height of the slit is about 10 mm. For accurate measurements it is recommended to reduce the height of the slit to 1-2 mm.

Follow the steps below to set up the detector.
- On the rotating wheel, select the 1 mm entrance slit aperture, which is located in front of the detector.
- Cover the edges of slit with black tape or other light-blocking material. Leave an opening in the center with a height of about 2 mm, as shown in the photo (Figure 1.3).

![Sensor input prepared for beam profiling](image)

**Fig. 1.3.** Sensor input prepared for beam profiling

7. Remove the screen and replace it with the detector. Go to the section 1.3 “Measurements of the beam profile”

1.2. **Visual detection of the beam size/shape and the structure**

Observe the shape and measure the size of the laser beam on the screen or sheet of white paper. Make sure that the beam diameter is the same as the diameter of the aperture installed on the lens L_2, 19 mm. Also observe the beam structure. Circular diffraction rings can be observed due to diffraction from the laser aperture.
1.3. Measurement of the beam profile with a detector

1. Connect the detector to a LabPro and computer (follow the Vernier instructions). Run LoggerPro software.
2. Place the detector at the brightest part of the beam and set an appropriate sensor range. Make sure the sensor is not saturated.
3. Move the detector to a dark area near the beam edge and zero the sensor.
4. Collect data by slowly moving the sensor across the beam

Figure 1.5 is an example of the intensity distribution across the diameter of the beam. The intensity distribution is essentially constant. The bumps are due to diffraction from the laser aperture. This profile will be considered as an approximation to uniform illumination. If a HeNe laser light source is used instead of a Vernier red diffraction laser, the profile would be Gaussian with truncation at the edges.

Fig. 1.4. Visual detection of the beam size/shape after beam expander.

Move the screen away from lens L2 and make sure that the beam size doesn’t change. If the beam is focused, slightly move the lens L2 towards L1 and vice versa if the beam is divergent. In all cases the beam must remain in the center of the screen. Also center the diffraction rings in the beam spot.
Figure 1.5. Beam profile along the diameter of the expanded beam. The distance between the red vertical lines shows the diameter of the aperture $\varnothing=19$ mm at lens $L_2$. Vernier laser

2. **NA at the fiber output.** Measure the output beam profile with a Vernier detector, make a graph and/or see the shape and size on a paper screen.

2.1. **Apparatus**

2.1.1. **Optical Layout**

![Optical layout diagram](image)

Fig. 2.1. Optical layout for measurement of the NA at the fiber output.
For this experiment the fiber must be either completely filled or overfilled. This means that the coupling lens $L_3$ focuses the beam with an angle $\theta$, which is equal to or larger than the numerical aperture of the fiber: $\theta \geq \theta_{NA}$. $NA = \sin(\theta_{NA})$.

2.1.2. Parts

In addition to parts listed in Section 1.1 “Beam shape:…” the apparatus includes:

Components from Thorlabs for coupling optics:
- Focusing lens $L_3$: Plano-Convex Lens, Ø1", f = 75 mm (LA1608) – 1 pc
- Lens Mount for Ø1" Optics (LMR1) – 1 pc
- (Optional. Useful if you want to go onto Sec. 3) Lens tube for Ø1" Optics 2" in length (SM1L20) – 1 pc
- (Optional. Useful if you want to go onto Sec. 3) Lens tube for Ø1" Optics 0.5” in length (SM1L05) - 1 pc
- Lens tube for Ø1" Optics 0.3” in length (SM1L03) – 1 pc
- Mounting Base, 2” x 3” x 3/8”( BA2) – 1 pc
- Mounting Base 1" x 2.3" x 3/8" (BA1S) – 1 pc
- Post Holder 1” in length (PH1) – 2 pc
- Optical Post Ø1/2” x 1” (TR1) – 2 pc
- 1” Travel Dovetail Translation Stage (DT25) – 1 pc

