Free space fiber optics experiments for photonics engineers and technician training

Elif Demirbas, Samuel F. Serna-Otalvaro, Edward F. Deveney
Department of Physics, Bridgewater State University, Bridgewater, Massachusetts 02325, USA

ABSTRACT

As part of new programs at Bridgewater State University (BSU), including a new Photonic and Optical Engineering BS program and a Photonics Technician certificate program, we have developed new optics and fiber optics courses based on discrete fiber and optical components that we have put together into a single kit. These courses and kits are useful to teach fundamentals of optics and fiber optics to various level audiences ranging from high school, community college students, university level physics and engineering students. In this paper, we are including the details of the fiber optics experiments as well as the equipment used for each experiment. A subsequent paper details the optics course and a dedicated paper on the kit itself will follow later. These experiments include laser safety training along with the details of laser safety goggles. Class 2 visible laser is used to couple the light into single-mode, multi-mode, polarization maintaining fibers and fiber couplers. Students learn the beam walking techniques for optical alignment by using the over-the-counter discrete optical components such as lenses, mirrors, iris and polarizers. In addition to the optical alignment skills, students work on power measurements, and calculate the coupling efficiency, propagation loss and bending loss. Polarization measurements are added to compliment the understanding of electromagnetic fields. These experiments emphasizing on the fundamentals of free space fiber optics, will open a pathway for students to continue to the field of integrated photonics and will help to fill the demands of both technicians and engineers in industry.

Keywords: laser safety, fiber optics experiments, multi-mode, single mode, polarization maintaining, fiber coupler, photonics and optical engineering, technician training.

1. INTRODUCTION

At BSU, we have developed 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 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 laser safety training required to get before conducting these experiments. Some key optical and mechanical pieces are included that comprise part of the eventual full optics and fibers kit.

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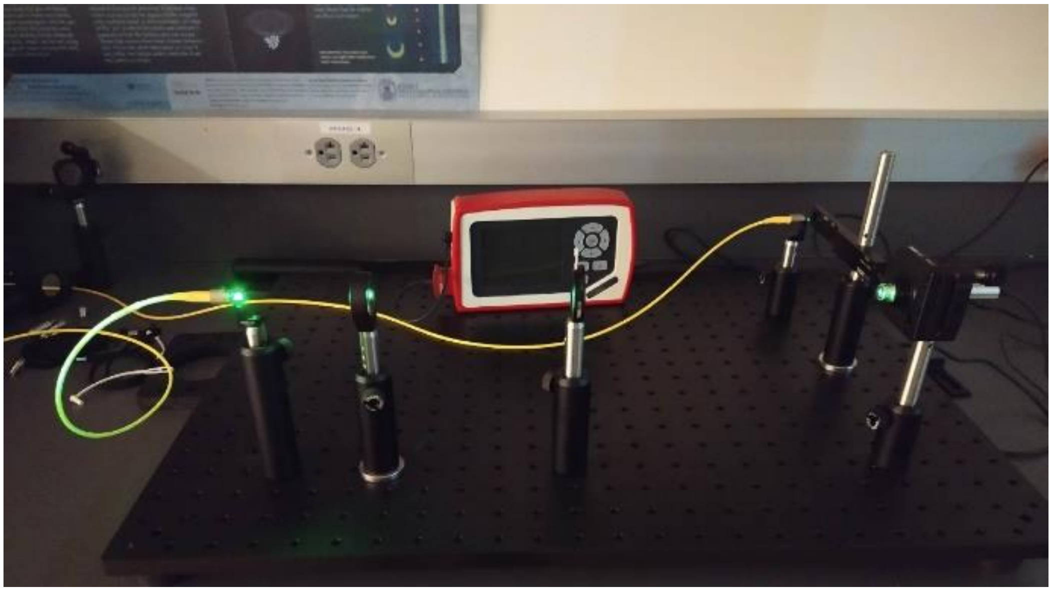

Figure 1. Optics and Fiber Optics Kit used in BSU Physics and Photonics and Optics Engineering Department Open House.

