# A free-space to fiber coupling lab as part of an optics and fiber kit being developed for undergraduate curricula and outreach


Elif Demirbas, Samuel F. Serna-Otalvaro, Edward F. Deveney

*Department of Physics, Bridgewater State University, Bridgewater, Massachusetts 02325, USA*



## Abstract

As part of an educational Optics and Photonics kit being developed for new programs at Bridgewater State University (BSU), including a new Photonic and Optical Engineering BS program and a Photonics Technician certificate, we are creating several lab exercises emphasizing both, skills and quantitative analysis, for the understanding of light, for instance the coupling of free-space laser light into fibers. These experiments include lenses, inverse telescope, objective, aperture and mirrors to couple class 2 visible laser light into single-mode and multi-mode fibers. In addition to the optical alignment and focusing skills required, students measure the transmitted power and minimize the coupling losses, quantifying them in decibels (dB). Students create scattering matrices and make numerical aperture (NA) estimations. Polarization control measurements are added to compliment the understanding of electromagnetic fields. In time we will expand the kit to include lab experiments that cover full courses in both free-space and fiber optics to meet the demands of both technicians and engineers in industry.


## Introduction

- Our goal to build the new kits and experiments formalizes lab-based courses in optics as well as fiber optics to be used for all our programs.
- The kits are cost-effective and suitable in terms of budget for as many as possible.
- The utility of the kits and experiments will find a place in not just the Technician and Engineering programs but may also in high school and as part of public outreach.
- Fiber-optics experiments are being developed first and from the start we are emphasizing experiences in free-space to fiber coupling as it is integral in our industry partner settings, our on-campus research and as currently required for educational and research program related to integrated photonics and Photonics Integrated Chips (PICs).
- This poster presents the new fiber optics experiments we are developing as well as the beginnings of some the key optical pieces of equipment required that comprise part of the eventual full optics and fibers kit.

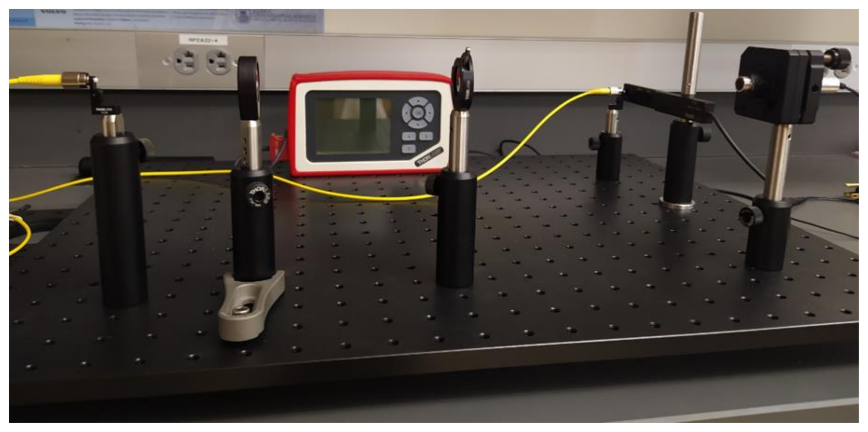

Figure 1. Laser to fiber coupling Experiment setup from Optics and Fiber Optics Kit.

## Optics and Fiber Optics Kit

Optics and fiber optics educational kits include optical bench, light sources, optical components, fiber optical components, light detecting devices and mechanical parts. A list of the elements required to reproduce the experiments is presented in Table 1.

### 1) Light Source

- Laser wavelength: 532 nm (green) and 635 nm (red) wavelength lasers.
- Laser Power: 1 mW and 5 mW power. Except where we need the power for transmission, the 1 mW will be used and the need for the safety goggles at all times will be reduced.
- Laser Safety: safety goggles, electrical and optical of all equipment as well as the absence of potential reflecting surfaces. Laser safety sign should be on during laser operation.

### 2) Optical Components

- 1" Plano-convex lens: 75 mm focal length will serve as an object to explain the laws of refraction and formation of images as well as to focus the light into the fiber core.
- 15 mm mounted standard iris will help the alignment of the set-up; it will help to reduce the beam size while focusing it onto fiber core.
- ½ " broadband dielectric mirrors and ½ " polarizing beam splitter cube will be used to further improve the optical path in order to increase the coupling efficiency.
- ½ "linear polarizer will serve as an analyzer for polarization experiments.

### 3) Fiber Optical Components

The fundamentals of single mode, multi-mode, polarization maintaining fibers as well as the fundamentals of fiber coupler. 1 m, 2 m and 5 m long fiber cables with FC/PC ends will be included in the kit.