Components from Thorlabs for fiber assembly:
- Lens Mount for Ø1" Optics (LMR1) – 1 pc
- Translating Lens Mount for Ø1" Optics (LM1XY) – 1 pc
- FC/PC Fiber Adapter Plate (SM1FC) or SMA type (SM1SMA) depending on the fiber connector you choose (see below) - 2 pc
- Post Holder 2” in length (PH2) – 2 pc
- Mounting Base, 2” x 3” x 3/8”( BA2) – 2 pc
- Optical Post Ø1/2” x 2” (TR2) – 2 pc
- Socket head cap screw ¼”-20, 3/8” length – 4 pc
- Socket head cap screw ¼”-20, 1/2” length – 1 pc

Fiber from Edmund Optics: part# 59-292, 0.12 NA UV/VIS Patchcord 200 Micron Fiber w/ FC Connector

Start with the expanded beam, described in Steps 1 through 5 in section 1.1.3 “Assembly and alignment.” THE BEAM SHOULD BE CENTERED WELL ON THE SCREEN.

2.1.3. Assembling translation stage module for coupling lens $L_3$

1. Attach one short (1”) post holder PH1 to base BA2 and another post holder PH1 to the mounting base BA1S using socket head cap screws ¼”-20, 3.8” length.
2. Place the base BA2 with a post holder on the track between the lens L₂ and the screen as shown below. Don’t mount it to the track at this point.

3. Attach lens mount LMR1 to a 1” post TR1 (assembly TR1-LMR1)
4. Attach another short post (TR1) to the translation stage DR25 using a socket head screws ¼”-20, 0.5” length.
5. Install the translation stage assembly on base BA2 with a post holder (left photo below). Place base BA1S with 1” post holder on translation stage DR25. Then insert assembly TR1-LMR1 into post holder on the base BAS1 (right photo below). Use the micrometer to center the stage.

6. Set the optical-mechanical module so that the distance from lens $L_2$ to the lens mount for coupling lens $L_3$ is $L = 145$ mm as shown in Figure 2.2 below. **Important: the translation stage must be parallel to the laser beam!**

![Figure 2.2. Setting optomechanical module for coupling lens $L_3$.](image-url)
2.1.4. **Assembly and alignment of the coupling lens $L_3$**

1. Insert Ø1" focusing lens $L_3$ (f = 75 mm, LA1608) into lens tube SM1L03 - flat side up as shown in the figure below. Secure it with a retaining ring. (The +75 mm lens will completely fill the fiber.)

![retaining ring](image)

**Note:** Read the figure caption 2.2.5. If you are going to use a set of coupling lenses for exercises described in Section 3, then go to the next step 2. If you will use only one coupling lens $f = 75$ mm, then skip steps 2 and 3, move the screen closer to the optical-mechanical module to a distance of about 85 mm from lens mount LMR1, and mount lens $L_3$ directly onto lens mount LMR1.

2. Assemble a spacer consisting of two lens tubes: 2” tube SM1L20 and 0.5” tube SM1L05.
3. Screw the spacer into the lens mount on the translation stage. Then screw the mounted lens $L_3$ into the spacer as shown in photo below. **Important: the mounted spacer must be parallel to the beam!**

![spacer assembly](image)

**Figure 2.2.5.** Use of lens tubes on translation stage assembly. Three lens tubes (2”, .5”, .3”) are shown. For the exercise described in this section (Sec. 2), only the 0.3” lens tube is necessary. But if you want to continue to the next exercise (Sec. 3), then adding 2” and .5” lens tubes will save time.
4. Center lens $L_3$ relative to the beam by moving it vertically in the post holder and horizontally with the base BA1S. The focused spot must be at the center of the screen.

2.1.5 Assembling fiber mounts

1. Attach lens mount LMR1 and translating lens mount LMR1XY each to 2” posts TR2.
2. Insert fiber adapter plates SM1FC (or SM1SMA) into lens mounts LMR1XY and LMR1. Secure adapters with retaining rings, as shown in the photos below.

3. Attach two 2” post holders PH2 to post bases BA2 using socket head cap screw ¼”-20, 3/8” length. Insert posts with lens mounts into the post holders.

