Fiber Optics

1 Background

The intent of this laboratory is to make you familiar with the fundamentals of optical fibers. While we give a very brief introduction to fiber optics, you should read corresponding chapters in textbooks to prepare for the lab (see, for instance Ref. [1]).

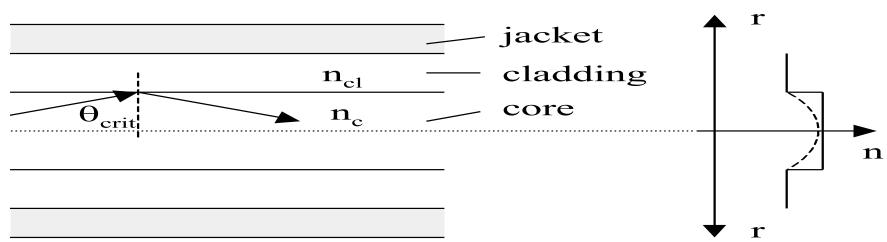

Figure 1: Layout of an optical step-index fiber. The refractive index profile for a graded-index fiber is shown as a dashed line for comparison.

One of the most common fibers is a step-index (see Fig. 1). It consists of a core and a cladding made from glass material whose respective refractive indices, n_c and n_{cl} are different. A protective (plastic) jacket encloses the glass structure. In the ray-optical picture, light is guided because it experiences total internal reflection at the core - cladding interface. The maximum angle of incidence on the fiber $\theta_c = \theta_{max}$ is given by $\arcsin\left(\frac{1}{n_i}\sqrt{n_c^2 - n_{cl}^2}\right)$, where n_i is the refractive index of the incident medium (= 1 for air). The numerical aperture, defined as,

$$\mathrm{NA} = n_i \sin\theta_{max} \tag{1}$$

is a measure of how much light can be collected by the optical system, that is, of the maximum cone angle of light that is accepted by the fiber guide. When the fractional refracted index,

$$\Delta = \frac{n_c - n_{cl}}{n_c} \ll 1 \tag{2}$$

the numerical aperture can be approximated by $n_c\sqrt{2\Delta}$.

In a graded-index fiber the refractive index of the core changes as a function of the radius coordinate r as

$$n_c^2(r) = n_o^2\left[1 - 2\Delta(r/a)^\alpha\right], \tag{3}$$

where a and n_o are the radius and refractive index at the center of the core, respectively. In the case of a parabolic index fiber ($\alpha = 2$) the total power that can be launched is one half of that of a step-index fiber with the same Δ (NA).

Graded-index fibers are found in most applications for telecommunications because this profile reduces the temporal broadening of a light pulse (for example, one bit of information) propagating through the fiber. In graded-index fibers the total internal reflection is replaced by periodic refocusing (see also graded-index lens).

A more accurate description of light propagation in fibers has to be based on wave optics. Possible field distributions in the fiber that represent guided waves are called modes. Each mode has a characteristic irradiance pattern. Formally the propagating electric field can be written in cylindrical coordinates (r, ϕ, z) as

$$E(r, \phi, z) = a(r)\cos(\omega t - \beta z + \gamma)\cos(q\phi). \tag{4}$$

Here $a(r)$ is the radius dependent field amplitude, ω is the frequency, q is an integer and β is the propagation constant. For a step-index fiber the field distribution $a(r)$ can be described by Bessel functions. In the limit of weak guiding ($\Delta \ll 1$), the exact solution of the waveguide problem can be approximated by a set of linearly polarized modes, called LP_{mn} modes. The indices m, n represent the number of azimuthal and radial nodes (zeros), respectively, of the field profile.

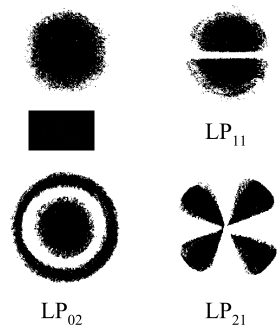

Figure 2: Intensity pattern of some low-order LP modes of a weakly guiding fiber.