- Single mode fiber cables: 0.10-0.14 numerical aperture (NA), operation wavelength between 488 nm and 633 nm wavelength.
- Multi-mode fiber: 0.22 NA. Operating wavelength for multimode laser is between 400 nm and 2400 nm.
- Polarization maintaining fibers: 18 dB-20 dB extinction ratio operates between 460 nm and 700 nm.
- 2x2 single mode fiber optic coupler: 50:50, 75:25 and 90:10 power splits, operation wavelength at 532 nm.
- 1" Band Pass Filter: for 523 nm and 635 nm laser can be included in the kit if the red laser in Table 2 is desired to be included in the kit.

### 4) Mechanical Components

- Posts, post holders, mounting base along with cap screw and setscrew kit are essential components to build optical alignment.
- xy translational stage can be optional tool to include in the kit, though it is highly recommended tool to increase coupling efficiency.
- Plastic viewing card and laser viewing card are used to monitor the light beam along optical path.

### 5) Light Detection

- The kit will have a Power meter (PM16-130, Table 1) to detect the light
- A less expensive alternative is possible, it consists in the use of a silicon photodiode (PD) with the electric components. This could be another additional and essential point in the hands-on training consisting on the evaluation of dark-current, calibration, electric contacts, current to irradiance conversion, etc.
- As the photodiode does not distinguish wavelength, it would be another experiment for the students to understand the photo-electric effect and the problem of ambient light noise.

Table 1. Light sources, optical and fiber optical components and mechanical parts used in the kit.

| Components | Part Number/Model | Quantity | Price |
|---|---|---|---|
| Optical Bench (12" x 18" x 0.5") | MB 1218 | 1 | $193.64 |
| **Light Source** | | | |
| 1 mW 532 nm Laser | CPS532-C2 | 1 | $172.06 |
| 5 mW 532 nm Laser | CPS532 | 1 | $172.06 |
| Laser Module Mounting Kit | CPS08K | 1 | $216.42 |
| Laser Safety Goggles | LG10 | 2 | $212.18 x 2 |
| Laser Safety Sign | LSS10D | 1 | $25.46 |
| **Optical** | | | |
| 1'' Plano-convex Lens | LA1608-A-ML | 2 | $48.15 x 2 |
| 1/2" Broadband Dielectric Mirrors | BB05-E02 | 2 | $53.06 x 2 |
| 15 mm Mounted Standard Iris | ID15 + TR3 | 2 | $50.59 x 2 |
| 1/2" Polarizing Beam splitter Cube | PBS121 | 1 | $206.68 |
| 1/2" Linear Polarizer | LPVISE050-A | 1 | $82.78 |
| **Fiber Optical** | | | |
| 488-633 nm Single Mode Patch Fiber Cable | P1-460B-FC-1<br>P1-460B-FC-2<br>P1-460B-FC-5 | 1<br>1<br>1 | $78.99<br>$86.85<br>$106.33 |
| Multi-Mode Fiber | M42L01<br>M42L02<br>M42L05 | 1<br>1<br>1 | $70.87<br>$74.40<br>$85.22 |
| Polarization Maintaining Fiber | P1-488PM-FC-1<br>P1-488PM-FC-2<br>P1-488PM-FC-5 | 1<br>1<br>1 | $217.38<br>$230.49<br>$339.79 |
| Single Mode Fiber Coupler | TN532R5F2<br>TN532R3F2<br>TN532R2F2 | 1<br>1<br>1 | $248.89<br>$248.89<br>$248.89 |
| Fiber Mount | FCM | 4 | $20.89 x 4 |
| **Mechanical** | | | |
| xy Translational Stage | XR25P-K1 | 1 | $872.18 |
| Posts | TR3 | 12 | $5.58 x 12 |
| Post Holders | PH3 | 12 | $8.52 x 12 |
| Mounting Base | BA2 | 12 | $7.52 x 12 |
| Rotation Mount | RSP-05 | 1 | $77.91 |
| Polarization Controller | FPC560 | 1 | $245.64 |
| Cap Screw and Setscrew Kit | HW-KIT2 | 1 | $121.20 |
| Plastic Viewing Screen | EDU-VS1 | 1 | $19.91 |
| Laser Viewing Card | VRC2 | 1 | $87.39 |
| Caliper | DIGC6 | 1 | $150.41 |
| **Detection** | | | |
| Powermeter | PM16-130 | 1 | $848.38 |
| **TOTAL** | | | **$6,803.51** |

- The total cost of the kit suggested nears $7,000 (per kit) which can be quite prohibitive.
- Price per kit can be reduced to meet user and program needs: A single laser source can be used in all experiments and some of the longer fiber optical cables can be eliminated, for example a 2nd xy translational stage has been excluded from the kit.
- On the other end and with additional resources, we include a second laser at 635 nm and related parts listed in Table 2. Thus far, this second laser is for a single free-space to fiber experiment but affords flexibility to expand and in addition our goal is to use this kit universally for our fibers and optics courses and in the latter the 635 nm laser will be used extensively.

