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

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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.

Keywords: laser to fiber coupling, single mode, multimode, polarization, loss, optical alignment, photonic and optical engineering, technician, workforce, properties of light.

1. INTRODUCTION

At BSU, we are developing an extensive kit and accompanying experiments for optics and fiber optics courses and training. For many years, BSU has used a Newport Optics Kit for experimental optics course covering geometric optics, wave optics and even some Fourier optics [1]. While there are resources for fiber optics experiments that could be used to form the basis of experimental courses [2] and kits, some of which we have been tested [3], we have yet to formalize a standalone fibers lab course. BSU students do learn both optics and fibers in a theory-only complimentary course at the level of Hecht [4] and or BYU [5]. The experimental fiber optics training and experience have however happened more informally as part of undergraduate research (laser cooling, and optical tweezers and most recently integrated photonics). Historically, thanks to the optics and fiber-optics education, experiences, and training at BSU, our students have gone on to build pathways into local industries that include gratings, lasers and other optics and fiber-optics manufacturing. Our expertise, particularly related to hands-on training, and solid jobs-related pathways into optics and fiber-optics manufacturing areas were both instrumental in our department to secure several capital equipment grants connected to federal and state manufacturing initiatives (cited in the Acknowledgements - Section 6). As a result, we have started new BSU four-year engineering BS degree programs to be rolled out in the upcoming academic year as well as a collaborative technician certificate program (cited in the Acknowledgements - Section 6). 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. As BSU did not formally have a fiber-optics lab courses prior, 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 paper chronicles 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.

An important update to the introduction is that these new fiber-based experiments were being implemented at BSU starting the spring of 2020 with the anticipation of full results, feedback and analysis for this publication. Unfortunately, due to restrictions as a result of the COVID crisis, we were not able to test these experiments and suggested pieces of equipment. Nor were we able to obtain full representative results or even test with our students. This situation extended into summer 2020. With the hopeful re-opening of our University and back to hands-on laboratories that have been approved within the

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constraints of BSU and state mandated COVID-safe requirements in the lab (that include for examples; one person per set up, adequate social spacing, cleaning of lab equipment before and after experiments, mandatory mask use and host of other local safety protocols and requirements) we hope to be able to report in subsequent communications our full experiences, final equipment recommendations and quantitative results for these experiments. We are eager to have our student cohorts from our Technician training program, our first year Engineering students and research students help us formalize all aspects of this work over the upcoming academic year.

