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Microengineering

Optics Laboratory Work MICRO-423: Fiber Optics

Optics Laboratory Work:
Fiber Optics and Gaussian Laser Beams

ROOM MED 2 1117

Discovery Learning Lab

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Contents

1 Objective

To gain basic theoretical understanding and practical knowledge of fiber optic coupling and Gaussian laser beam optics.p

2 Safety

2.1 General rules

Laser radiation poses several risks for the operator, mostly for the skin and eyes. For that reason it is paramount to evaluate the safety of any laser before use, based on measurements and by reading the corresponding laser safety notes. The first task of the TP is to perform the following basic safety checks:

2.2 Safety evaluation

- Check the class of the lasers being used (Research the parameters before coming to the lab)
- Check laser safety equipment. Note the model number and specifications.
- Never look into direct or reflected laser beam.
- Do not wear watches, rings or any other object that can reflect laser beam
- Block or turn off the laser beam during alignment or any other optics manipulation

- Keep eyes level higher than laser level i.e. avoid sitting on the chair during experiment
- Check where the beam is going by discussing with the supervisor. It is a good idea to keep the beam at a fixed height, whenever possible and to have beam dumps.
- Optical fibers are made of glass; be careful during fiber manipulation

3 Prerequisites

See course

Optical engineering II, MICRO-322

- Chapter 4, Multimode fibers
- Chapter 5, Monomode fibers

4 Theory

4.1 Gaussian Beam Optics

4.1.1 Beam profile

In this practical work a Helium-Neon (HeNe) laser is used as a light source. This gas laser emits red light at 632.8 nm (due to 5s-3p transition of the Ne atom). HeNe lasers are often used for alignment purposes, because they are easy to use, have long lifetime, very good stability and beam properties. Lasers can emit light in the forms of different modes. Here, we will limit the discussion to the fundamental, the lowest-order transverse electromagnetic (TEM_{00}) mode. This mode is described by the fundamental solution (of the Eigenvalue equation derived from the separation of variables) of the paraxial Helmholtz equation in cylindrical coordinates under slow-varying approximation for a resonator with spherical mirrors. Practically, this solution has a *Gaussian* transverse intensity profile, is cylindrically symmetric about principal axis of propagation, has the lowest divergence compared to other modes. As the wave propagates, the beam size changes, but the Gaussian shape of the intensity profile in always preserved, as illustrated in Figure 1 a, thus the nomenclature "*Gaussian* beams".

Equation 1 describes the complex electric field of a *Gaussian* beam depending on the propagation distance z ((Saleh and Teich 2007), Chap. 3):

$$E(r,z) = E(r,0)\frac{w(0)}{w(z)}\exp\left(-\frac{r^2}{w^2(z)}\right)\exp\left(-i\left(kz + k\frac{r^2}{2R(z)} - \psi(z)\right)\right) \qquad (1)$$

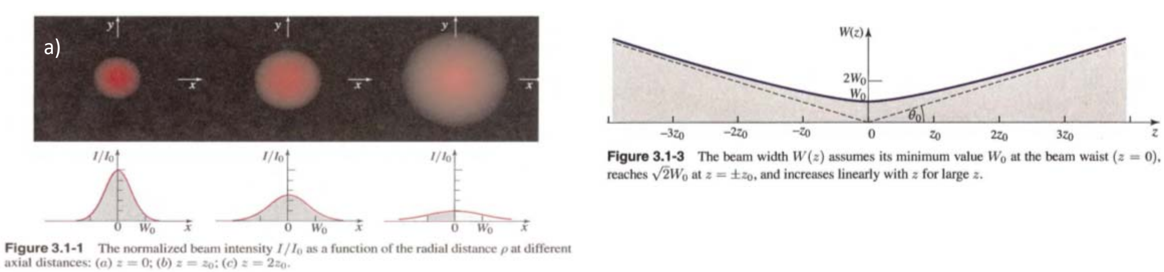

Figure 1 Gaussian beam: a) Radial power distribution for different positions b) beam width and Rayleigh range ($z_R = z_0$) (Ref. (Saleh and Teich 2007)).

The **beam radius (or beam width)** $w(z)$ depends on the distance z as

$$w(z) = w_0\sqrt{1 + \frac{z^2}{z_R^2}} \qquad (2)$$

The width[1] of the intensity pattern is minimum at $z=0$ ((Saleh and Teich 2007), Chap. 3), which is called the **beam waist** $w_0 = w(0)$. The Rayleigh range z_R is related to the minimum beam radius w_0 by

$$z_R = \frac{\pi w_0^2}{\lambda} \tag{3}$$

where λ is the vacuum wavelength, $k = \frac{2\pi}{\lambda}$ the wave vector.

The radius of curvature of the wave front $R(z)$, which is the isocontour of phase, follows the functionality ((Saleh and Teich 2007), Eq. 3.1-9):

$$R(z) = z\left(1+\left(\frac{z_R}{z}\right)^2\right) = z + \frac{z_R^2}{z} \tag{4}$$

4.1.2 Measureable parameters

Using beam profiler/translating knife edge/translating slit, the irradiance of transverse electric field $I(\rho,z)$ can be measured:

$$I(\rho,z) = E(\rho,z)\bar{E}(\rho,z) = I_0\left|\frac{w_0}{w(z)}\right|^2 \exp\left[-\frac{2\rho^2}{w^2(z)}\right] \tag{5}$$

Using a power meter larger than the beam gives the optical power $P(z)$:

$$P(z) = \int_0^\infty I(\rho,z)\, dA \tag{6}$$

The units of the power and of irradiance are $[P] = Watt$ and $[I] = \frac{Watt}{cm^2}$, respectively.