The mode pattern of the lowest order modes are shown in Fig. 2. The number of possible modes that a fiber can support depends on the V number. This quantity, also called characteristic waveguide parameter or normalized wavenumber, is defined as

$$V = \frac{2\pi}{\lambda_0}(\mathrm{NA})a \tag{5}$$

where λ_0 is the vacuum wavelength. Figure 4 shows the propagation constant β as a function of the V-number. From this graph one determines which modes can exist in the fiber since for the propagation constant of a guided mode $n_0(1-\Delta)k_f < \beta < n_0 k_f$. For $V < 2.405$ only the LP_{01} mode is possible and the fiber is called single-mode fiber. Conversely, multi-mode fibers require $V > 2.405$. For a fiber with $V = 4$, for instance, four modes are possible. The power in each mode depends on how the light is coupled into the fiber. After light has propagated a certain distance in the fiber, a stable mode distribution develops. Depending on the launch conditions, during this initial propagation, a certain amount of light is coupled into the cladding because the condition for total internal reflection is not satisfied. These modes are called radiation modes and result in a power loss. Once a stable mode pattern has been established, the losses are due mainly to absorption and scattering. In a typical optical fiber, they reach a minimum of less than 1 dB/km at 1.3 μm and 1.5 μm. Therefore these wavelength regions are of particular interest for optical telecommunications.

In an ideal (non real) perfectly isotropic fiber, the propagation constant of the light beam is independent of the polarization direction. In real fibers, however, the polarization is not preserved, and the fiber shows birefringence, also known as *modal birefringence.* In this case, the propagation constant depends on the polarization. In fibers with an elliptical core, the

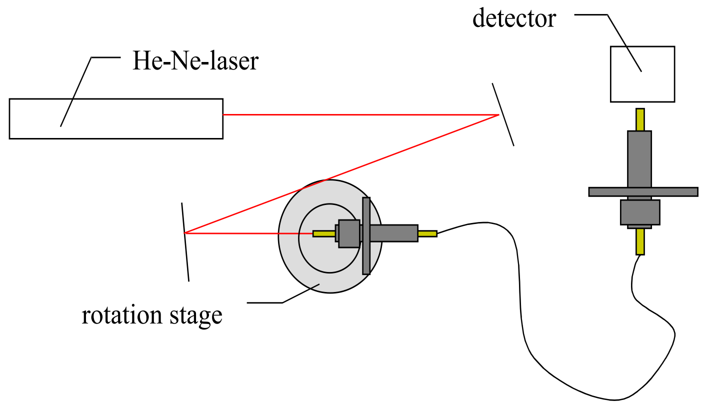

Figure 3: Experimental setup to measure the NA of a multimode fiber.

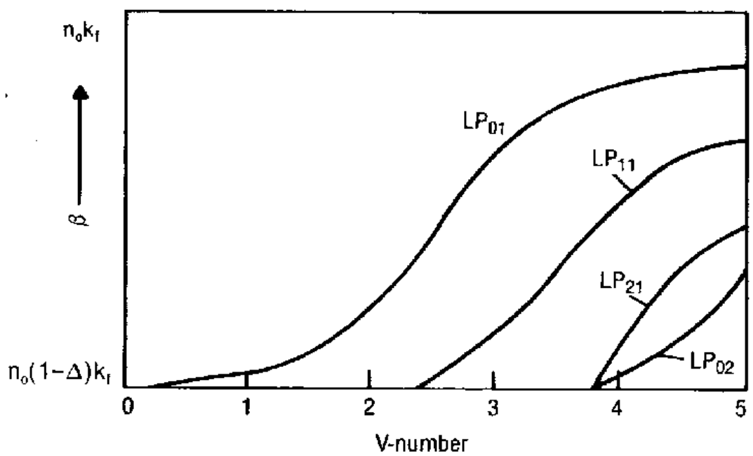

Figure 4: Propagation constant as a function of the V-number. $k_f = 2\pi/\lambda_0$