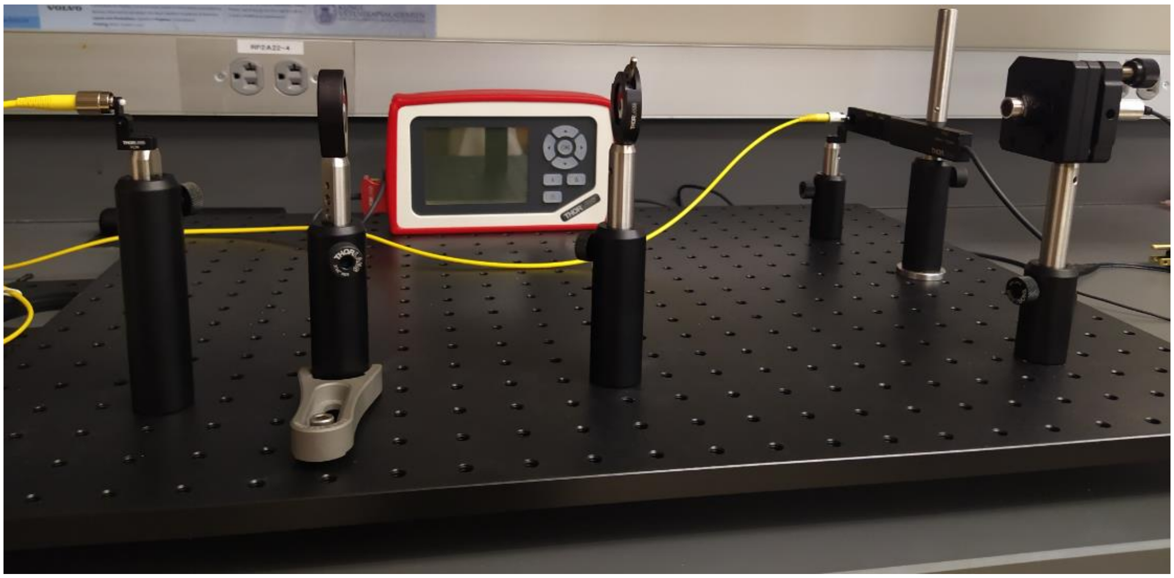

Figure 1. Laser to fiber coupling Experiment setup from Optics and Fiber Optics Kit.

2. GOAL AND LEARNING OUTCOMES

The goals and learning outcome for our free-space to fiber coupling have been built as part of feedback from the local industries that have supported our BSU students and from industry surveys part of the collaborative technician program we are part of [6]. In addition, as we prepare for our engineering degree program, we are basing the goals and learning outcomes of our program into the ABET accreditation engineering standards [7]. Tallying our feedback and combining with the stated resources, we have focused our goals for the free-space to fiber coupling experiments. These include broad theoretical understanding of light, lasers, fiber optics and optical elements such as microscope objectives. As noted, these aspects are covered more explicitly in our theory courses. However, our research narrowed to skills related ability and experiences (as much hands-on as possible) with actual laser operation, optical alignment, critical angles and NA, light polarization, measure and testing. In all our surveys and as is standard in our educational and research facility, laser safety was the main goal and outcome. The free-space and fiber understanding objectives are clearly in line with our goals to meet industry needs, on campus undergraduate research (which may end up in graduate school research) and our emphasis in Integrated Photonics and PICs.

3. OPTICS AND FIBER OPTICS EDUCATIONAL KIT (EQUIPMENT AND PARTS)

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. Table 1 summarizes the instruments included in the kit for the extensive fiber optics experiments described in Section 4.

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 P1-460B-FC-2 P1-460B-FC-5	1 1 1	$78.99 $86.85 $106.33
Multi-Mode Fiber	M42L01 M42L02 M42L05	1 1 1	$70.87 $74.40 $85.22
Polarization Maintaining Fiber	P1-488PM-FC-1 P1-488PM-FC-2 P1-488PM-FC-5	1 1 1	$217.38 $230.49 $339.79
Single Mode Fiber Coupler	TN532R5F2 TN532R3F2 TN532R2F2	1 1 1	$248.89 $248.89 $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. Unfortunately, the price of fiber components that are in general what would also be used in industry can be expensive. 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 FL635-10	1 1	$101.72 $101.72
TOTAL			**$7,562.64**

3.1 Light Source

Laser source with visible wavelength will be used in the kit to make the alignment easier for students. 532 nm (green) and 635 nm (red) wavelength lasers are going to be the main light sources in the kit. Lasers with 1 mW and 5 mW power will be used depending on the experiment type when the components require higher power (e,g, losses in fiber experiment). Except where we needed the power for transmission, the 1 mW was used and the need for the safety goggles at all times was reduced. In any case, students are instructed to check the safety goggles and the proper working conditions, electrical and optical of all equipment as well as the absence of potential reflecting surfaces. Laser safety sign should always be displayed during the laser operation.

3.2 Optical Components

Students will be given different optical components to couple the laser light to the fiber. They can choose to create optical paths in a way that coupling efficiency is maximum. 1" Plano-convex lens with 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.

3.3 Fiber Optical Components

Students will learn 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 with 0.10-0.14 numerical aperture (NA), operates between 488 nm and 633 nm wavelength. At 488 nm, the mode field diameter is in the range of 2.4-4.1 µm and cladding diameter is 125 µm for single mode fiber. Multi-mode fiber with 50 µm core diameter, 125 µm cladding diameter has 0.22 NA. Operating wavelength for multimode laser is between 400 nm and 2400 nm. Polarization maintaining fibers with 18 dB-20 dB extinction ratio operates between 460 nm and 700 nm. 2x2 narrowband single mode fiber optic coupler centered at 532 nm wavelength with 50:50, 75:25 and 90:10 power splits included in the kit. Also, students can use stripped fiber cable for coupling from fiber to fiber as well as for creating fiber coupler. Finally, 2.5 mm ferrule clamp for fiber is included as fiber holder. 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.