At the beam axis $\rho = 0$ the intensity is ((Saleh and Teich 2007), Eq. 3.1-13)

$$I_{0,z} = I(0,z) = I_0\left|\frac{w_0}{w(z)}\right|^2 = I_0\frac{1}{1+\left(z/z_R\right)^2} \tag{7}$$

If the aperture is taken out, i.e. $\rho \to \infty$ the total power is ((Saleh and Teich 2007), Eq. 3.1-15)

[1] Following Saleh, B. E. A. and M. C. Teich (2007). Fundamentals of photonics. New York, N.Y., Wiley-Interscience. we define the beam width as half the beam diameter.

$$P(\infty) = \lim_{\rho\to\infty} P(\rho) = I_0 \frac{\pi w_0^2}{2} \qquad (8)$$

which relates the irradiance (intensity) at the beam center to the total power in the beam. This confirms that the power $P(z)$ should be constant over z, which corresponds to conservation of energy.

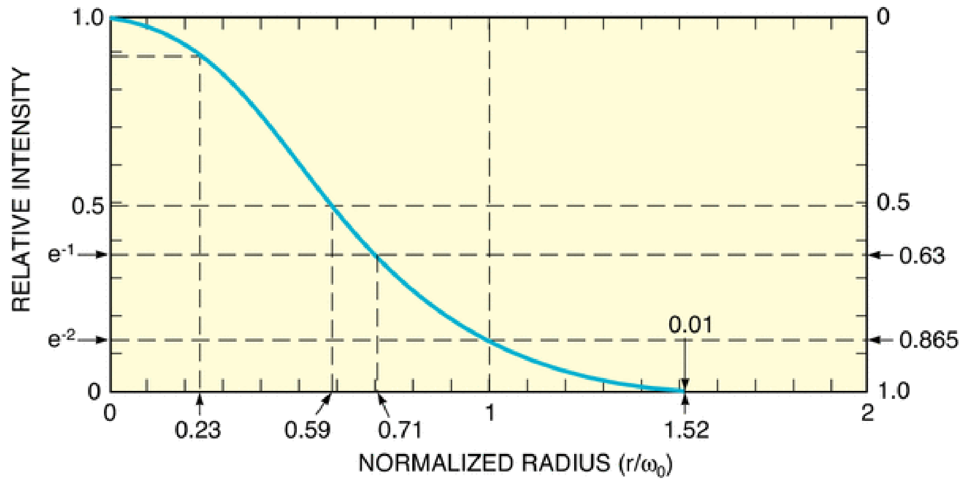

Figure 2 Relative Irradiance (intensity) versus normalized radius (from Ref. http://www.newport.com/Gaussian-Beam-Optics/144899/1033/content.aspx)

Since a *Gaussian* beam intensity is smooth, it is necessary to define a radius of the beam for all practical purposes. The irradiance distribution is a Gaussian function. Its value at $\rho = w(z)$ is :

$$I(\rho = w(z), z) = I_{0,z} \exp[-2] = I_{0,z} / e^2 \qquad (9)$$

This provides the most common definition of a Gaussian beam diameter. $D_0(z) = 2w_0(z)$ is defined as the diameter of the laser beam that contains all but $1/e^2$ (13.5%) of the total beam power as shown in Figure 2.

Table 3 (Annex) summarizes the relation between different beam size definitions.

4.1.3 Estimation of beam parameters

The wavefront (isocontour of phase) of the Gaussian beam, $kz + k\frac{r^2}{2R(z)} - \psi(z)$, resembles a spherical beam (point source) with radius of curvature $R(z) = z$ in the far field $z >> z_R$ and resembles a plane wavefront at $z = 0$ (see Eq. 4) In the far field Eq. (2) becomes $w(z) = w_0 \frac{z}{z_R}$. The angular divergence of the beam (half angle of the cone) is $\theta_0 = \frac{w(z)}{z}$ (Figure 1 b). Using Eq. 3 the angular divergence becomes

$$\theta_0 = \frac{w_0}{z_R} = \frac{\lambda}{\pi\, w_0} \tag{10}$$

The wavelength of the laser is either given or measurable by a spectrometer. The divergence is measured in the far field $z >> z_R$.

4.1.4 Practical implications:

There are many points of practical interest to note from these equations:

1. The irradiance at the center (beam axis) falls by a factor of 2 between $z=0$ and $z=z_R$. This has to be considered during coupling to waveguides and microscopy.
2. The area of the beam is defined by a hyperbola. Further, for large $z: w(z) \approx w(0)\frac{z}{z_R}$.
3. The divergence of the Gaussian beam, which is measurable with intensity detectors and some form of beam clipper (pixels, knife-edge, slit) at large z (in the far-field).
4. At $z=0$, the wave front is flat (curvature is infinite). This is the best condition to couple to another mode which has a flat wave front, for example the fundamental mode of a fiber waveguide described in section 4.4.