Table 2. Optional second laser in addition to the equipment listed in Table 1.

| | | | |
|---|---|---|---|
| **Table 1 Total Cost** | | | **$6,803.51** |
| **Components** | **Part Number/Model** | **Quantity** | **Price** |
| 1 mW 635 nm laser | CPS635R | 1 | $97.39 |
| Laser Safety goggles | LG7 | 2 | $229.15 x 2 |
| 1" Band Pass Filter | FL532-10<br>FL635-10 | 1<br>1 | $101.72<br>$101.72 |
| **TOTAL** | | | **$7,562.64** |

## Experiments included in the kit

### A) Optics Experiments

- Optics is the understanding of light and has the potential to revolutionize our societies and bring new ideas in addressing the challenges of our century such as climate change, communication limitations and access to information, illumination and the scalability of quantum technologies among others.
- As an example of an experiment: Polarization of light will play an essential role as well in the optics experiments as the Malus Law will be experimentally verified with a set of measurements respectively addressed with error and statistical analysis.

### B) Fiber Optics Experiments

Fiber Optics Experiments include the free-space coupling of laser into fibers by the beam walking technique. Students will perform experiments by using single mode fiber, multi-mode fiber, polarization maintaining fiber and fiber couplers.

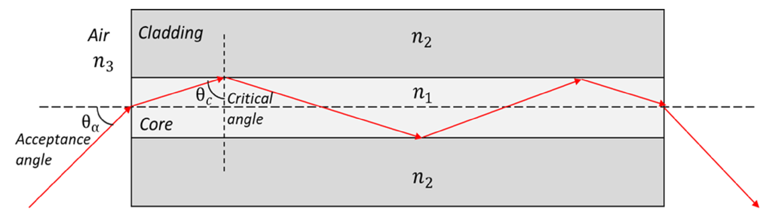


Figure 2. Schematic diagram of fiber optic cable and light propagation based on total internal reflection.

The theory of optical fibers is based on the principle of total internal reflection of light between two media. The critical angle $\theta_c$ required for the total internal reflection can be calculated through Snell's Law.

$$\theta_c > \frac{\arcsin(n_2)}{n_1} \qquad n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

Acceptance angle $\theta_\alpha$ is another important parameter for light to be coupled into fiber successfully. Input light with higher angle than the acceptance angle will hit the core and cladding interface higher smaller than the critical angle, therefore will not undergo total internal reflection. At air-fiber core interface, the acceptance angle $\theta_\alpha$ can be determined through Snell's law that is written as:

$$n_3 \sin(\theta_\alpha) = n_1 \sin(90 - \theta_c) = n_1\sqrt{(1 - sin^2\theta_c)}$$

$$n_3 \sin(\theta_\alpha) = NA \qquad NA \equiv \sqrt{n_1^2 - n_2^2}$$

The number of modes propagating through a fiber can be determined by solving the Maxwell's equations in cylindrical coordinates and applying the appropriate boundary conditions at core-cladding interface [1]. The solution for the maximum number of modes $p$ propagating through the fiber with radius of $a$ can be written as

$$p\pi = \frac{2\pi a}{\lambda_0}\sqrt{n_1^2 - n_2^2} \qquad V = \frac{2\pi a}{\lambda_0} NA$$

$$\lambda_c = \frac{2\pi a}{V} NA$$

Cutoff wavelength depends on the numerical aperture, maximum number of modes and the core-radius.

By using above theory, students will be able to understand the fundamentals of fiber optics and utilize the knowledge in the free-space fiber optics experiments.

### 1) Laser to Single Mode Fiber Coupling

- The laser source will be coupled into a single mode fiber by using various optical components such as lenses, irises and mirrors.
- The height of each component will be adjusted to align them to obtain the correct optical path.
- Students will couple the laser light passing through lens and pinhole by aligning the light by using the beam walking technique while maximizing the power of the light coming out of the fiber.
- Students can measure the power of the light after each component to record how much power is lost on the light path. Coupling efficiency $\eta_c$ can be calculated by the ratio $P_{out}/P_{in}$.

$$\eta_c = \frac{P_{out}}{P_{in}}$$

where $P_{in}$ is the power of light coming into one end of the fiber whereas $P_{out}$ is the power of light coming out of other end of the fiber.