3.4 Mechanical Components

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

3.5 Light Detection

Depending on the precision required in the experiment, the kit will have a Power meter (PM16-130, Table 1), or in other cases 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.

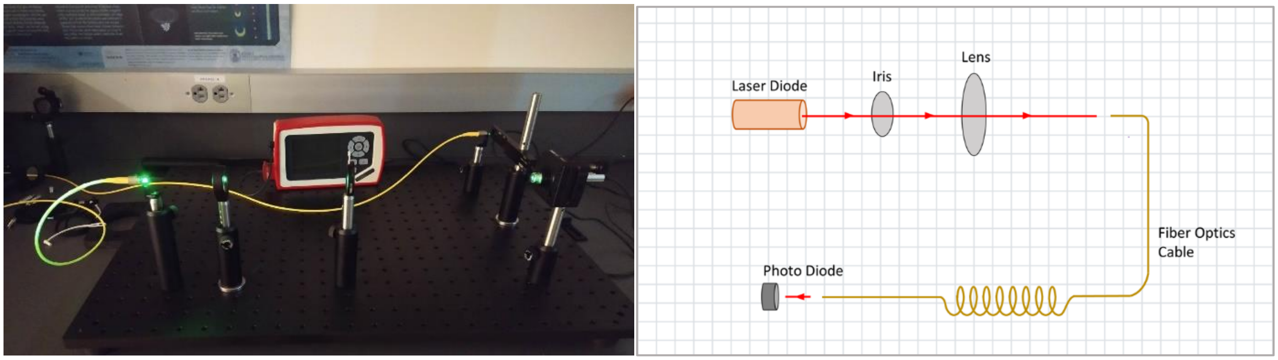

Figure 2. Optics and Fiber Optics Kit used in BSU Physics and Photonics and Optics Engineering Department Open House.

4. EXPERIMENTS IN THE KIT

4.1 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. The experiments using light start with basic geometrical optics experiments to understand the focal point, numerical aperture, optical power of lenses and then after some image formation systems and aberrations. Then, exploratory demonstrations are presented in the form of optical interferometers that are the beginning of the concept of modulation, essential for telecommunications nowadays. 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. The final relations of birefringence and polarization is verified by the students, providing a hands-on understanding of waveguided light, stress in materials and the oscillation of the electric field. An important point of the course is the critical thinking, so the students will be encouraged to think about applications of each concept and being able to introduce them and discuss further developments.

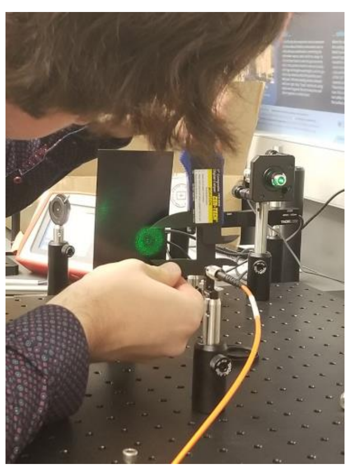

Figure 3. b) BSU student measuring the diameter of the modes of output light coming out of multi-mode fiber.

4.2 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.