2. FIBER OPTICS THEORY

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.

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \quad (1)$$

where n_1 and n_2 are the refractive index of core and cladding material. The numerical aperture (NA) is widely used in the optical fiber system to define the maximum acceptance angle for the light to enter the fiber.

$$NA \equiv \sqrt{n_1^2 - n_2^2} \quad (2)$$

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

$$V = \frac{2\pi a}{\lambda_0} NA \quad (3)$$

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

$$\lambda_c = \frac{2\pi a}{V} NA \quad (4)$$

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

More details in for fiber optics theory can be found in our previously published paper 'A free space to fiber coupling lab as part of an optics and fiber kit being developed for undergraduate curricula and outreach'[9].

3. FIBER OPTICS EXPERIMENTS

In this paper, we have focused our goals for the free-space laser 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 more emphasis and initiative in Integrated Photonics and PICs.

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

3.1 Laser Safety

As an initial step, it is crucial that students take extensive laser safety training before they perform fiber optical experiments.

BSU has online laser safety training and quiz that generates a laser safety certificate after successful training. Students learn the fundamentals of laser radiation, laser classes, eye protection, optical density (OD) and they learn the determination of appropriate laser safety goggle based on the laser wavelength and the laser power.

$$Optical\ Density\ (OD) = log_{10}\left(\frac{H_o}{MPE}\right) \tag{5}$$

where H_o is the incoming laser intensity and MPE is the maximum permissible exposure. MPE is the maximum level of laser radiation that a person may be exposed to without experiencing any hazardous effects or biological change in the eye and the skin. MPE is determined by the laser wavelength, energy involved and the exposure duration.

Figure 2. Laser Safety Training teaches the students laser classifications, labels and warning signg, optical density and laser eye protection equipment that is laser safety goggle.

In our experiments, we use 635 nm laser diode with around 1.27 mW (Class 2 Laser) and 5 mW (Class 3R). Thorlab laser safety goggle LG 13 has 1.5+ OD in the wavelength range of 630 and 700. This particular goggle provides a good protection for 1 mW and 5 mW laser power and provides a 39% visibility which is very useful for students to see and trace the laser beam.

3.2 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 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. 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 625 nm wavelength with 50:50 and 75:25 power splits included in the kit. Finally, ferrule clamps are included in the kit.

3.3 Optical and Mechanical Components

To couple the laser light to fiber optical cable, various optical and mechanical components such as iris, lens, half wave plates, polarizer, and mounts for each component are included in the kit. Convex lens with 75 mm focal length, iris with adjustable aperture, half wave plate showing the slow and the fast axis and polarizer are used in the fiber optical experiments.

Figure 3. Parts are used in the fiber optics experiments. a) Laser Mount (KM100T), b) Laser diode (CPS635), c) Iris (ID20), d) Convex Lens (LA1608-A-ML), e) Lens Mount (LMR1), f) Half Wave Plate (WPH10ME-633), g) Rotational Mount (RSP1D), h) Polarizer (LPVISE100-A), i) Ferrule (FCM), j) Multi-mode fiber (M42L01), k) Single mode fiber (P1-460B-FC-1), l) polarization Maintaining fiber (P1-488PM-FC-1), m) Fiber Coupler (TW630R5F2), n) Viewing Screen (EDU-VS1), o) Viewing Card (VRC2), p) Caliper, r) Translational Stage (XR25P).