Since a Gaussian beam intensity is smooth, it is necessary to define a radius of the beam for all practical purposes. The power contained in a circular aperture of surface $A = \pi\rho^2$ and radius ρ is

$$P(\rho) = I_0 \frac{\pi w_0^2}{2}\left(1 - \exp\left(-\frac{2\rho^2}{w_0^2}\right)\right) \tag{11}$$

If the aperture is taken out, i.e. $\rho \to \infty$ the total power is ((Saleh and Teich 2007), Eq. 3.1-15)

$$P(\infty) = \lim_{\rho\to\infty} P(\rho) = I_0 \frac{\pi w_0^2}{2} \tag{12}$$

which relates the irradiance (intensity) at the beam center to the total power in the beam. Unsurprisingly, this confirms that the power $P(z)$ should be constant over z, due to conservation of energy. Beam diameter measurement using the slit or knife edge method. Using a slit of width $\Delta_{Slit} \leq 2w(z)/5$, the intensity distribution and the beam radius from the 1/e^2 points are directly obtained (Figure 3 top). Using a knife-edge requires taking derivative (Figure 3 bottom). Commercial slit and knife-edge devices are for example the Thorlabs (BP109-VIS) beam profiler used in this TP.

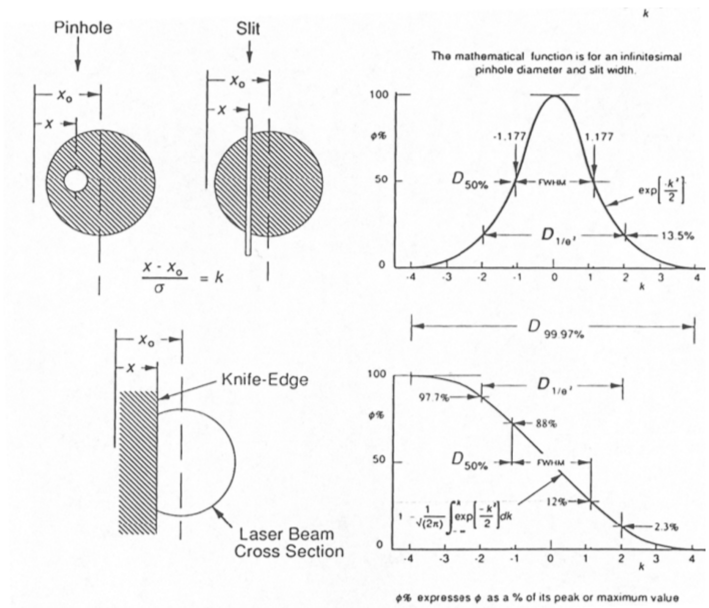

Figure 3 Principle of beam diameter measurement: a. slit and hole b. knife edge (Ref. (Marshall 1985))

4.2 Gaussian Beam transformation

A Gaussian beam can be reshaped and manipulated using lenses, mirrors and other optical elements. Figure 4 shows the laser beam focused with a lens of focal length f positioned at z_{01}.

Basic equations

The following equations describe changes of the laser beam parameters by the lens of focal length *f* :

$$\begin{aligned}\Gamma &= \frac{f^2}{\left(z_{02}-f\right)^2+z_{R2}^2}\\ w_{01} &= \sqrt{\Gamma}w_{02}\\ z_{R1} &= \Gamma z_{R2}\\ \left(z_{01}-f\right) &= \Gamma\left(z_{02}-f\right)\end{aligned} \qquad (13)$$

Where Γ is the lens transformation factor which is related to the magnification *M* as $\Gamma = \frac{1}{M^2}$, z_{Ri} is the respective Rayleigh range, and z_{0i} are defined in Figure 4.

We can separate 3 cases depending on the location of the lens:

a. The distance laser – lens is within the Rayleigh length of the laser: $z_{01} \ll z_{R1}$

b. The distance laser – lens corresponds to the Rayleigh length of the laser: $z_{01} \cong z_{R1}$

c. The distance laser – lens is longer than the Rayleigh length of the laser: $z_{01} \gg z_{R1}$

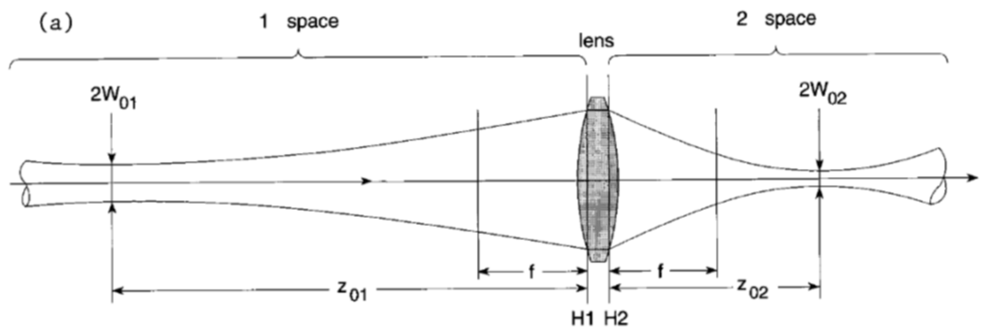

Figure 4 Transformation of a Gaussian beam through a simple lens (Johnston 1998)

4.3 Optical fiber properties

The optical fiber is cylindrical dielectric waveguide. The main parts of the optical fiber are core (where the light is guided), cladding (with slightly higher refractive index than core) and outer jacket layer for physical protection. Typical cross section and refractive index profile are shown in (Figure 5). The core has a higher refractive index allowing light to be guided by total internal reflection (Figure 6).

