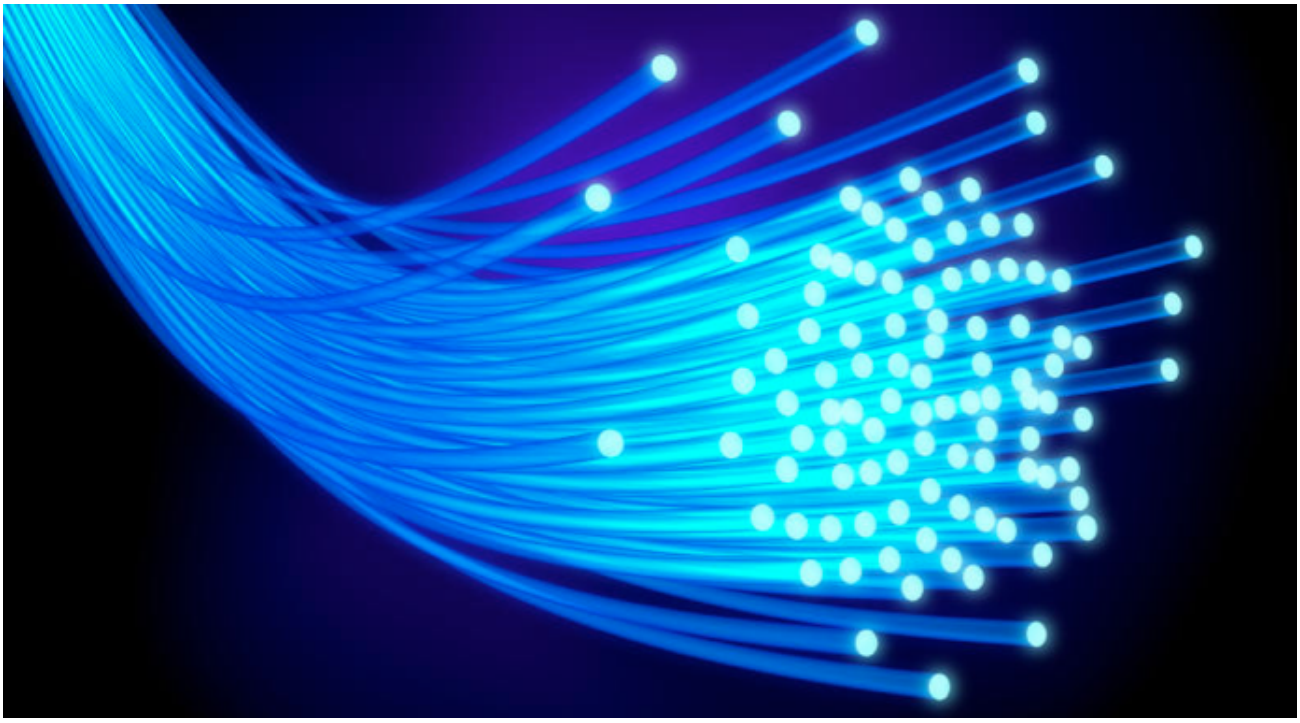
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Fiber Optics and Gaussian Laser Beams



Tanguy Falkenback (†), Ambrine Douhane (§)
Sciper: [350603] (†), [282708] (§)
Course: MICRO - 423
Teachers: Ye Pu & Demetri Psaltis
TA: Li Zhang
Date: March 11, 2026

EPFL

CONTENTS

LIST OF FIGURES

LIST OF TABLES

***Abstract*—This report summarizes the experimental results obtained to gain theoretical understanding and practical knowledge of fiber optic coupling and Gaussian beam optics.**

I. Introduction

Nowadays, optical fibers are a prevalent component for telecommunications and computer networks. These are replacing conventional electrical wires for communications because of their ability to carry some information over long distances, due to their highly reflective matter. These are often coupled with lasers that income some light signals in it.

The *Global Optical Fiber Market* published a report in which they estimated that the global optical fiber market will reach 8,153 million US-dollars by 2025, growing at a CAGR of 11.6% from 2018 to 2025 [1], which gives a good global idea of how essential fiber optics are today and will be in the future.

In this report, we will first have a look on the theory of basic optics, then we will measure the waist w_0 of the laser beam, and finish with the study of laser-fiber coupling.