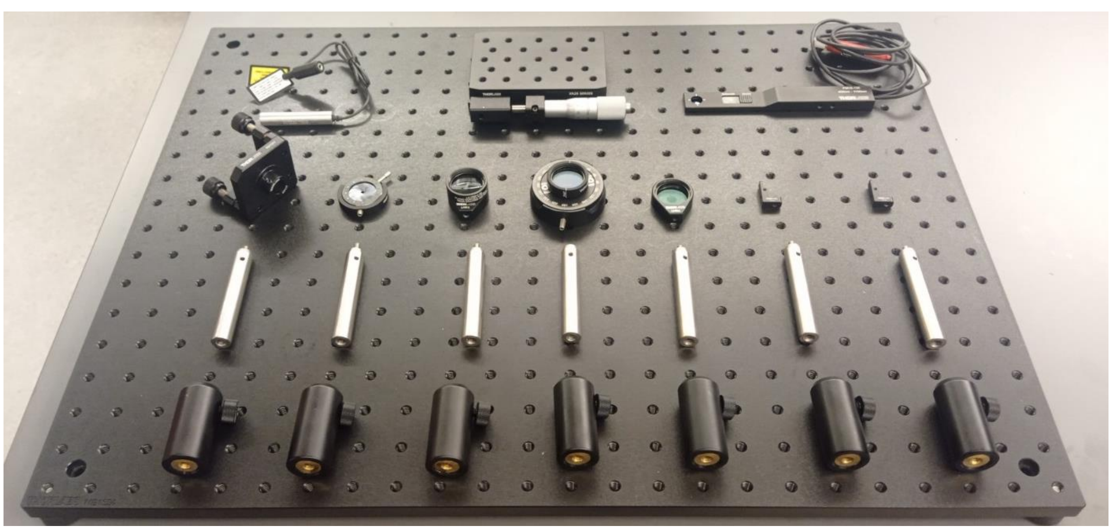

Figure 4. Laser, power meter, optical and mechanical components used in the fiber optics experiments.

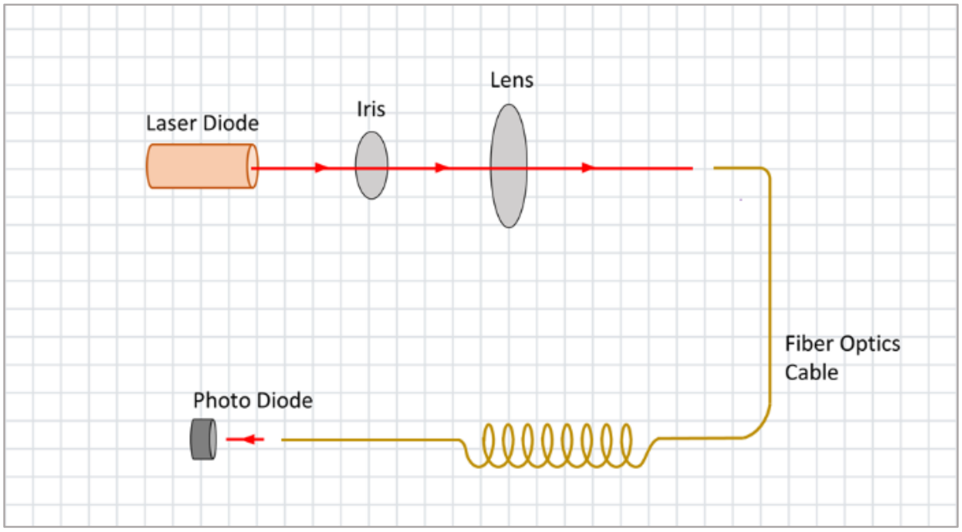

Figure 5. Laser to fiber coupling experiment setup. Laser diode, iris, convex lens, fiber optical cable and power meter.

3.4 Experimental Setup and Alignment Techniques

As a first step, after mounting the laser to laser mount, it is important to measure the height of laser beam at close proximity and far proximity. This will help the students to adjust the laser position which results in the laser light is parallel to the optical axis, optical bench in this case. Height of each component, laser, iris, lens and fiber core, should be the same.