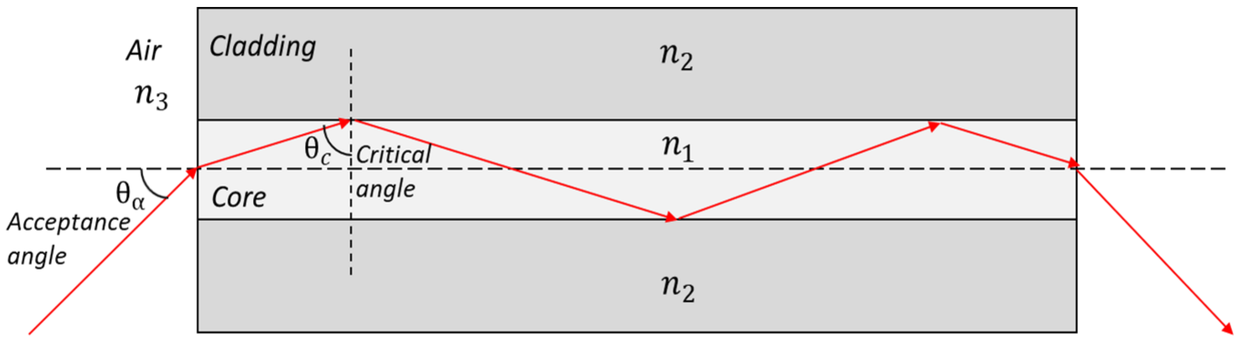

Figure 4. Schematic diagram of fiber optic cable and light propagation based on total internal reflection.

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

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \tag{1}$$

$$\theta_c > \frac{\arcsin(n_2)}{n_1} \tag{2}$$

Acceptance angle θ_α 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 θ_α can be determined through Snell's law that is written as Eq. (3):

$$n_3 \sin(\theta_\alpha) = n_1 \sin(90 - \theta_c) = n_1\sqrt{(1 - sin^2\theta_c)} \tag{3}$$

By using the relation $\sin\theta_c = n_2/ n_1$, Eq. (3) can be rewritten as

$$n_3 \sin(\theta_\alpha) = NA \tag{4}$$

where NA is defined as numerical aperture;

$$NA \equiv \sqrt{n_1^2 - n_2^2} \tag{5}$$

The numerical aperture is widely used in the optical fiber system to define the maximum acceptance angle for the light to enter the fiber.

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 [8]. The solution for the maximum number of modes p propagating through the fiber with radius of a can be written as

$$p\pi = \frac{2\pi a}{\lambda_0}\sqrt{n_1^2 - n_2^2} \tag{6}$$

In optical fibers, it is conventional to define a V parameter related to the maximum number of modes p as $V = p\pi$ and

$$V = \frac{2\pi a}{\lambda_0} NA \tag{7}$$

where λ_0 is free-space wavelength. Cutoff wavelength can be obtained from above equation as

$$\lambda_c = \frac{2\pi a}{V} NA \tag{8}$$

Cutoff wavelength depends on the numerical aperture, maximum number of modes and the core-radius [8].

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.