II. Theoretical background

The purpose of this chapter is to answer the questions asked in the assignement in order to develop the theory of optical fibers. Most of the answers can be found in the assignement theory chapter [3].

- Laser class for HeNe laser.

The HeNe laser is a 3B class laser which means it is hazardous for eye exposure.

- How does the HeNe laser work ?

A helium–neon laser (or He-Ne laser) is composed by a mixture of helium and neon gases with ration of usually 10:1 or 5:1. The creation of the laser beams happens when the inversion of population occurs, i.e. when the numbers Ni of electrons in the higher energy states E_i are bigger than the N_0, the number of electrons in lower energy state E_0. To do this, one shall pump the mean. This is done by placing two electrodes in the cavity: one cathode and one anode. Then, some high DC voltage is applied which creates an electric field that ionizes the gas. Since the energy of the excited states of helium atoms is very similar to neon's ones, the energy of helium is transferred to the second by successive collisions which bring thus helium atoms to ground state and neon atoms in higher metastable E3 and E5 energy states. After a while, spontaneous emission happens: the latters spontaneously fall down into the next lower energy states (E2 and E4) by yielding some optical energy. This energy is basically photons with a certain wavelength, in particular $\lambda = 632.8\,\mathrm{nm}$ (see Figure 1).

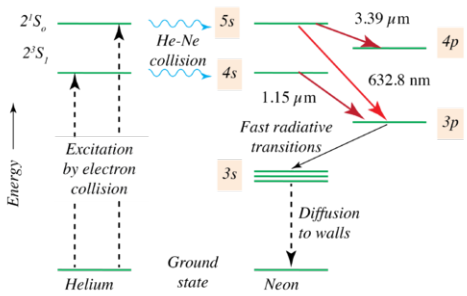


Fig. 1. Energy levels in a He-Ne Laser [2]

- What is the beam profile of the HeNe laser ?

The beam profile of the HeNe laser is circular and almost an ideal gaussian TEM_{00}. *"It is the lowest-order transverse electromagnetic 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"* [3].

- What is the approximate Rayleigh range of the HeNe laser?

The approximate Rayleigh range of the HeNe laser is given by the equation (1) with $w_0 = 0.24\ mm$ and $\lambda = 632.8\ nm$.

$$z_R = \frac{\pi w_0^2}{\lambda} \tag{1}$$

After replacing the variables by their actual values, the Rayleigh range is $0.286\ m$. This Rayleigh range will define different areas to put the lens (see page 8 of assignment).

- What does the specified NA of a lens mean?

NA means "Numerical Aperture" and is a number between 0 and 1 which characterizes the ability of a lens to accept a certain range on angles of incoming light. It is defined as $NA = nsin(arctan(\frac{D}{2f}))$ for $D[\mathrm{m}]$ and $f[\mathrm{m}]$ both shown in Figure 2.

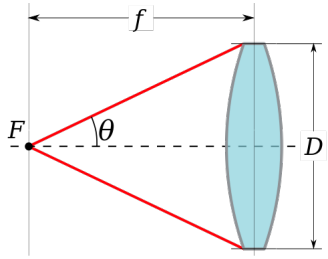


Fig. 2. Numerical aperture of a lens [4]

- What is the real NA of a focusing setup?

The real NA of a focusing setup is related to the beam size. It is a dimensionless number defining the range of angles accepted. Within this range, the system is able to emit and receive light.

- How is the NA of an optical fiber defined?

For an optical fiber, the numerical aperture can be computed with Equation 2.

$$NA = sin(\theta_{inc})_{max} = \frac{1}{n_{ext}}\sqrt{n_1^2 - n_0^2} \tag{2}$$

where the different indexes of refraction are shown in Figure 3. $(\theta_{inc})_max$ is the maximum acceptance angle below which the fiber is not able anymore to guarantee the propagation of the incoming light. Indeed, for bigger θ_{inc}, the light is not totally refracted at the interface between the core and the cladding.

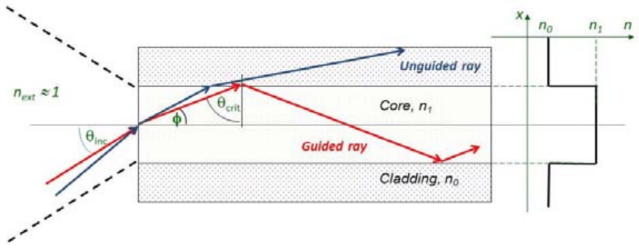


Fig. 3. Light guiding inside optical fiber and definition of numerical aperture [3]

- What is the dimension of the multi-mode fiber core?