Second important tip for beam alignment is to start with iris with smallest aperture. Laser beam should center the aperture. The light passing though the small aperture will pass through the lens. The distance between and fiber core should be approximately at focal length of the lens. Our goal is to focus the light on core, that is also results in the smallest beam diameter. With a viewing card, light beam can be traced and observed where it has the smallest beam diameter. This position where the light is focused the most.

To obtained the focused light on the fiber core, lens can be placed on a one-dimensional translational stage, and it will give flexibility to move the lens, back and forth with a small increment. Note that, when moving the lens back and forth, it will change the beam position on the core, down and up, respectively. That can be adjusted either changing the position of the fiber from its post or through the knobs on the laser mount. Later one will result in a slight change in the horizontal beam.

Since multimode fiber has wider core region than the single mode, numerical aperture is higher compared to the one in single mode. It is relatively easier to couple the light to multimode fiber than the single mode fiber. Hence, it is highly recommended to start with multimode fiber experiment in this sequence of fiber optics experiments.

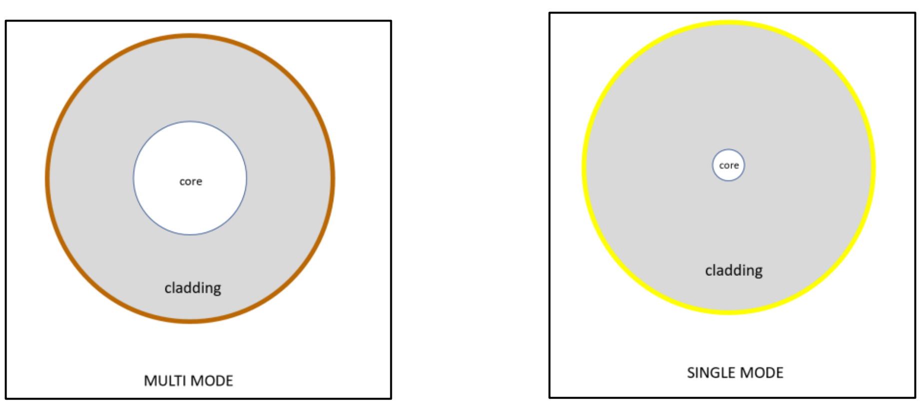

Figure 6. a) Multi-mode laser has a wider core diameter compared to b) the one of single mode diameter.

1) Laser to Multi Mode Fiber Coupling

This individual experiment targets students to couple the laser source into a multi mode fiber by using various optical components such as lenses, irises and mirrors. Over the shelf components, posts, and holders 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 pinhole and convex lens 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}.

$$\eta_c = \frac{P_{out}}{P_{in}} \tag{6}$$

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.

Equipment used in this experiment: Optical Bench, Laser Diode (CPS635), Laser Power Supply (LDS5), Laser Safety Goggle (LG13), Power meter (PM16-130), Convex lens (LA1608-A-ML), Iris (ID20), Viewing Screen (EDU-VS1), Viewing Card (VRC2), Multi-mode fiber cable (M42L01), Ferrule Clamps (FCM), Posts and Post holders (PH2, TR2, BA2), Mounts (FCM, LMR1, KM100T), Caliper.

2) Laser to single mode fiber coupling

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

Equipment used in this experiment: Optical Bench, Laser Diode (CPS635), Laser Power Supply (LDS5), Laser Safety Goggle (LG13), Power meter (PM16-130), Convex lens (LA1608-A-ML), Iris (ID20), Viewing Screen (EDU-VS1), Viewing Card (VRC2), Single mode fiber cable (P1-460B-FC-1), Ferrule Clamps (FCM), Posts and Post holders (PH2, TR2, BA2), Mounts (FCM, LMR1, KM100T), Caliper.