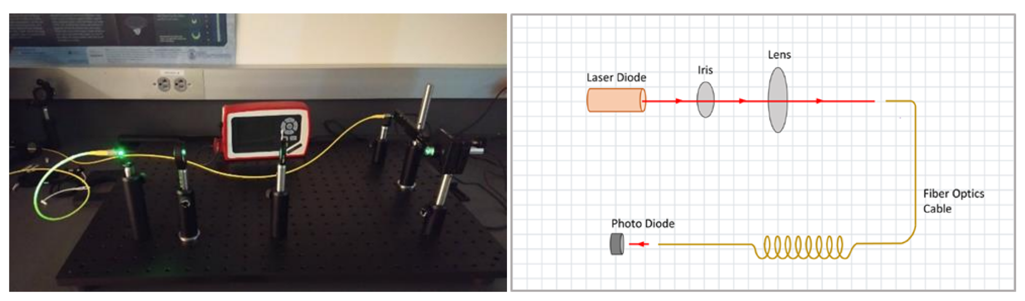


Figure 3. Laser to fiber coupling, laser diode, iris, lens, single mode fiber cable and potodiode.

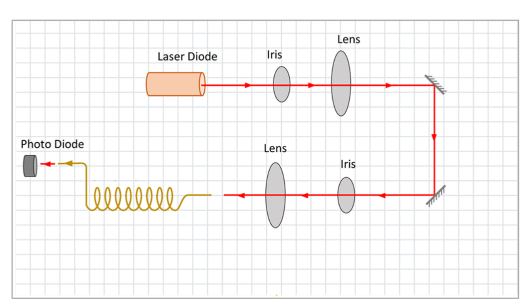


Figure 4. Laser to fiber coupling by using two irises, two lenses and two mirrors, as an alternative combination of components.

### 2) Losses in Fibers

- The loss of light while it propagates through the fiber will be investigated in this experiment.
- Power loss/length will be measured by using fibers with different length.
- Power loss by various bending curvature can be measured.

$$Loss\ (dB) = 10 \log g(\frac{P_{out}}{P_{in}})$$

### 3) Laser to Single Mode Fiber Coupler

- Power division between the fiber channels will be measured by using 50:50, 75:25 and 90:10 fiber couplers.
- Light will be coupled to one port and the power of the light coming from the two output ports will be measured to verify the power division between the ports.

$$P_1 = P_2 + P_3$$

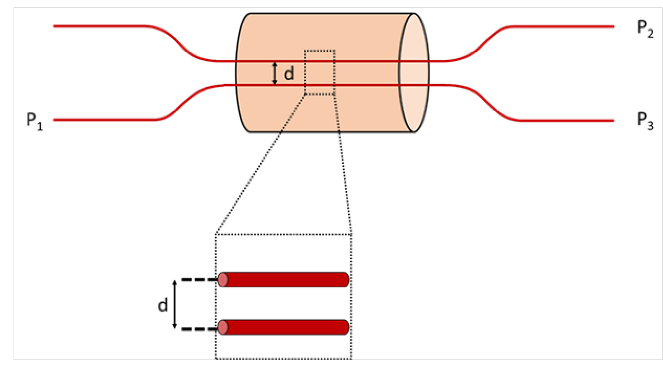


Figure 5. Schematic diagram of fiber coupler.

### 4) Separation of Two Beams with Band Pass Filters

- Two lasers with different wavelength (532 nm and 635 nm) will be coupled into a single fiber.
- After efficient coupling, students can use appropriate band pass filters to obtain the other laser light.
- The coupling efficiency and power loss/length loss for each laser source will be calculated and the results for 532 nm and 635 nm wavelengths will be compared.

### 5) Laser to Multi Mode Fiber Coupling

- Multimode fiber will be used for coupling.
- The coupling efficiency, numerical aperture, cut-off wavelength, number of allowed modes will be calculated and can be compared with the one obtained from coupling into single mode fiber.
- The diameter of each mode can be measured at different distances from the output.

### 6) Laser to Polarization Maintaining Fiber Coupling

- Polarization of the light coupled into fiber will be controlled by using the polarization paddles.
- Distinct polarization states, right and left elliptically polarized, and linearly polarized light can be achieved.
- The power minimization technique will be used, consisting in the measurement of the output power, in free-space and after the paddle as a reference, then use a polarizer as analyzer.

## Programs

The free space laser to fiber coupling experiments and the kit can be used in several programs.

- Photonics and Optics Engineering BS Curricula
- Technician Training Certificate Program
- Open House and Outreach Activities
- High School Courses


## Acknowledgement

- MIT IKIM, formerly (AIM Photonics Academy), Office of Naval Research (ONR) grant (N00014-18-1-2890)
- Lab for Education and Application Prototype (LEAP) funding supported by the state of Massachusetts through Mass Manufacturing Innovation Initiative M2I2 grant