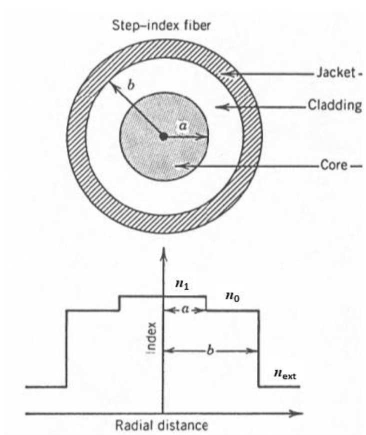

Figure 5 Refractive index profile of step-index fiber

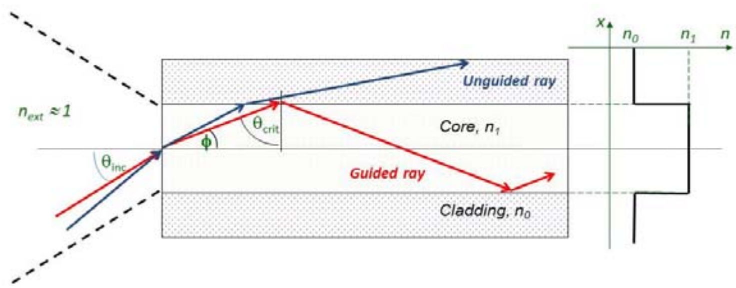

Figure 6 Light guiding inside optical fiber and definition of numerical aperture NA (right).

The optical fiber in this experiment is a single mode, low birefringence, highly photosensitive fiber. The high photosensitivity is achieved by a high germanium doping of the fiber core. The Numerical aperture is defined as $NA = \sin(\theta_{inc})_{\max} = \frac{1}{n_{ext}}\sqrt{n_1^2 - n_0^2}$ (see Figure 6). In air for $n_{ext} = 1$ and using $\Delta = \frac{n_1^2 - n_0^2}{2n_1^2} \Rightarrow 2n_1^2\Delta = n_1^2 - n_0^2$ the Numerical aperture is

$$NA = \sin(\theta_{inc})_{\max} = \sqrt{n_1^2 - n_0^2} = n_1\sqrt{2\Delta} \qquad (14)$$

The cladding refractive index is obtained from the Sellmeier equation in (Malitson 1965), the core refractive index from the fiber NA.

All waveguide properties [effective index ((Okamoto 2006) Fig. 3.4, 3.15), electric field confinement (overlap integral, Eq. 3.5), waveguide (Eq. 3.14) and chromatic dispersion (Eq. 3.17), group delay (Eq. 3.12, Eq. 3.16)] depend on the v-number that determines the waveguide properties of the single mode fiber.

$$\mathrm{v} = ka\sqrt{n_1^2 - n_0^2} = kan_1\sqrt{2\Delta} = ka\ NA \tag{15}$$

The fiber is single-mode for a v-number that is below the LP_{11} cut-off frequency, which is given by the first root of the Bessel function $J_0(u=0)$, i.e. LP_{11} : first root of $J_0 : \mathrm{v}_c = j_{0,1} = 2.4048 = \frac{2\pi}{\lambda_c} a\sqrt{n_1^2 - n_0^2}$.

The propagation constant β is the wavenumber along the propagation axis. The transverse wavenumbers are related to β by

$$\begin{aligned} \kappa^2 &= k^2 n_1^2 - \beta^2 \\ \sigma^2 &= \beta^2 - k^2 n_0^2 \end{aligned} \tag{16}$$

Eliminating β we obtain $\kappa^2 + \sigma^2 = k^2\left(n_1^2 - n_0^2\right)$ and multiplying with the square of the fiber radius we get $a^2\kappa^2 + a^2\sigma^2 = a^2k^2\left(n_1^2 - n_0^2\right)$. Introducing normalized transverse wavenumbers by

$$\begin{cases} u = a\kappa \\ w = a\sigma \end{cases} \tag{17}$$

we obtain the relation between the transverse wavenumbers in the core u and in the cladding w:

$$u^2 + w^2 = \mathrm{v}^2 \tag{18}$$

The equation that relates the field in the core with the field in the cladding is called eigenvalue or dispersion equation. This is a transcendent equation for optical fibers and needs graphical or numerical solutions (Okamoto 2006) chap. 2.1.3 and 3.3) to obtain u and w.

The effective index of a mode depends on the waveguide properties, i.e. the propagation constant β and is defined as

$$n_{eff} = \frac{\beta}{k} \tag{19}$$

where $k = \frac{2\pi}{\lambda}$ is the magnitude of wave vector where λ is the vacuum wavelength of the electromagnetic wave. For guided wave n_{eff} can vary between the cladding refractive index n_1 and the core refractive index n_0. Introducing a normalized propagation constant b by

$$b = \frac{n_{eff}^2 - n_0^2}{n_1^2 - n_0^2} = \frac{\beta^2/k^2 - n_0^2}{n_1^2 - n_0^2} \quad (20)$$

leads to a eigenvalue equation that is independent of the geometry and the material. Using Eq. 3 we get from Eq. 7 the relations between the normalized propagation constant, the normalized frequency and the normalized transverse wavenumbers:

$$b = \begin{cases} \dfrac{w^2}{\mathrm{v}^2} \\ 1 - \dfrac{u^2}{\mathrm{v}^2} \end{cases} \quad (21)$$

The relative power of the fundamental mode in the core is

$$\frac{P_{core}}{P} = 1 - \frac{u^2}{\mathrm{v}^2}\left[1 - \xi_0(w)\right] \quad (22)$$

where $\xi_0(w) = \frac{K_0^2(w)}{K_1^2(w)}$. Some authors call $\eta = \frac{P_{core}}{P}(\mathrm{v})$ the overlap integral of the fundamental mode with the fiber core.