Based on the Thorlabs specifications [18], the core diameter is $50\ \mu m \pm 2\%$, the $NA = 0.22 \pm 0.02$ and the cladding diameter is $1.25 \pm 1\ \mu m$. With this specifications, some assumptions can be made. The first one is that the light has to be focused on a smaller aperture than the circle created by the core diameter otherwise there will be losses. The second assumption is related to optimal coupling and is explained in the next point.

- 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?

A good coupling makes the power of the incoming light close to the light going out of the fiber. It is important for optimal coupling to have $NA_{setup} \leq NA_{fiber}$ to permit all modes to propagate through the fiber [8]. If the user assures that the maximal ray of the focused beam is well within the NA of the fiber, then effective coupling will be accomplished.

- At what position should the fiber be placed with respect to the focused beam to have maximum coupling? Why?

If it is possible, the fiber should be placed as close as possible to the spot where the light is the most focus (after a focal length of the lens concentrating the rays). This allows all the information to go inside the core of the optical fiber.

- How can you avoid cladding power to be measured?

Two good ways to avoid cladding power to be measured are using a pinhole placed between the laser and the fiber to only transmit the light of the core ; but also using cladding mode strippers. These can be used to remove any light being propagated in the cladding and thus not to measure the cladding power.

- How does the beam profiler work?

A beam profiler is a device with which we can measure the intensity profile of a laser beam. To do this, it captures, displays, and records the spatial intensity profile of a laser beam at a particular plane transverse to the beam propagation path [5].

- n_{core} and $n_{cladding}$

This small clarification point is dedicated to explain how the value of n_{core} and $n_{cladding}$ are found using a equations system and the numerical aperture. It is possible to characterize an optic fiber by its reflection index difference. Therefore, Equation (3) is obtained.

$$\delta = \frac{n_{core}^2 - n_{cladding}^2}{2n_{core}} \approx 1 - \frac{n_{cladding}}{n_{core}} \tag{3}$$

It is possible to link this new variable to the numerical aperture under the assumption that n_{core} is greater than $n_{cladding}$.

$$NA \approx n_{core}\sqrt{2\delta} \tag{4}$$

To obtain the second equation and complete the system, the formula (5) is used.

$$n_{core} = \sqrt{n_{cladding}^2 + NA^2} \tag{5}$$

This system is difficult to solve so values from the literature are used instead.

TABLE I
SINGLE MODE FIBER PARAMETERS (3M FIBER)

	Fiber parameter	Symbol	Equation	Units	Value	Reference
1	Wavelength	λ	-	μm	0.6328	Assignment
2	Wave vector	k	$k = \frac{2\pi}{\lambda}$	μm^{-1}	9.93	-
3	LP11 cut-off V-number	v_c	$v_c = j_{0,1} = \frac{2\pi}{\lambda_c} a\ NA$	-	2.4048	Assignment
4	Air RI (15°C, 1 atm)	n_{air}	-	-	1.000293	Wikipedia
5	LP11 – cut-off	λ_c	-	μm	< 0.62	Ref (1)
6	Numerical aperture	NA	$NA = \sqrt{n_1^2 - n_0^2}$	-	$0.12\ \pm 0.02$	Ref (1)
7	Core radius	a	$a = \frac{\lambda_c v_c}{2\pi NA}$	μm	1.976	-
8	Cladding radius	a_{cladd}	-	μm	62.5 ± 0.5	Ref (1)
9	Fiber coating radius	$a_{coating}$	-	μm	122.5 ± 7.5	Ref (1)
10	Core RI	$n_{core}(\lambda)$	-	-	1.5	-
11	Cladding RI	$n_{cladd}(\lambda)$	$\sqrt{n_{core}^2 - NA^2}$	-	1.495 ± 0.0343	-
12	Germanium concentration	X	-	$mol\ \%$	?	-
13	v-number	v	$v = kaNA$	-	2.35 ± 0.39	-
14	Normalized propagation const.	b	$b = (1.1428 - \frac{0.996}{v})^2$	-	0.517 ± 0.09	-
15	Norm. transv. wavenum, core	u	$u = v_c e^{\frac{-0.8985}{v}}$	-	1.529 ± 0.09	-
16	Norm. transv. wavenum, cladd	w	$1.1428v - 0.996$	-	1.69 ± 0.45	-
17	Transverse wavenumber, core	κ	$\kappa = \frac{u}{a}$	μm^{-1}	0.774 ± 0.046	-
18	Transverse wavenumber, clad.	σ	$\sigma = \frac{w}{a}$	μm^{-1}	0.855 ± 0.23	-
19	Propagation constant	β	$\beta = \sqrt{\sigma^2 + k^2 n_{cladd}^2}$	μm	14.55 ± 0.018	-
20	Effective index	n_{eff}	$n_{eff} = \frac{\beta}{k}$	-	1.465 ± 0.0021	-
21	Mode field diameter	MFD	-	μm	4	Ref (1)
23	Effective area	A_{eff}	$A_{eff} = 2\pi\omega^2$	μm	?	-
24	Attenuation	α_{fiber}	-	dB/km	10 ± 2	Ref (1)