2.1.6 Installation and alignment of the fiber

1. Place the fiber input assembly (LM1XY and SM1FC) on the track in the focal plane of lens $L_3$ (f = 75 mm). Turn on the laser, use a piece of white paper, and look for the beam that travels through the fiber input center hole. With horizontal $X$ and vertical positioning $Y$, center the hole relative to the focused beam. Rough adjustment should be done by moving the post and base. Fine adjustment should be done with the XY screws on lens mount LM1XY.
2. Place the fiber output assembly (LMR1 and SM1FC) at some distance from the fiber input.

3. Connect both ends of the fiber patchcord to the input and output adapters (see Figure below).

4. Place a screen or white paper at about 105 mm from the fiber output.

5. Find the output beam by adjusting XY. You may have to adjust Z a little by turning the micrometer on the translation stage. Autocollimate the beam by looking at the reflection from the fiber input onto lens L3, and turning the fiber input post slightly. Find the output beam again by adjusting XY and maybe a little Z.

6. With proper XY positioning of the fiber input and linear translation of L3, visually maximize the beam intensity at the fiber output.

Note: The alignment of the fiber is an important process. When the beam is far out of alignment in the XY directions, either rings will be seen due to skew rays (see Saleh and Teich for explanation) or the beam will be diminished. Sometimes these rings are pronounced, other times not, depending on the accuracy of the alignment throughout the system. Turn each adjustment screw from one extreme to the other, i.e. from the formation of skew rays on one side to the formation on the other side. The goal is to find the midpoint of the screw setting. Adjustment of the linear translation stage will improve the output power. The adjustment of XYZ is an iterative process. The goal is to maximize the total power integrated across the beam spot. Throughout the alignment process, you will be able to see changes in the mode structure in the fiber, which will depend on the spectral laser line width.

2.2. **Visual measurement of the NA at the fiber output**

Place a screen at the distance L from the fiber output and measure the beam spot diameter D. Calculate the beam cone and NA. Compare with the nominal value of the NA provided by the manufacturer of the fiber. Figure 2.3 illustrates mode structure in the output beam.
Our results: \( D = 24.5 \pm 0.5 \text{ mm}, L = 100 \text{ mm}. \)
\[
\tan \theta = \frac{(D/2)}{L} \Rightarrow \sin \theta = \text{NA} = .12, \text{ which is equal to the nominal value.}
\]

**Figure 2.3.** Visual detection of the output beam. Bright and dark spots are associated with mode structure.

### 2.3. Measure output beam profile with Vernier detector. Data analysis.

1. Prepare detector as described in Section 1.1.3 (step 6) and Figure 1.3.
2. Install the detector on the track at a distance \( L \approx 105 \text{ mm from the fiber input. The value of } L \text{ depends on the signal level that is desired.} \)
3. Connect the detector to a LabPro and computer. Run *LoggerPro* software.
4. Move the detector to the brightest part of the beam and set an appropriate sensor range.
5. Make sure that the sensor is not saturated.
6. Move the detector to a dark area near the beam edge and zero the sensor.
7. Collect data by slowly moving the sensor across the beam spot.

### 2.4. Data processing and analysis.

Construct a graph of the normalized intensity across the diameter of the beam. Measure the distance between zero points – this is the beam diameter $D$ at the distance $L$ from the fiber output. Figure 2.4 is an example of the beam profile at the fiber output.

**Figure 2.4.** Beam profile at a distance of 105 mm from the fiber output. Fiber specifications: NA = 0.12, core diameter 0.2 mm, length 2 m (Edmund Optics). The distance between red vertical lines represents beam spot diameter $D = 25.4$ mm, which corresponds to NA = 0.12. The distance between blue dashed lines shows the diameter that corresponds to NA = 0.08. The peaks and dips are the result of mode structure (see photo in Figure 2.3).

**Questions and analysis**

- Based on $D$ and $L$, calculate NA at the fiber output and relate it to the manufacturer’s specification.
- Calculate the diameter that corresponds to the specified NA and plot it on the same graph.
- Find the diameter of the central spot $D’$ where the intensity begins to drop on both sides of the beam. Calculate NA for $D’$. 
• What causes the drop in intensity along the beam diameter? In other words why does the beam profile not have a rectangular shape?