4.4 Optical fiber fundamental mode approximations

The electric field of the single mode fiber can be approximated by a Gaussian function ((Marcuse 1977), Eq. 4):

$$E_y = E_0 \exp\left(-\frac{r^2}{\omega^2}\right)\exp(-i\beta z); \qquad Z_0 = \sqrt{\varepsilon_0/\mu_0} \quad (23)$$

where $E_0 = E(r=0) = 2\left[\frac{P/Z_0}{\pi n_0 \omega^2}\right]^{1/2}$ and $E_y(r=\omega, z) = \frac{E_{y0}(z)}{e}$ and

$$P_y(r = w, z) = \left|\frac{E_{y0}(z)}{e}\right|^2 = \frac{P_0}{e^2} \quad (24)$$

There are different definitions of the mode field diameter, which coincide all for the Gaussian fundamental mode. In this case the mode field diameter is defined as $MFD = 2w$.

Marcuse relates the mode field radius ω to the fiber core radius a for a step index fiber (Marcuse 1977), Eq. 8):

$$\frac{\omega}{a} = 0.65 + \frac{1.619}{\mathrm{v}^{3/2}} + \frac{2.879}{\mathrm{v}^6}$$
$$2 < \mathrm{v} < 4 \qquad accuracy < 1\% \quad (25)$$

From this approximation we can conclude that for $\mathrm{v} \le 2.80772$ the mode field diameter is larger than the core diameter.

The effective area of a single mode fiber can be approximated by

$$A_{eff} = 2\pi\omega^2 \tag{26}$$

The equation that relates the field in the core with the field in the cladding is called eigenvalue or dispersion equation. This is a transcendent equation for optical fibers and needs graphical or numerical solutions (Okamoto 2006) chap. 2.1.3 and 3.3) to obtain u and w.

Approximations for the eigenvalue equation of a step index fiber are given by several authors. Marcuse proposed to calculate *u(v)* by (Marcuse 1976):

$$u = 2.4048\,\mathrm{e}^{-\frac{0.8985}{\mathrm{v}}} \tag{27}$$

The approximation can be used in the range $0.9 < \mathrm{v} < 2.4048$ with an error that is smaller than 0.5 %. Rudolf and Neumann proposed the following equation (Rudolf and Neumann 1976):

$$w = 1.1428\,\mathrm{v} - 0.9960 \tag{28}$$

which should have an error smaller than 0.1% in the range $1.5 \le \mathrm{v} \le 2.5$. Using Eq. 8 and Eq. 16 we get an approximation for $b(\mathrm{v})$:

$$b(\mathrm{v}) = \left(\frac{w}{\mathrm{v}}\right)^2 \simeq \left(1.1428 - \frac{0.9960}{\mathrm{v}}\right)^2 \tag{29}$$

4.5 Measurement of fiber numerical aperture

In this part of the experiment students should measure the divergence of the out coupled laser beam to determine the fiber NA. The divergence is obtained by measuring the beam profile as a function of distance to the fiber exit (see Figure 1). From the plot of ρ_{87} versus z the slope can be calculated:

$$m = \tan\theta_{87} \tag{30}$$

Then the NA is obtained from θ_{87} by $NA = \sin\theta_{95} = \sin(1.22\cdot\theta_{87})$.

The mode field diameter $MFD = 2w_0$ can be calculated using the relation between the far field w_{87} and the nearfield relation for a Gaussian beam in air:

$$\theta_{87}(z) = \tan^{-1}\left(\frac{W_{87}(z)}{z}\right) = \tan^{-1}\left(\frac{\lambda}{\pi w_0}\right) \tag{31}$$

For commercial fibers, NA and MFD are mentioned as specifications, along with the cut-off wavelength.

For measuring the core-cladding index contrast of a step-index fiber, a useful approximation is to imagine the light rays inside the fiber to be guided due to total internal reflection (Figure 6). To couple light effectively in the core of the fiber the incident angle of the light have to be smaller than θ_i as shown in (Figure 6). In analogy with lenses $\sin\theta_i$ is called numerical aperture (NA) and can be approximated with:

$$NA = n_0 \sin\theta_i = n_1\sqrt{2\Delta} \qquad \Delta \simeq \frac{n_1 - n_2}{n_1} \tag{32}$$

where n_1 and n_2 are core and cladding indices, respectively.

5 Outcome of the TP tasks

Upon completion of this practical work, you should be able to:

- Characterize a He-Ne laser beam (Beam profile, polarization, divergence)
- Maximize light coupling into a multimode fiber
- Maximize light coupling into a single mode optical fiber
- Compare the two coupling and their sensitivity to the setup parameters (alignment, angle etc).
- Characterize output profile of a single mode fiber
- Estimate the core-cladding index contrast
- Estimate the NA of a multimode fiber
- Determine the NA of a single mode fiber

5.1 Task 1: Questions for preparation of the TP

1. Laser class for HeNe laser.
2. How does the HeNe laser work?
3. What is the beam profile of the HeNe laser?
4. What is the approximate Rayleigh range of the HeNe laser?
5. What does the specified NA of a lens mean?
6. What is the real NA of a focusing setup?
7. How is the NA of an optical fiber defined?
8. What is the dimension of the multi-mode fiber core?
9. Which are the parameters defining coupling? Especially what is the relation between the NA of the focusing setup and the NA of the fiber, for optimal coupling? Why?
10. At what position should the fiber be placed with respect to the focused beam to have maximum coupling? Why?
11. How can you avoid cladding power to be measured?
12. How does the beam profiler work?