fast and the slow axis are along the minor and major axis of the ellipse, respectively. Such birefringence can be produced by including stress regions in the fiber during the manufacturing process. If light that has polarization components along both axes of the ellipse is launched into the fiber, the situation is more complex. Owing to the birefringence, the relative phase of the two polarization components changes during the propagation through the fiber. The resulting polarization (the sum of two vectors) thus is periodic. This periodic change in the polarization can be observed as a modulation in the light scattered at right angles. The fiber length over which the polarization rotates by 360^o is called the beat length (L_B), and it is a parameter used as a measure of the fiber's degree of modal birefringence (Fig. 5). In highly birefringent fibers, if light whose polarization is parallel to one of the axis is coupled into the fiber, the output is still linearly polarized despite fiber bending. Polarization preserving fibers, also referred to as polarization maintaining fibers (or PMF) are strongly birefringent fibers that use stress-induced birefringence to maintain the linear polarization of a light beam aligned to either its slow or fast axis. They are used whenever the polarization of the light is important as, for example, in fiber interferometers.

To couple light from one fiber to another fiber without imaging elements, the fiber ends have to be placed exactly opposite to each other. Their separation should be as small as possible. Any small misalignment gives rise to coupling losses. For a small lateral displacement Δx and graded-index fibers, the coupling loss is given by [2]

$$\gamma = \frac{2}{\pi}\left(\frac{\alpha+2}{\alpha+1}\right)\frac{\Delta x}{a}. \tag{6}$$

This formula assumes that the power is evenly distributed among the fiber modes.

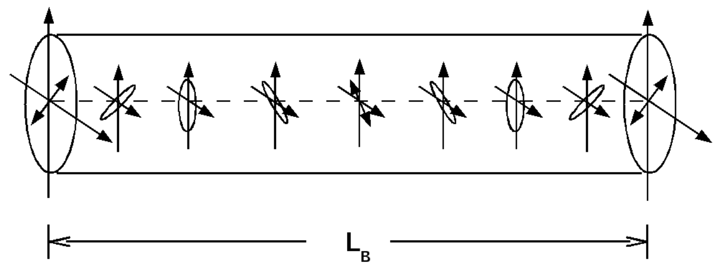

Figure 5: Illustration of polarization state change in a fiber and its relation to the beat length.

List of questions

1. Show that the maximum angle of incidence on the fiber $\theta_c = \theta_{max}$ is given by $\arcsin\left(\frac{1}{n_i}\sqrt{n_c^2 - n_{cl}^2}\right)$.
2. Show that if the fractional refractive index $\Delta = \frac{n_c - n_{cl}}{n_c} \ll 1$, the numerical aperture can be approximated by $n_c\sqrt{2\Delta}$.
3. How is the beat length related to difference of the refractive index of the fast and slow axis, $\Delta n = |n_x - n_y|$?

Fiber parameters

Fiber 1 (Newport F-MLD): Multimode fiber, NA= 0.29, $\lambda_0 = 633$ nm, $D_{co} = 100 \pm 4$ μm

Fiber 2 (Newport F-SV): Single mode fiber, NA= $0.10 - 0.14$, $\lambda_0 = 633$ nm, mode-field diameter = 4.3 μm.

Fiber 3 (Newport F-SPV): Polarization-preserving fiber, Bow-Tie, NA= 0.14, $\lambda_0 = 633$ nm, mode-field diameter = 3.2 μm.

Fiber 4 (Newport F-SMF28): NA= 0.13, $\lambda_0 = 1300 - 1500$ nm, mode-field diameter = 9.3 μm.