TABLE II
MULTI MODE FIBER PARAMETERS

	Fiber parameter	Symbol	Equation	Units	Value	Reference
3	LP11 cut-off V-number	v_c	$v_c = \frac{2\pi}{\lambda_c} a\ NA$	-	2.4048	Assignment
4	Air RI (15°C, 1 atm)	n_{air}	-	-	1.000293	Wikipedia
5	LP11 – cut-off	λ_c	-	μm	< 0.62	Ref (1)
6	Numerical aperture	NA	-	-	0.1 ± 0.015	Ref (2)
7	Core radius	a	-	μm	5 ± 1.5	Ref (2)
8	Cladding radius	a_{cladd}	-	μm	62.5 ± 1	Ref (2)
9	Fiber coating radius	$a_{coating}$	-	μm	122.5 ± 5	Ref (2)
10	Core RI	$n_{core}(\lambda)$	-	-	1.46	Ref (2)

Ref (1) = the 3M Optical Fiber Single Mode from Thorlabs [10].
Ref (2) = FG010LDA Datasheet from Thorlabs [18].
Note that for the multi mode LP11 cut-off V-number, no value was found so the value of the single mode was reused.

III. Measurement of the beam waist w_0

This experiment will define the value of the beam waist w_0 (see Figure 4). To do so, multiple measurements are taken at different distances in order to fit as much as possible a curve with equation profile as in formula (6).

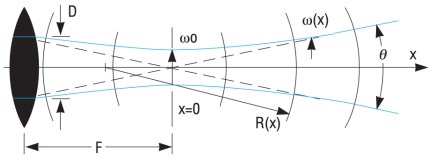


Fig. 4. Gaussian Beam representation [19]

Note that in Figure 4, the x-axis of propagation is called z-axis in this report.

$$w(z) = w_0 \sqrt{1 + (\frac{z}{z_R})^2} \tag{6}$$

In this equation, two parameters can be chosen to have the best curve for a given set of points. In fact, because of Equation (7), z_R can be expressed as a function of w_0.

$$z_R = \frac{\pi w_0^2}{\lambda} \tag{7}$$

The final profile is then the expression here under and it contains only one unknown (w_0). Indeed, z and $w(z)$ are the data previously acquired.

$$w(z) = w_0 \sqrt{1 + (\frac{z\lambda}{\pi w_0^2})^2} \tag{8}$$

A. Setup

The setup is shown on Figure 5. It is made of a He-Ne laser (see Figure 21) emitting a ray at a wavelength of $\lambda = 632.8\ nm$. The reflector allows to redirect the ray on the camera. It is a $BP209-VIS\_M$ beam Profiler of Figure 15 with 25 μm slit width furnish by Thorlabs and connected to a computer. This computer runs a program to show the laser behaviour detected by the camera.