Explanation: (1) The reflectivity of the core-cladding interface is not rigorously equal to 1 (R<1). Multiple reflections with R<1, when incident θ is large but still below NA, result in decrease of fiber transmission. (2) Microbending. (See Dugas et al, “Accurate characterization of the transmittivity of large diameter multimode optical fibers,” Appl Optics, vol 26, 4198-4208 (1987).)

• How to explain the peaks and dips on the graph.

Explanation: formation of mode structure in the fiber. (See Griffiths, Saleh.)

### 3. Coupling light into a fiber using a set of lenses with different focal lengths. Understand underfilling and overfilling.

#### 3.1. Apparatus

##### 3.1.1. Optical Layout

**Fig. 3.1.** Optical layout for exercises in coupling at the fiber input.

General idea:
To understand underfilling and overfilling, students vary the focal length of lens L₃ and measure the total power at the fiber output. Six interchangeable coupling lenses L₃ each produce a different focusing angle θ at the fiber input. Three lenses focus the beam with an angle significantly smaller than the numerical aperture of the fiber: θ < θ_{NA} where NA = \sin \theta_{NA}, i.e., the fiber is underfilled. Two lenses are close to the fiber NA: θ ≈ θ_{NA}: the fiber is either slightly underfilled or close to completely filled. One lens makes the fiber significantly overfilled: θ > θ_{NA}. The power P at the fiber output is measured for each lens, and plotted as a
function of $\sin \theta$. Analysis can be done to understand the effect of spherical aberration. When combined with Section 4 on “Measuring NA with a rotation stage,” the shape of the curve for $P$ can be understood quantitatively.

To speed up the process of aligning the fiber after each lens is replaced, the system has been designed to keep the distance between lens $L_3$ and the fiber essentially constant by the use of lens tubes of different lengths (Fig. 3.3). Then only fine adjustments in XYZ need to be done to optimize the coupling.

### 3.1.2. Parts

The following parts are needed in addition to the ones listed in Section 2. The parts for the detection system are different in this section.

Additional parts for coupling from Thorlabs:

1. Ø1” Plano-Convex Lenses
   - $f = 50.0$ mm (LA1131)
   - $f = 75$ mm (LA1608) – use from previous setup (Section 2)
   - $f = 100$ mm (LA1509)
   - $f = 125$ mm (LA1986)
   - $f = 150$ mm (LA1433)
   - $f = 200$ mm (LA1708)

2. Lens tubes for Ø1” Optics
   - 0.3” in length (SM1L03): 5 pc + one used in Section 2 with 75-mm lens
   - 0.5” in length (SM1L05) - 3 pc
   - Lens tube for Ø1” Optics 2” in length (SM1L20) – 1 pc

Detection system using a Vernier light sensor:

1. From Thorlabs
   - Bi-Convex Lens, Ø2”, $f = 60.0$ mm (LB1723) – 1 pc
   - Lens Mount for Ø2” Optics (LMR2) – 1 pc
   - Mounting Base, 2” x 3” x 3/8” (BA2) - 1 pc
   - Post Holder 2” in length (PH2) - 1 pc
   - Optical Post Ø1/2” x 2” (TR2) - 1 pc

2. From Vernier: Light sensor, LS-BTA

(Alternative) A simpler detection system uses a Thorlabs DET100A. You will need:

- DET100A detector (Thorlabs), post, postholder, base.
- Neutral density filter, NE20B
- Lens tube for Ø1” Optics, 0.3” in length (SM1L03)

The neutral density filter can be installed directly on the DET100A. The DET100A/filter assembly can be installed directly on the lens mount at the fiber output. You do not need the 60-mm lens. See Section 4 for details.
Use the same apparatus as described in Section 2 on “NA at the fiber output.” The detection system will be modified, as described below.

3.1.3. Mounting coupling lenses in lens 0.3” tubes

Insert each of six coupling lenses L₃ into 0.3’’ lens tube SM1L03. Two lenses, f = 150 mm and f=200 mm, should be mounted flat side down; four lenses, f = 50 mm, f = 75 mm, f = 100 mm, and f = 125 mm, should be mounted flat side up as shown below.