5.2 Task 2: Optical fiber

Complete Table 2 and Table 3, add the equations, units, and the value at the laser wavelength.

Table 1 Single mode fiber parameters (3M fiber)

	Fiber parameter	Symbol	equation	units	Value	Reference
1	wavelength	λ		μm		
2	Wave vector	k		μm^{-1}		
3	LP_{11} cut-off V-number	V_c				
4	Air RI (15°C, 1 atm)[2]	n_{air}				
5	LP11 – cut-off	λ_c		μm		
6	Numerical aperture	NA				
7	Core radius	a		μm		
8	Cladding radius	a_{cladd}		μm		
9	Fiber coating radius	$a_{coating}$		μm		
10	Core RI[3]	$n_{core}(\lambda)$				
11	Cladding RI [4]	$n_{cladd}(\lambda)$				
12	Germanium concentration	X		mol%		
13	v-number	V				
14	Normalized propagation const.	b				
15	Norm. transv. wavenum, core	u				
16	Norm. transv. wavenum, cladd	w				
17	Transverse wavenumber, core	κ		μm^{-1}		
18	Transverse wavenumber, clad.	σ		μm^{-1}		
19	Propagation constant	β		μm		
20	Effective index	n_{eff}				
21	Mode field diameter	MFD		μm		
23	Effective area	A_{eff}		μm		
24	Attenuation	α_{fiber}		dB/km		
26	Fresnel reflection at the fiber end					

Table 2 Multi mode fiber parameters

	Fiber parameter	Symbol	equation	units	Value	Reference
3	Numerical aperture	NA				
4	Core radius	a		μm		
5	Cladding radius	a_{cladd}		μm		
6	Fiber coating radius	$a_{coating}$		μm		
7	Cladding RI	$n_{cladd}(\lambda)$				
8	Core RI	$n_{core}(\lambda)$				
9	Germanium concentration	X		mol%		
10	v-number	V				

[2] See (Lide 1996)
[3] See (Fleming 1984)
[4] See (Malitson 1965), (Fleming 1984)

6 Experiment

6.1 Experimental setup and equipment

To perform experiments following equipment is used:

- Helium-Neon (HeNe) laser, 632.8 nm wavelength
- Power meter with detector head
- Fiber coupling lens (f=4.5 mm, N.A.= 0.42)
- BP209-VIS_M Beam Profiler with 25 µm slit width
- Fiber stripper
- Fiber cleaver
- Optical fiber aligner
- Single-mode, multimode fibers and fiber pigtails

6.2 Beam waist measurement using scanning

6.2.1 Setup

The set up for performing beam size is shown in Figure 7 and Figure 8. To measure beam diameter follow these steps:

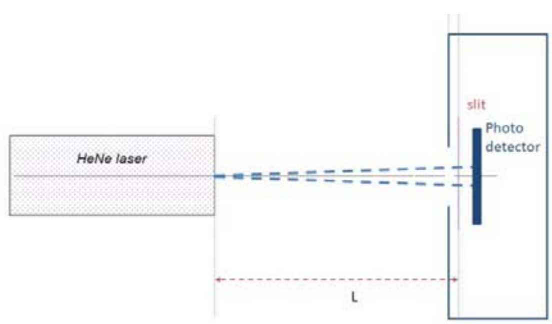

Figure 7 Setup for measuring beam diameter

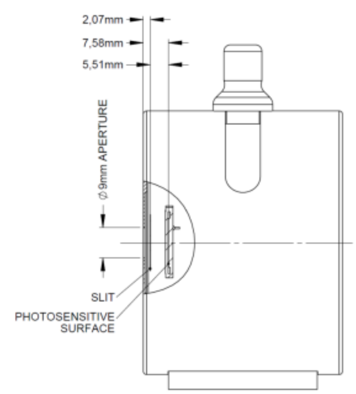

Figure 8 Detail of scanning unit

6.2.2 Beam waist measurement using beam profiler

See BP209 manual:

6.2.3 Task 3 Measure and determine the HeNe beam parameters

1. Align the entrance of the beam profiler in a way that the entire beam enters the entrance aperture, is scanned by the slit and is detected by the photodiode.
2. Determine the positions of these elements.
3. Measure the beam radius, w_0 .

4. Calculate the divergence of the laser. Use assumptions if necessary.
5. Calculate the Rayleigh range of the laser
6. Compare the results with typical HeNe characteristics
7. Determine which focusing condition in section 4.3 describes the setup.
8. Calculate the beam size at the fiber entrance.

6.3 Coupling of the HeNe laser into optical fibers

6.3.1 Setup

Figure 9 shows the set up for coupling light into an optical fiber.