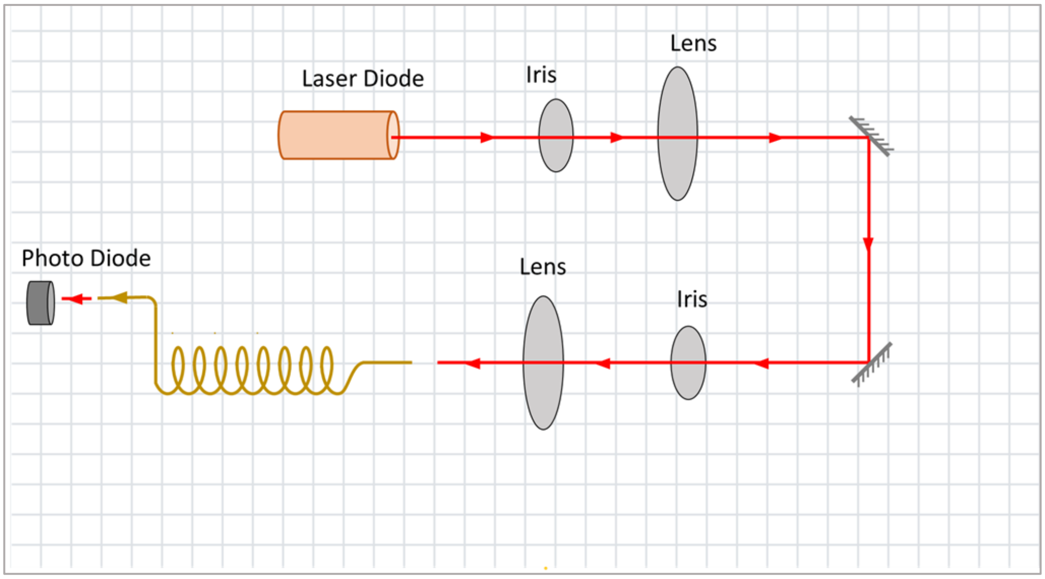

Figure 5. Laser to fiber coupling by using two irises, two lenses and two mirrors, as an alternative combination of components to the one in Figure 1.

1) Laser to single mode fiber coupling

This individual experiment targets students to couple the laser source into a single mode fiber by using various optical components such as lenses, irises and mirrors. Components, holders and posts will be provided to students, they are expected to adjust the height of each component 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.

Initial step of coupling is to focus the light source onto fiber core. After coarse alignment, coupling efficiency can be further improved by the fine adjustment of the positions of each component, 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 η_c can be calculated by the ratio P_{out}/P_{in}.

$$\eta_c = \frac{P_{out}}{P_{in}} \tag{9}$$

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.

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 vs fiber length can be plotted.

$$Loss\ (dB) = 10 \log\left(\frac{P_{out}}{P_{in}}\right) \tag{10}$$

In addition to propagation loss, the effect of bending can be demonstrated by measuring the loss in fibers with different bending curvature. Power loss vs. bending curvature can be plotted.

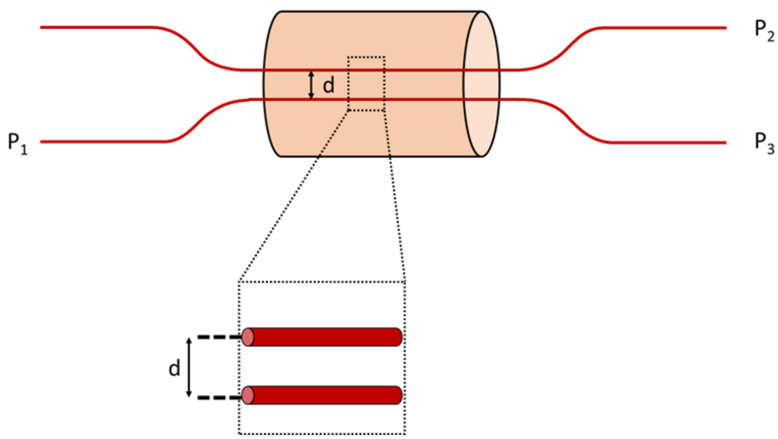

Figure 6. Schematic diagram of fiber coupler.

3) Laser to Single Mode 50:50 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.

$$P_1 = P_2 + P_3 \tag{11}$$

where P_1 is the power of the input light to port 1, P_2 and P_3 are the power of the output light after splitting into two channels (Figure 6). By measuring the power of each channel, two input and two output channels, students will be able to form scattering matrices.

In the second part of the experiment, cleaved fiber cables will be aligned parallel to each other. Coupling between these two parallel fibers can be adjusted by changing distance between them. Students will be able to generate fiber coupler with desired power from both output ports. P_{out} vs. separation d (which is the distance between two parallel fibers) can be plotted L_c (the length light propagates through one fiber before couples to the other one) can be measured by varying separation d. Students will observe that coupling length increases by increasing separation.

4) Separation of two beams (532 nm and 635 nm) with band pass filters

This experiment uses two lasers with different wavelength coupling into a single fiber. After efficient coupling, students can use appropriate band pass filters to obtain the other laser light. They can calculate the coupling efficiency and power loss/length loss for each laser source and compare the results for 532 nm and 635 nm wavelengths.

5) Laser to Multi Mode Fiber Coupling

In this experiment, multimode fiber will be used for coupling. Students can measure the coupling efficiency and can compare with the one obtained from coupling into single mode fiber. Numerical aperture, cut-off wavelength, number of allowed modes can be calculated.