3.1.4. Installation and alignment of the first coupling lens and fiber

If you have already completed Section 2 using 2” and 0.5” lens tubes with the +75 mm lens, then your system is already set up.
1. Remove all lens tubes from the L₃ lens mount. Build a spacer consisting of a 2” lens tube and three 0.5” lens tubes. Screw the spacer onto the L₃ lens mount.
2. Screw the +50 mm lens onto the lens tubes. Place the screen or white paper at about 105 mm from the fiber output. Align the fiber and visually maximize the output, following the instructions in Section 2.

3.1.5. Installation and alignment of the detection system

1. Mount the Vernier light sensor on the track at a distance of 240 mm from the fiber output as shown in Figure 3.2.
2. With proper positioning of the fiber output, center the large beam over the sensor. You may want to use a screen to help with the alignment.
3. Assemble the imaging lens L₄ using:
   a. 2” post holder PH2, base BA2, socket head cap screw ¼”-20, length 3/8”. It is recommended to attach the holder to the side opening in the base (see Section 1.1.3, step 1)
b. 2” post TR2, Ø2” lens mount LMR2, Ø2”, 60-mm lens LB1723, retaining ring.

4. Place the +60 mm assembly on the track at a distance of 120 mm from the fiber output as shown in Fig. 3.2. Make sure the fiber output beam is centered on the lens. After the lens, the spot should look symmetric.

5. Focus the beam at the center of the sensor. The sensor should collect the whole beam, so minimize the light on the outskirts of the sensor. You may want to use a screen to help with the alignment.

![Figure 3.2. Detection system at the fiber output. Lens L₄ images the fiber output onto the active area of the sensor.](image)

**3.2. Measurements of the fiber output with different lenses at the input**

**3.2.1. Measurement procedure**

Connect the light sensor to a LabPro and computer and run LoggerPro software. Make sure that the sensor is not saturated. Depending on the light source, you may need to attenuate the light. In this case place a neutral density filter near the sensor. To measure the intensity with each of the coupling lenses, perform the following steps:

1. Maximize the output signal with proper XYZ positioning of the input end of the fiber, according to Section 2. This is an iterative process.

2. After maximizing of the signal make sure that the sensor is not saturated. **Note: the signal with the 50-mm lens should be about 30% below saturation.**
3. Block the laser beam between lenses L1 and L2 (expander) and take the background signal $P_{bg}$.
4. Open the beam and read the total signal $P_t$. Subtract the background from the total signal: your laser signal is $P = P_t - P_{bg}$.
5. Replace the coupling lens. Each lens needs to be installed with a separate extension tube (spacer) specified in Table 3.1. When replacing the 125-mm lens with the 150-mm lens, turn the LMR1 mount $180^\circ$ as shown in Figure 3.3. With each lens, you do not need to change the distance between $L_3$ and the fiber by much. Just use XYZ positioning to make fine adjustments in the alignment of the fiber.

**Table 3.1.**

<table>
<thead>
<tr>
<th>Coupler $L_3$</th>
<th>Tube assembly</th>
<th>Position of LMR1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f = 50$ mm</td>
<td>One 2” tube SM1L20 and three 0.5” tubes SM1L05</td>
<td>Open side towards fiber</td>
</tr>
<tr>
<td>$f = 75$ mm</td>
<td>One 2” tube SM1L20 and one 0.5” tubes SM1L05</td>
<td>Open side towards fiber</td>
</tr>
<tr>
<td>$f = 100$ mm</td>
<td>Three 0.5” tubes SM1L05</td>
<td>Open side towards fiber</td>
</tr>
<tr>
<td>$f = 125$ mm</td>
<td>One 0.5” tubes SM1L05</td>
<td>Open side towards fiber</td>
</tr>
<tr>
<td>$f = 150$ mm</td>
<td>none</td>
<td>Open side towards lens $L_2$</td>
</tr>
<tr>
<td>$f = 200$ mm</td>
<td>One 2” tube SM1L20</td>
<td>Open side towards lens $L_2$</td>
</tr>
</tbody>
</table>
Figure 3.3. Replacing coupling lenses $L_3$. 
3.2.2. Data processing and analysis