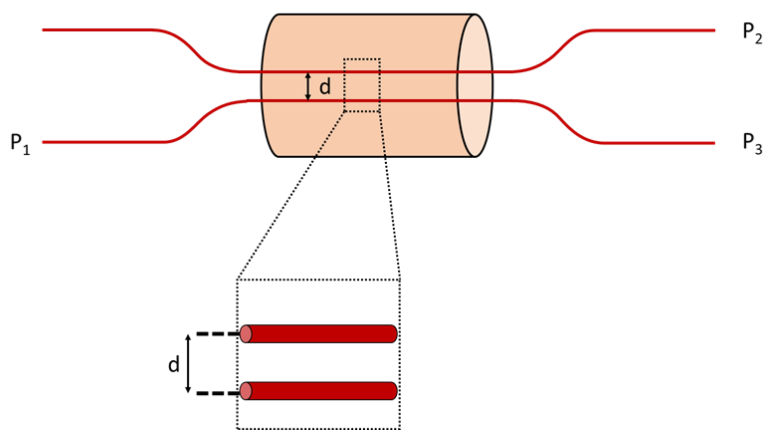

Figure 7. Schematic diagram of fiber coupler.

3) Laser to Single Mode Fiber Coupler

Power division between the fiber channels will be measured by using 50:50 and 75:25 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.

$$P_1 = P_2 + P_3 + Loss \tag{7}$$

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.

For 50:50 coupler, $P_2 = P_3$; and for 75:25 coupler, $P_2 = 3\ x\ P_3$.

Equipment used in this experiment: Equipment used in this experiment: Optical Bench, Laser Diode (CPS635), Laser Power Supply (LDS5), Laser Safety Goggle (LG13), Power meter (PM16-130), Convex lens (LA1608-A-ML), Iris (ID20), Viewing Screen (EDU-VS1), Viewing Card (VRC2), Single mode 50:50 Fiber Coupler (TW630R5F2) and Single Mode 75:25 Fiber Coupler (TN632R3F2), Ferrule Clamps (FCM), Posts and Post holders (PH2, TR2, BA2), Mounts (FCM, LMR1, KM100T), Caliper.

4) Laser to Polarization Maintaining Fiber Coupling

Light is an electromagnetic wave that has electric field and magnetic field vector components oscillates perpendicularly to the direction of propagation. Light is called unpolarized if the electrics field oscillates randomly in time. If the direction of oscillation is well-defined, then the light is called polarized light. Depending on the orientation of electric field, polarization of the light can be classified into three different groups.