The diameter of each mode can be measured at different distances from the output. Gaussian bending of the output light can be plotted, and core radius of the multimode fiber can be calculated.

6) Laser to Polarization Maintaining Fiber Coupling

Polarization of the light coupled into fiber will be controlled by using the polarization paddles. Fiber paddle controllers allow achieving distinct polarization states, from right and left elliptically polarized up to the simplest and very useful case of linearly polarized light.

Usually, the degree of polarization can be measured by a polarimeter, but in this experiment, students will use the FPC, a polarizer and a photodetector or powermeter. The polarizer is set up as a linear analyzer to decrease the costs, but a circular analyzer could be implemented by adding a quarter waveplate. The operation principle of the FPC consists in continuously adjusting the stress-induced birefringence, allowing any arbitrary input polarization state to be converted to any desired output polarization state. Stress-induced birefringence in the fiber is created through two mechanisms: twisting and bending.

Twisting parts of the fiber by rotating a paddle an angle β rotates the polarization by an angle: θ=Ωβ, being $\Omega = -n^2 p_{44}$ where n is the refractive index of the core and p44 the fiber elasto-optical coefficient [9].

When bending, the number of loops (N) about the coil diameter (D) creates a bend-induced retardation that can be calculated by

$$\delta = 2\pi^2 aN \frac{d^2}{\lambda D} \tag{12}$$

where a, λ and d are the fiber photo-elastic coefficient, wavelength, and the fiber diameter, respectively [10].

The students will trace the expected retardation as a function of the number of loops, that is expected to be linear. This will help students determine the number of loops required for the paddles to have the closest behavior to a λ/2 and λ/4 wave plates as possible.

The experimental procedure will be based in the ability of students to have collimated light in and out the fiber. We will use the power minimization technique, consisting in the measurement of the output power, in free-space and after the paddle as a reference, then use a polarizer as analyzer. The analyzer (in this case the linear polarization) should be aligned orthogonal to the desired polarization state. Then the student will rotate the middle-paddle ($\lambda/2$) across the full range while registering the output power though the free-space polarizer. Leave the paddle fixed at the minimum power. Finally, use the two adjacent paddles ($\lambda/4$) only one at a time, while registering the angles and the power. The procedure ends when the lower minimum is found. This process usually requires numerous iterations to reach the desired polarization.

5. PROGRAMS WHERE THE FREE-SPACE TO FIBER COUPLING EXPERIMENTS AND KIT CAN BE USED

This paper has described several free-space to fiber coupling lab experiments that are being developed in our department to be used in several related program and degree offerings. At the same time, detailed parts and equipment list have been presented in connection to a new fiber and optics kit to be used to perform the new labs. The labs and kits are both in response to academic accreditations (where appropriate) and industry noted suggestions. Clearly hands on real-world experiences are we hope to achieve with safety always taking center stage. Our programs that the labs and kits will be used in extend for our four-year BS degrees in both Physics (with Applied concentration) and soon to be rolled out Photonics and Optical Engineering program that we hope to receive ABET accreditation for in due time to ur Photonics technician training fifteen-month and even our outreach programs such as in our Center for the Advancement of Stem Education. We also believe both the lab experiments and kits can be used in a high school setting given appropriate qualifications of the teacher. The content of the labs is written at the level appropriate for the Technician program but that can be easily extended by the instructor to the four-year degree programs. Kit cost can be prohibitive. BSU transitioned form less expensive fiber kits to the kits described in order to emphasize hands-on work with discrete components and real-lab issues (free-space to fiber coupling) that are common in the undergraduate and graduate research lab settings and in industry. Unfortunately, this does mean that the kits cost is substantial. Nearly $7k per kit for up to ten set ups requires forethought and means. The goal however is clear, true hands on experiences that translate to knowledge and skills that are highly sought in the research lab spaces (for example BSU's laser cool, optical tweezer and Integrated Photonics research labs) as well as in industry as noted by our interactions and collaborations..

6. ACKNOWLEDGEMENT

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