2 Experiments

2.1 Preparation of a Multimode Fiber (Fiber 1)

Please consult the Teaching Assistant for this step. You will need about 1 m of multimode fiber for the experiment. The fiber has to be cut and stripped. The last step involves cleaving the

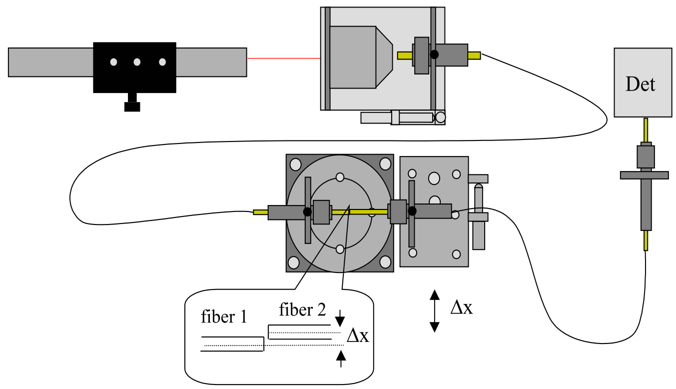

Figure 6: Experimental setup to measure coupling losses between to multi-mode fibers.

fiber to ensure an end face of optical quality. Check the quality of the end faces of the fiber under a microscope.

2.2 Numerical aperture (Fiber 1)

Both ends of the prepared fiber are mounted in a fiber chuck and positioner. One end is placed in front of a photodiode. Connect the photodiode to a digital Voltmeter. The other fiber end is mounted on a rotation stage, see Fig. 3. Make sure that the fiber end is as close as possible to the center of rotation (how?). The beam of a HeNe laser is aligned such that it is incident normally on the fiber. Rotate the stage and measure the detector signal. Plot a graph that shows the signal as a function of the angle of incidence. Use a logarithmic plot (explain why). From the width of this graph at the 5% power level determine the NA of the fiber. Compare your result with the theoretical value given by the manufacturer.

2.3 Coupling losses between two multi-mode fibers (Fiber 1)

Use the same multimode fiber as in the previous experiment. Leave one end of the fiber in the chuck mounted to the rotation stage. Place the other end in the fiber holder-objective assembly to couple the HeNe laser in. First measure the total power transmitted through the fiber using a second microscope objective in front of the detector. Next, place the ends of a second multimode fiber in fiber chucks. Mount one fiber end on a translation stage opposite to the end of the first fiber (see Fig. 6). Position the other end in front of the detector. Make sure that the fiber ends are close together without touching each other and maximize the coupling through optimizing the lateral position. Measure the signal as a function of the lateral displacement Δx that you can change with the translation stage. Plot the relative loss as a function of Δx. From that, determine α of the graded-index fiber.

2.4 Single-mode fiber (Fiber 2)

The task is to measure the profile of the radiation coupled from a single-mode fiber in the far-field. You will use a single-mode fiber with NA = 0.11 and a mode-field diameter of 4.3 μm. To couple light into the fiber you will use one of the microscope objectives. Your first goal is to couple as much light into the guided mode as possible. To do that your focusing system has to satisfy certain requirements (which?). You will find it necessary to change the beam parameter

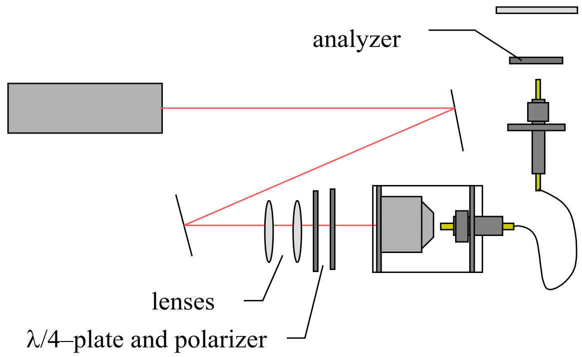

Figure 7: Experimental setup to study a polarization-preserving fiber.

of the HeNe laser using lenses. To design your optics you need to know the (Gaussian) beam parameters of the HeNe laser. One way to obtain this data is to measure the beam profile at two positions after the laser. You can use the multimode fiber and detector for this experiment.