Calculate the half angle $\theta$ of convergence of the focused beam at the fiber input. Use the beam diameter at the coupling lens ($D = 19$ mm) and the focal length of each lens. The numerical aperture of the coupling optics is $NA_{\text{coupl}} = \sin \theta$, where $\tan \theta = (D/2)/f$. Plot the output power $P$ versus $\sin \theta$. You may normalize $P$ to the maximum power $P_m$ at the smallest $\sin \theta$. Figure 3.4 is an example of $P/P_m$ vs $\sin \theta$ for a fiber with $NA = 0.12$ (nominal) and core diameter 200 m.

![Figure 3.4](image)

**Figure 3.4.** Normalized output $P/P_m$ vs the numerical aperture of the coupling optics ($NA_{\text{coupl}} = \sin \theta$). The data are shown for a fiber with $NA = 0.12$ (nominal), core diameter 200 m (Edmund Optics). The red vertical line shows $\sin \theta = 0.12$. The blue dashed line shows the end of the plateau at $\sin \theta = 0.08$. The beam diameter at the coupling lens was $D = 20$ mm. Coupling lenses listed in Table 1 were used.
**Questions:**

1. Analyze your graph. Where does the intensity drop off and how is it related to the fiber NA? Compare the graph with Figure 2.4. In both graphs the drop starts at the point corresponding to NA = 0.08. Why?

2. Why does the drop off occur at a point less than the NA of the fiber? The curve drops off at about \( \sin \theta = 0.08 \), which is less than the fiber NA = 0.12.

   *Explanation:* (1) The reflectivity of the core-cladding interface is not rigorously equal to 1 (\( R < 1 \)). Multiple reflections with \( R < 1 \), when incident \( \theta \) is large but below NA, result in a decrease of fiber transmission. (2) Microbending. (See Dugas et al.)

3. Why do you still see a signal when \( \sin \theta \) is larger than the NA of the fiber?

   *Explanation:* (1) The central portion of the beam has a smaller angle than NA and can travel down the fiber. (2) Skew rays. Focused spot is not a point, but has a finite size. This means that some large-angle rays launch into the fiber, and are not exactly in the center. These rays propagate in a spiral, where the real angle of incidence on the core-cladding interface may be larger than the critical angle so that total internal reflection occurs.

**Understand the focused spot size, which is (1) diffraction-limited and (2) enlarged due to spherical aberration.**

Compare the focused spot size and the fiber core diameter 200 µm.

\[
\text{spot size}_{\text{total}} = \text{spot size}_{\text{diffraction}} + \text{spot size}_{\text{aberration}}
\]

- Diffraction-limited spot size = \( 2.44 \lambda \frac{f}{\#} \)
- Approximate on-axis spot size of a plano-convex lens at the infinite conjugate resulting from spherical aberration = \( \frac{0.067f}{\#^3} \)

F-number is \( f/# = f/D \), where \( f \) is the focal length and \( D \) is the beam diameter at the lens. The above formulas pertain to uniform illumination.
Table 3.2. Calculation of the size of the focused spot for each coupling lens. Beam diameter at the coupling lens: \( D = 19 \text{ mm} \).

<table>
<thead>
<tr>
<th>Focal length, mm</th>
<th>( \sin \theta )</th>
<th>( \text{Spot size, m} )</th>
<th>( \text{Diffraction-limited} )</th>
<th>( \text{Spherical aberration} )</th>
<th>( \text{Total} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.0474</td>
<td>16.7</td>
<td>11.5</td>
<td>28.2</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>0.0632</td>
<td>12.5</td>
<td>20.4</td>
<td>32.9</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>0.0758</td>
<td>10.4</td>
<td>29.4</td>
<td>39.8</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.0946</td>
<td>8.3</td>
<td>45.9</td>
<td>54.3</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>0.126</td>
<td>6.3</td>
<td>81.7</td>
<td>88.0</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.187</td>
<td>4.2</td>
<td>183.8</td>
<td>188.0</td>
<td></td>
</tr>
</tbody>
</table>

The central spot typically contains less than 85% of the total beam energy. This causes an additional drop in power even if the total spot size is comparable or slightly less than the core diameter.