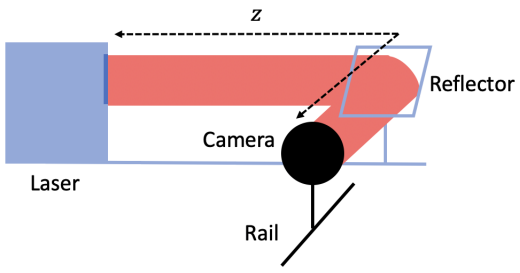


Fig. 5. Experimental setup for beam waist measurement

B. Results

The data was extracted from the computer as csv files. They are matrices of data where one number represents the value of a pixel at a given place on the output image. From this matrix, the row containing the maximal value is extracted. Indeed, the gaussian behaviour is logically located where the laser hits the camera and therefore where the intensity is the highest. Based on this observation these rows are plotted for different distances. The distances are taken from 36 cm to 42 cm with gaps of 1 cm between each measurement. Figure 6 shows the gaussian curves for each distances. The small shifts between the gaussians could be due to a movement of the camera but this won't impact the results. Indeed, the purpose here is to compute the spacing between the peak of the curve and the place were the curve has decreased by a factor e^{-2} (see Figure 7).

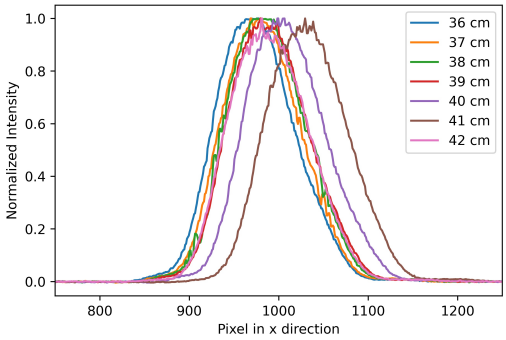


Fig. 6. Gaussians curves for every distances

The results of the experiment performed are given in Table III where z is the distance shown on the setup (Figure 5) and $w(z)$ can be found based on the distance between the two red lines on Figure 7. To obtain the value of $w(z)$, it is needed to multiply the number of pixels between the two lines by the size of one pixel. According to the data sheet [12], the pixel dimension is $5.2\,\mu m^2$. It is obtained by dividing the number of pixels the camera contains by its size. The distance is given by Equation (9) where M is the number of pixels and d is the width of a pixel.

$$w(z) = M \times d \tag{9}$$

TABLE III
Results to obtain beam waist w_0

z	Units	$w(z)$	Units
36	cm	462.8	μm
37	cm	343.2	μm
38	cm	520	μm
39	cm	525.2	μm
40	cm	530.4	μm
41	cm	483.6	μm
42	cm	504.4	μm

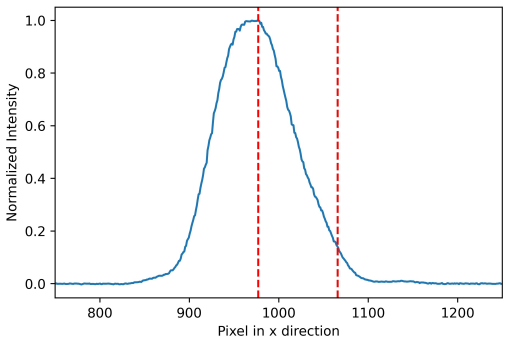


Fig. 7. Gaussian curve for $z = 36\ cm$

It is now possible to plot the points (z,$w(z)$) on a graph to find a curve fitting these data. This curve must be a function of the type represented in Equations (6) and (8).

Based on the equations, w_0 is found by taking the value of $w(z = 0)$. To find the best value of w_0 for the points on Figure 8, a set of value for w_0 is taken and each value is tried. The one minimizing the error is then kept as the best w_0 value.

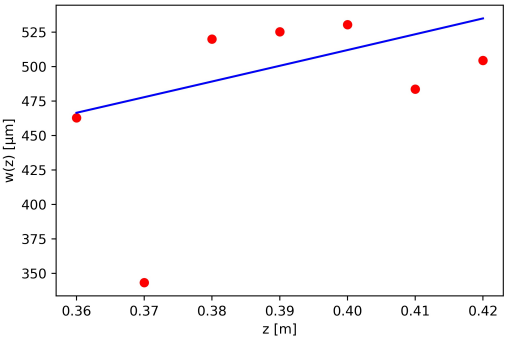


Fig. 8. Curve fitting the data

Note that the value for $z = 37\ cm$ is probably an error of measurement as the normal behaviour should be rising with z increasing.

The curve can be extended to $z = 0$ to see the value of w_0 obtained. This curve is shown on Figure 9. For this case the value of w_0 is $0.17\ mm$ and therefore the value of z_r is $13\ cm$.