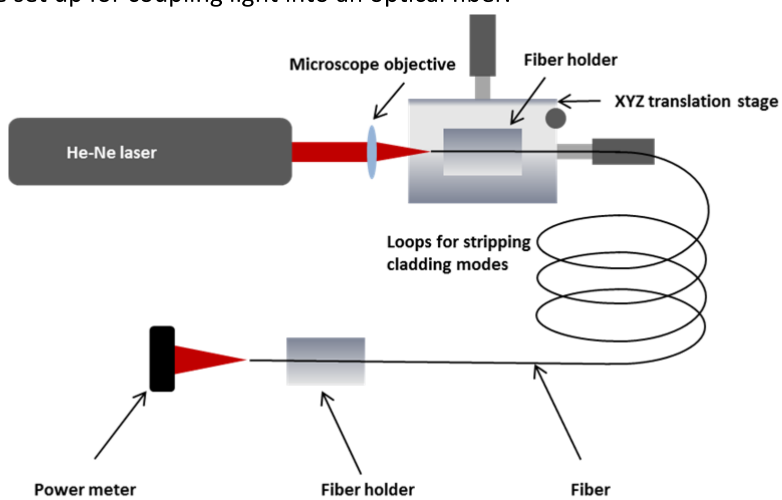

Figure 9 Setup for measuring laser-fiber coupling efficiency

6.3.2 Task 4 HeNe laser fiber coupling

1. Couple the HeNe laser into multimode and the single mode fiber and determine the coupling efficiency
2. Measure the laser output power and the power transmitted by the lens
3. Strip and cleave multimode fiber and position it inside fiber holder at xyz stage
4. Use the translational stage to optimize the coupling efficiency
5. Measure the maximum power (average, error)
6. Repeat 1-4 with a single-mode fiber Calculations and discussion
7. What is the value (also in dBs) of the coupling efficiency for the multimode and single-mode fiber?
8. Estimate the error in the coupling efficiency, with error bars.
9. Compare the coupling efficiencies between the two fibers.

10. Which fiber is more robust to misalignment?

6.4 Measurement of the single mode fiber out coupling

6.4.1 Setup

The set-up consists of a scanning slit (BP209-VIS_M) with a beam analyzer software (Figure 10 and Figure 11).

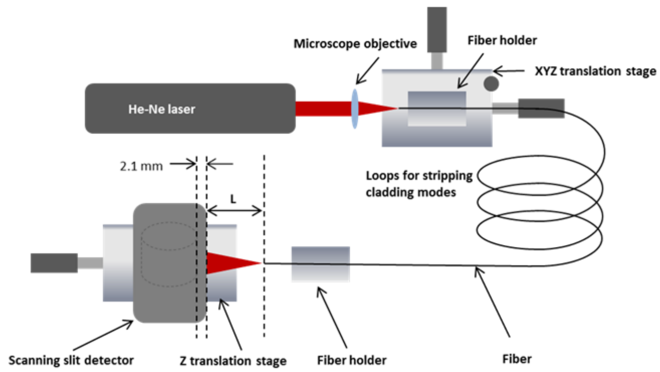

Figure 10 Setup for measuring fiber NA

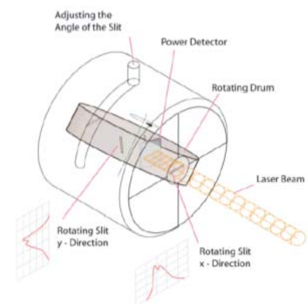

Figure 11 Detailed view of the scanning unit

6.4.2 Task 5 Beam size measure of the multimode fiber

Cleave the far end of the fiber and fix it on the translation stage. Then place the scanning unit at the distance *L* from the far end of the fiber. To get an approximate measure of the fiber's NA use the image formed on the BP209 detector (Figure 12). Measure the size, *D*, of the spot and the distance, *L*. The NA of the fiber is approximately given by $NA = \sin\left(\theta_{inc}\right)_{\max}$. Check how the image depends on the fiber movement.

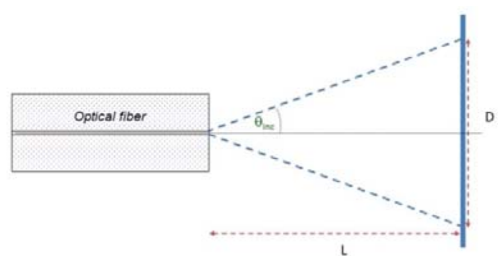

Figure 12 Measurement of multimode NA estimate

The size of the spot, *D*, at distance L gives the divergence $\theta_{inc} = \tan^{-1}\left(D/(2L)\right)$ which leads to the estimate of NA:

$$NA = \sin\left(\tan^{-1}\left(D/(2L)\right)\right) \approx D/(2L)^{5} \quad (33)$$

[5] Approximations: $\tan^{-1}(x) \approx x$ and $\sin(x) \approx x$

6.4.3 Task 6 Beam size measure of the single mode fiber and fiber parameters

Figure 13 shows the set-up for the beam size measurement. The slit is inside the beam profiler (2.07 mm) and the aperture of 9 mm limits the maximum distance (see also Figure 8).

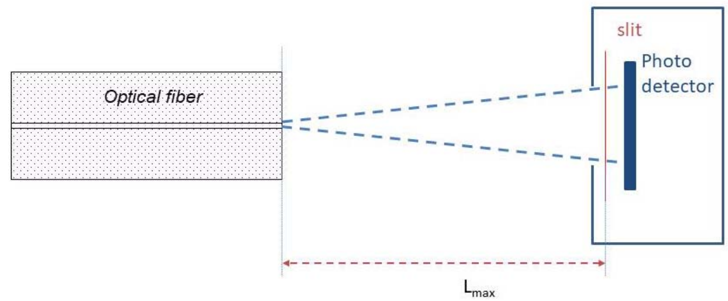

Figure 13 Measurement of fiber beam profile. The aperture (9 mm) limits the maximum distance.

1. Place the fiber end into the xyz translation stage
2. Measure the output beam dimensions at several distances z from the fiber end (z_{min}, z_{max}, Δz)
3. Get the data from the system for further analysis

Calculations

1. Calculate the NA of the out coupled beam, and the mode field diameter, MFD
2. Calculate the core and cladding indices.
3. Compare the measured distribution with a Gaussian fit (linear and log scale) and discuss the difference.
4. Determine the ellipticity.