**Solution:** A common practice to avoid spherical aberration is the use of aspheric lenses.

4. **Measuring input NA with a rotation stage**

4.1. **Apparatus**

4.1.1. **Optical Layout**

This apparatus measures the output power versus the incident angle at the fiber input. The fiber is illuminated with a collimated laser beam. The incident angle \( \theta \) is varied by rotating the input end of the fiber relative to the beam. In principle, if the incident angle is less than the acceptance angle, light should reach the detector. However, there are complications.

![Optical layout](image)

**Figure 4.1.** Optical layout for measuring acceptance angle at the fiber input.
4.1.2. Parts

Parts from Vernier:
- Combination 1.2 m dynamics track/optics bench
- Replacement Screen (SCRN-OEK)
- Red Diffraction Laser (RDL-DAK)

Components from Thorlabs:
- Lens Mount for Ø1" Optics (LMR1) – 1 pc
- Translating Lens Mount for Ø1" Optics (LM1XY) – 1 pc
- FC/PC Fiber Adapter Plate (SM1FC) or SMA type (SM1SMA) depending of the fiber connector you choose (see below) - 2 pc
- Mounting Base, 2” x 3” x 3/8” (BA2) – 3 pc
- Post Holder 2” in length (PH2) – 3 pc
- Optical Post Ø1/2” x 2” (TR2) – 3 pc
- Rotation Platform (RP01) – 1 pc
- Si Detector with large active area (DET100A)
- Unmounted Absorptive ND Filter, Ø25 mm Optical Density: 2.0 (NE20B) – 1 pc
- Lens tube for Ø1" optics 0.3” in length (SM1L03) – 1 pc

Other:
- Multimeter or oscilloscope and cables.
- Screws and nuts to mount bases to optics bench
  - Knurled-head thumb screw, 1/4x20, 5/8” L, ½” head diam (McMaster Carr #94567A540) – buy several
  - Square nut, 1/4x20 (McMaster Carr # 94855A247) – buy several
- socket head cap screw ¼”-20, 3/8” length – 3 pc (Thorlabs, to mount post holder to base)
- cup point set screw ¼”-20, ½” length – 1 pc (McMaster Carr #92313A537, to mount post holder to rotation platform; other screws can work)
4.1.3. **Assembling the mounts for the fiber**

1. Attach lens mount LMR1 and translating lens mount LMR1XY each to 2” posts TR2.
2. Insert fiber adapter plates SM1FC (or SM1SMA) in lens mounts LMR1XY and LMR1. Secure adapters with retaining rings as shown in photos below. **Important: the adapter for the output end must be installed so that the connector faces the ring** (right photo below).

3. Attach a 2” post holder PH2 to post base BA2 using socket head cap screw ¼”-20, 3/8” length (see Figure 4.3 left). Insert post with lens mount LMR1 into the post holder. This will be the fiber output.
4. Attach a 2” post holder PH2 to the rotation platform using a cup point set screw ¼”-20, 1/2” length (see Figure 4.3 right). Insert post with translating lens mount LMR1XY into the post holder. This will be a fiber input.
4.1.4. **Assembling the detector**

1. Insert ND filter NE20B into a 0.3” lens tube and secure it with a retaining ring.

2. Attach 2” post holder PH2 to post base BA2 using socket head cap screw ¼”-20, 3/8” length (Figure 4.3 left).

3. Attach detector DET100A to the 2” post and install it into the post holder (Fig. 4.4 left).

4. Screw lens tube/ND filter onto the input window of the DET100A (Figure 4.4 right).
4.1.5. Installation and alignment of the apparatus

1. Install a Red Diffraction Laser on the end of the track. Secure it to the track with a mounting screw.
2. Install a Replacement Screen on the track at a distance of about 600 mm from the laser. Align the red beam with the center of the screen using two adjusters on the back panel of the laser mount.