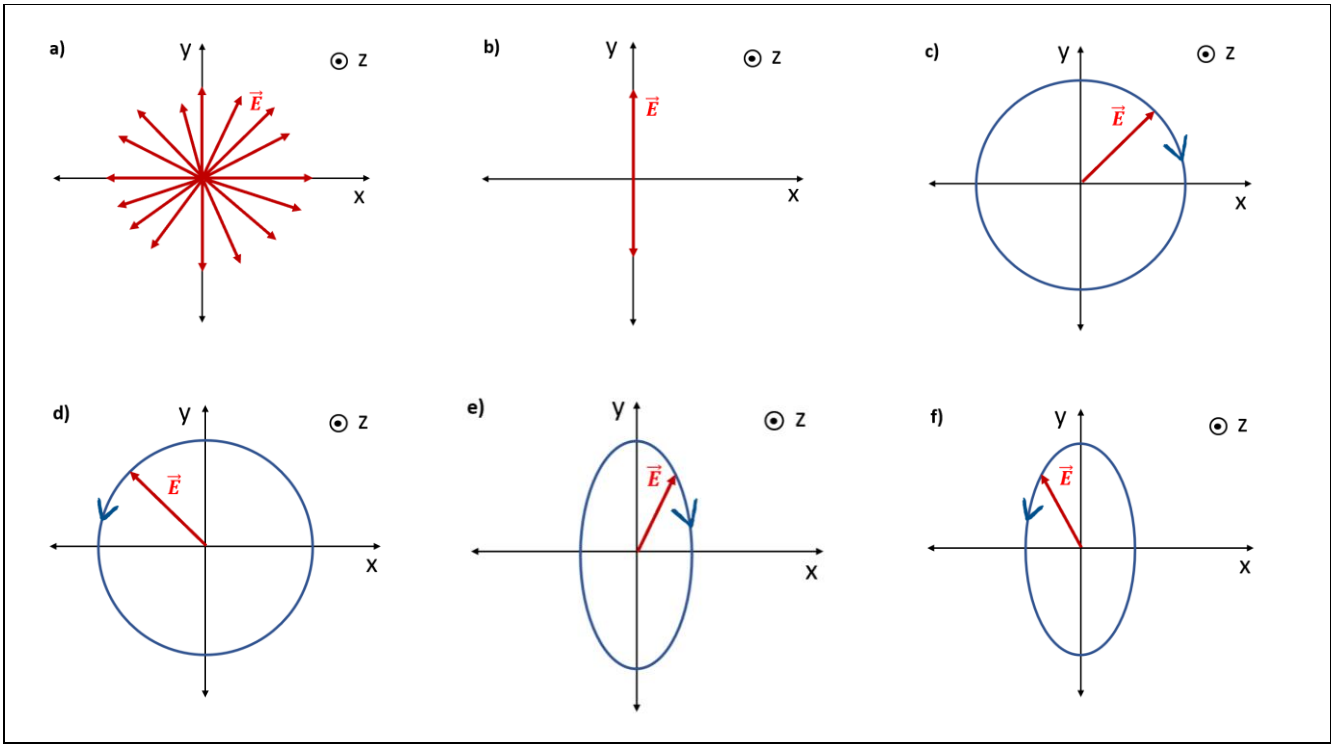

Figure 8. a) unpolarized light, b) linearly polarized light, c) right and d) left circularly polarized light, e) right and f) left circularly polarized light.

Linear polarization: The electric field oscillation is confined in one single plane.

Circular Polarization: The electric field of light has two components that are perpendicular to each other and in equal amplitude. When the phase difference between these two components is π/2 (90°), the resultant electric field rotates in a circle around the direction of propagation. Depending on the orientation of rotation, it is called right and left circularly polarization.

Elliptically: Similar to circular polarization, there are two electric field components, but with different amplitude. Different amplitudes with π/2 phase difference, resultant electric field rotates elliptically.

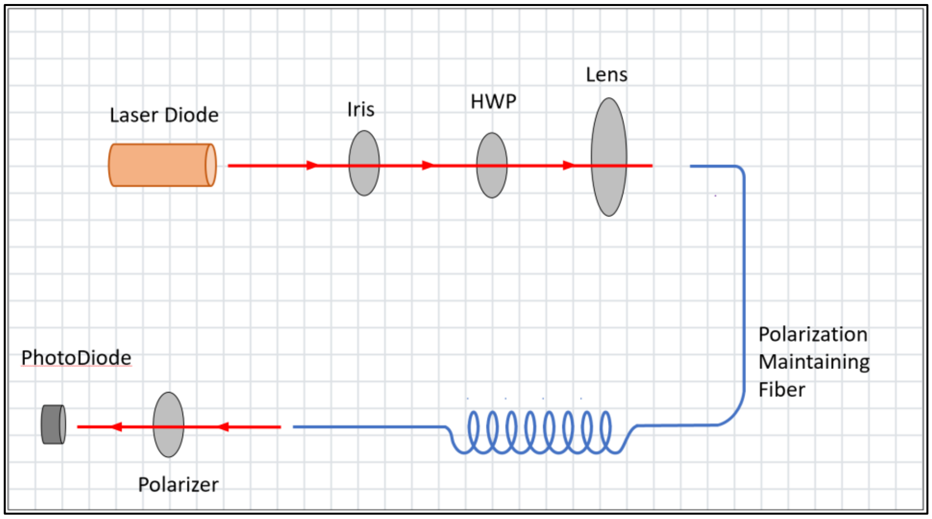

Figure 9. Polarization of the incoming light can be maintained throughout the fiber cable. Half wave plate can be used to insert linearly polarized light.