Align your focusing system and optimize the coupling into the single-mode fiber. You need to translate the fiber transversely and longitudinally using the fiber holder-objective assembly. The other fiber end is placed into the fiber chuck on the rotation stage. Estimate the total transmission of the coupler-fiber sequence after your optimization is completed. Place the detector in the far-field of the fiber output. Measure the intensity as a function of the angle between the fiber axis and detector normal. From this plot determine the NA of the fiber. Compare your result with the theoretical value. Compare your curve with a Gaussian and explain.

2.5 Polarization preserving fibers (Fiber 3)

There are several types of polarization preserving fibers, and their names are usually associated with the shape of their cross-section (i.e PANDA, BOW TIE, or Elliptical). There are also several ways in which one can measure the beat length of a fiber. In this exercise, you will measure the beat length by observing the scattered light pattern coming out of the fiber. To perform this task in a rigorous way, you must first find the orientation of the fiber axes. You may use the same focusing optics as in the previous experiments. Add a quarter-wave plate and a polarizer as shown in Fig. 7. After coupling light into the fiber you should see an elliptical output profile on a sheet of white paper. Verify that the orientation of the ellipse does not change when you rotate the polarization of the input light. Mark the direction of one the axes of the ellipse on the output chuck. Exchange output and input chuck. Align the polarization of the input light such that it forms an angle of 45^o with the major axis of the fiber. Using a magnifying glass, estimate the beat length L_B from the scattered light at the small stripped part of fiber coming out of the chuck.

Alternatively, and in a more direct approach, you can measure the beat note by simply remembering that all you need is to make sure that linearly polarized light is coupled into the fiber at 45^o with respect to either the slow or fast axis. By carefully rotating the input chuck, there will be a particular position where the input linearly polarized light is oriented at 45^o with respect to the axes. At this point, it is easy to see the scattered light pattern at the tip of the fiber[1]. Measure the distance between the two brightest spots. Calculate the refractive index difference $\Delta n = |n_x - n_y|$.

2.6 Mode coupling with $V > 2.405$ (Fiber 4)

For this experiment you will use a single-mode fiber for a wavelength of 1.3 μm which can be a multi-mode fiber for 632 nm (why?). Use the experimental setup shown in Fig. 8. Use the second microscope objective to image the mode pattern on a screen. By aligning the incoupling you will observe mode patterns of various complexity. Sketch three of them and interpret the pattern.

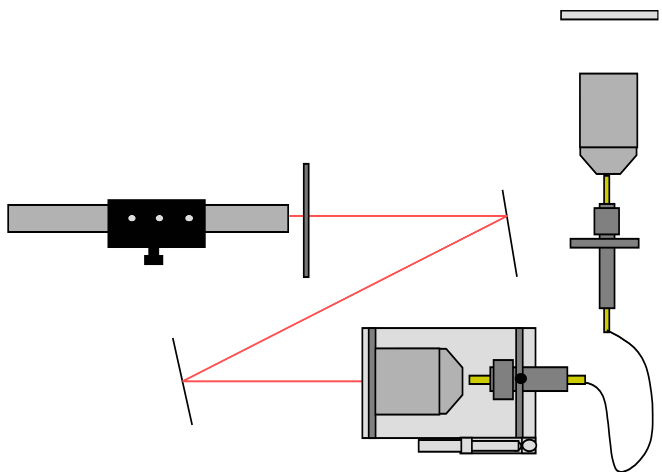

Figure 8: Experimental setup to observe mode patterns produced in a single mode fiber.

3 Summary

1. Measure the numerical aperture of a multimode fiber. Determine Δ.
2. Measure coupling losses between two multi-mode fibers. Determine α.
3. Optimize a HeNe laser beam for coupling in a single-mode fiber. Measure the radiation pattern in the far-field of the output face of a single-mode fiber.
4. Determine the beat length of a polarization-preserving fiber.
5. Study the mode-pattern for $V > 2.405$.

[1]make sure you leave enough stripped off space at the tip of the fiber.

References

[1] M. Teich and E. Saleh. *Fundamentals of Photonics*. Wiley, 1992.

[2] D. Gloge. Offset and tilt loss in optical fiber splices. *Bell Syst. Technical Journal*, 55:905–916, 1976.