3. Remove the white screen. Install the rotation platform with the X-Y Translating Mount (LM1XY) and Fiber Adapter Plate (SM1FC). With proper horizontal and vertical positioning, center the hole in the adapter relative to the beam. This is the fiber input.
4. Place a post assembly with Lens Mount (LMR1) and a Fiber Adapter Plate (SM1FC) at some distance from the fiber input. This is the fiber output.
5. Connect both ends of the fiber patchcord to the input and output adapters.
6. Find the reflected beam from the fiber input. Loosen the locking screw on the side of the rotation platform. By rotating the fiber end on the rotation platform, autocollimate the
beam by directing the reflected beam back to the laser (see figure below). Tighten the locking screw in the rotation platform to fix the angular position of the fiber.

![Diagram of laser, incident beam, and reflected beam]

7. Place a screen or white paper at the fiber output. With a proper XY positioning of the fiber input, visually maximize the beam intensity at the fiber output.
8. Install the detector/filter as close as possible to the fiber output. Center the detector (DET100A) relative to the fiber output. Connect the detector to a voltmeter.
9. Use XY positioning of the fiber on the translating mount (LM1XY) to maximize the signal from the detector.

4.2. Measurements

4.2.1. Measurement procedure

Turn on the laser. Make sure the sensor is not saturated. To measure the intensity with each angular position of the fiber, perform the following steps:

1. Make sure the fiber is autocollimated relative to the incident beam. This is incident angle $\theta = 0^\circ$.
2. Loosen the locking screw on the side of the rotation platform, and turn it by $12^\circ$ or any value well past the acceptance angle. Tighten the locking screw.
3. Maximize the signal from the detector using X-Y positioning of the fiber with the translating mount (LM1XY). Take the voltage.
4. Loosen a locking screw and turn the rotation platform $2^\circ$ degrees towards “0.” Tighten the locking screw. This is 10 degrees.
5. Maximize the signal from the detector using XY positioning. Measure the voltage.
6. Continue turning the platform in increments of $2^\circ$ until you pass the entire range of $24^\circ$ from $12^\circ$ to $-12^\circ$. For each angular position, maximize the signal and measure the voltage.

4.2.2. Data processing and analysis

The output power $P$ is plotted as a function of $\sin \theta$. $P$ is normalized with respect to the maximum power $P_m$ at $\theta = 0$. Note that after manual adjustment, the surface of the fiber input
may not be absolutely orthogonal to the incident beam due to inaccuracies in the adjustment. Furthermore, in some cases, the fiber end may not be exactly orthogonal to the fiber axis due to imperfections in the patchcord. This can result in a non-symmetric curve relative to $\theta = 0$. You can symmetrize the curve by shifting it to the right or left. Figure 3.4 is an example of $P/P_m$ vs $\sin \theta$ for a fiber with NA = 0.12 and core diameter 200 m.

**Figure 4.5.** Variation of the transmitted power with respect to $\sin \theta$, where $\theta$ is the angle of incidence. The data are shown for a fiber with $NA = 0.12$, core diameter 200 m (Edmund Optics). The red vertical line shows $\sin \theta = 0.12$. The blue dashed line shows the end of the plateau at $\sin \theta = 0.08$.

**Questions:**

1. Observe the drop off. How is it related to the fiber NA? Compare the graph with those shown in Figures 2.4 and 3.4. In all graphs, the drop starts at $NA = 0.08$, which is less than the fiber NA = .12. Why?
   
   **Explanation:** (1) The reflectivity of the core-cladding interface is not rigorously equal to 1 ($R < 1$). Multiple reflections with $R < 1$, when incident $\theta$ is large but still below NA, result in decrease of fiber transmission. (2) Microbending.

2. Why do you still see a signal when $\sin \theta$ is larger than NA of the fiber?
Explanation: (1) Skew rays – large-angle rays launch into the fiber not exactly in the center. These rays propagate in a spiral and the real angle of incidence on the core-cladding interface may be larger than the critical angle (TIR).