Fast/Slow axis in half wave plates: Electric field polarization in light beam can be altered through fast and slow axis in half wave plates as well as in PM fibers. Birefringence is manufactured in half wave plates and quarter wave plates and stress rods in PM fibers creates slow axis that does not allow the E-field in this direction. Only E-field along the fast axis is allowed to pass through and that creates the polarized light and maintain the polarization along the fast axis in PM fibers. There are PANDA and bow-tie PM fibers depending on the shape of the stress rods included in the cladding area.

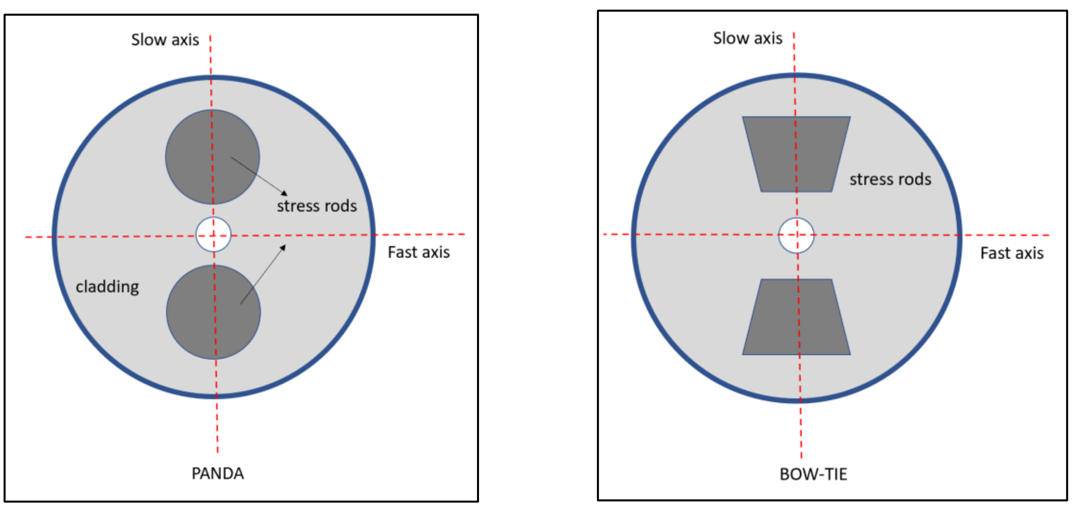

Figure 10. Cross-section of panda and bow-tie polarization maintaining fiber. Stress rods placed along the slow axis results in phase retardation. Polarized beam along the fast axis does not experience phase retardation.

Polarization maintaining fiber preserves the polarization of incoming light. The laser diode we use in this experiment emits unpolarized light. We can use various optical components such as half wave plate or quarter wave plate to change unpolarized light into linearly polarized light or circularly polarized light. In this experiment, polarization of the light coupled into fiber will be controlled by using half wave plates.

Equipment used in this experiment: Equipment used in this experiment: Equipment used in this experiment: Optical Bench, Laser Diode (CPS635), Laser Power Supply (LDS5), Laser Safety Goggle (LG13), Power meter (PM16-130), Convex lens (LA1608-A-ML), Iris (ID20), Viewing Screen (EDU-VS1), Viewing Card (VRC2), Polarization Maintaining

Fiber (P1-488PM-FC-1), Half Wave Plate (WPH10ME-633) or Quarter Wave Plate (WPQ10ME-633), Ferrule Clamps (FCM), Posts and Post holders (PH2, TR2, BA2), Mounts (FCM, LMR1, KM100T, RSP1D), Caliper.

4. CONCLUSION

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..

5. ACKNOWLEDGEMENT

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