7 Further questions

- Which fiber is better for optical communication? Why?
- Which fiber is easier to use for imaging applications?
- Which fiber is better for power delivery? Why?

8 Annex

8.1 Gaussian beam size definitions

Table 3 Summary of Gaussian beam size definitions

Aperture	Normalized Intensity I/I_0	Normalized power inside the aperture: $1-\left(P(\rho)/P(\infty)\right)$
$\frac{\rho_{63}}{\omega_0}=\sqrt{-\frac{\ln\left(e^{-1}\right)}{2}}=\frac{1}{\sqrt{2}}$	$1/e=0.37$	0.63
$\frac{\rho_{87}}{\omega_0}=\sqrt{-\frac{\ln\left(e^{-2}\right)}{2}}=1$	$1/e^2=0.135$	0.865
$\frac{\rho_{95}}{\omega_0}=\sqrt{-\frac{\ln(0.05)}{2}}=1.22$ [6]	0.05	0.95
$\frac{\rho_{99}}{\omega_0}=\sqrt{-\frac{\ln(0.01)}{2}}=1.517$	0.01	0.99

8.2 Data sheets

- Beam profiler BP 209 VIS
- BP209-VIS_M-Manual

8.3 Optical fibers

Figure 14 Multimode fiber

Figure 15 Single mode fiber

8.4 Fiber preparation

From (Yablon 2005)

[6] This beam diameter ($2\cdot\rho_{95}$) corresponds to the general definition of N.A. However sometimes the diameter at $I/I_0=0.01$ is used for the definition ($2\cdot\rho_{99}$).

8.4.1 Coating stripping

We can find basically three processes:

i. *Mechanical*
ii. *Thermo-Mechanical Stripping Techniques*
iii. *chemical stripping"*

8.4.2 Fiber cleave

"*A general cleaving strategy that is employed is known as the scribe-and-tension strategy or the scribe-and-break strategy. This process involves introduction of a crack in the fiber, generally by means of cutting tool made from a material such as diamond, sapphire, or tungsten carbide, followed by the application of tensile stress in the vicinity of the crack. However, the specific implementations of the cleaving vary and result in cleaves of different qualities:"* (Yablon 2005)

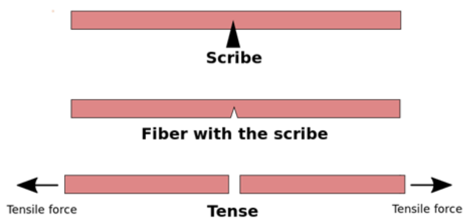

Figure 16 Fiber cleave:
Schematic illustration of scribe-and-tension strategy for cleaving optical fibers (Fig. 2.4. in (Yablon 2005)) and (https://en.wikipedia.org/wiki/Cleave_(fiber))

8.4.3 Fiber mode conditioning

See http://www.thefoa.org/tech/ref/testing/test/loss.html

"There are three basic ways to condition the modal distribution in multimode or few mode fibers:

- *mode strippers which remove unwanted cladding mode light,*
- *mode scramblers which mix modes to equalize power in all the modes, and*
- *mode filters which remove the higher order modes to simulate equilibrium modal distribution (EMD) or steady state conditions.*

Light coupled into the cladding of a few-mode fiber is in general strongly attenuated. For short fibers (meter range) one might use cladding mode stripping technique with cladding removed over 50-75 mm immersed in index matching liquid and/or gentle S-bends. Another technique is the mandrel wrap

Single mode fibers shorter than 10 m may have several modes. To insure short cables have only one mode of propagation, one can use a simple mode filter made from a 50-150 mm loop of the cable."

9 Literature

Basic literature and further reading

1. (Saleh and Teich 2007) Recommended
2. (Marshall 1985)
3. (O'Shea 1985)
4. (Taylor 1997)
5. (Drosg 2009), http://link.springer.com/book/10.1007/978-3-540-29608-9/page/1
6. (Johnston 1998)
7. (Agrawal 1992)
8. (Bevington and Robinson 1992)
9. (Okamoto 2006), http://www.sciencedirect.com/science/book/9780125250962
10. (Murata 1996)
11. (Colladon 1842)
12. (Hecht 1999)

Web sites

- http://www.lanshack.com/fiber-optic-tutorial-basics.aspx (21.4.2016)
- http://www.newport.com/store/genContent.aspx/Fiber-Optic-Coupling/144877/1033 (21.4.2016)
- http://www.newport.com/store/genContent.aspx/Gaussian-Beam-Optics/144899/1033 (21.4.2016)
- http://www.newport.com/Tools/OpticalAssistant/ (21.4.2016)
- http://www.newport.com/store/genContent.aspx/Tutorial-Light-Collection-and-Systems-Throughput/381845/1033 (21.4.2016)
- http://www.nxtbook.com/nxtbooks/newportcorp/resource2011/#/0 (21.4.2016)
- https://en.wikipedia.org/wiki/Cleave_(fiber) (26.2.2019)
  http://www.thefoa.org/tech/ref/testing/test/loss.html (27.2.2019)

10 List of Figures

11 List of tables

12 List of tasks

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Saleh, B. E. A. and M. C. Teich (2007). Fundamentals of photonics. New York, N.Y., Wiley-Interscience.
Taylor, J. R. (1997). An introduction to error analysis : the study of uncertainties in physical measurements. Sausalito, California, University Science Books.
Yablon, A. D. (2005). Optical Fiber Fusion Splicing. Berlin, Springer.