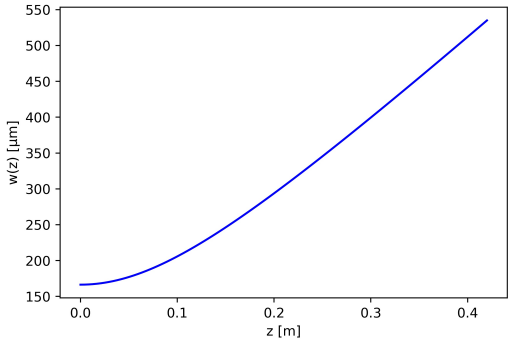


Fig. 9. Curve fitting the data going to $z = 0\ m$

It is possible to find the divergence of the beam (θ_0). It represents the half angle of the cone created by the laser. The equation for θ_0 is given by equation (10). Using equation (7), it is possible to simplify the equation to have an expression of θ_0 as a function of w_0 and z_r. Note that this divergence is computed in the far-field ($z > z_r$). This hypothesis is here fulfilled because $z_{min} = 36\ cm$ and $z_r = 13\ cm$. The value of θ_0 is then $1.21\ mrad$.

$$\theta_0 = \frac{w(z)}{z} = \frac{w_0}{z_r} \tag{10}$$

To see how efficient the method used is and to validate the results, it is important to compare what was obtained with real values of the laser. By looking in the literature ([20]), it is found that the beam waist of the laser used is $w_0 = 0.24\ mm$ (diameter of $.48\ mm$). The divergence is also given and is equal to $1.7\ mrad$.

TABLE IV
COMPARISON OF EXPERIMENTAL AND REAL VALUES

	w_0	Units	θ_0	Units
Experimental	0.17	mm	1.21	$mrad$
Real	0.24	mm	1.7	$mrad$

This gives a relative error of 29.2% for the waist and 28.9% for the divergence. These results make our experiment not very satisfying, even if the orders of magnitude are correct.

IV. COUPLING OF THE HENE LASER INTO OPTICAL FIBERS

A. Setup

The setup used for measuring the laser-fiber coupling efficiency is shown in Figure 10. It is made of the laser, which light is focused by a microscope for reaching the thin fiber. The fiber is held by an instrument that can translate in the three dimensions, this to achieve the coupling. It is clear that the most difficult part of the coupling is the step consisting in the alignment of the incoming light and the fiber. The use of a white paper sheet can help for getting the precise location of the light spot, and thus for knowing where exactly the end of the fiber shall be. Then light propagates in the fiber and reaches

the power meter. Both the fiber and the power meter are fixed. More generally, every tool of such a sensitive measurement has to be fixed to get accurate results and not to take any risk with the laser.

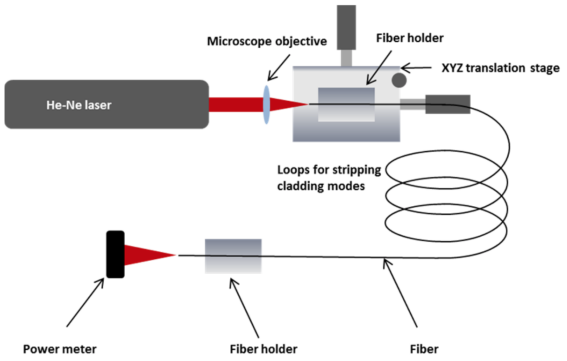


Fig. 10. Setup for measuring laser-fiber coupling efficiency [3]

To achieve coupling, the coating is removed with a stripping tool 18. This step is very sensitive. It is hard to remove the coating without breaking the core. Then, the end of the fiber is cut with a cleaver shown in Figure 20 to make the end surface as normal as possible to the fiber axis. Note that this removal decreases the efficiencies of the transmission, but it is essential for making the coupling possible, otherwise the light would never have reached the core. Then, the fiber is washed with some paper and sanitizer.

B. Coupling efficiency

To compute the efficiency, different measurements of power are needed. The computation is done for multi mode and single mode optic fibers. In both cases, to have an order of efficiency, the output power of the fiber has to be divided by the input power. The question is: what input power to take. In order to only characterize the fiber, the input power must be measured after the lens.

$$\eta_{single} = \frac{P_{output,single}}{P_{output,lens}} = 0.83\% \tag{11}$$

$$\eta_{multi} = \frac{P_{output,multi}}{P_{output,lens}} = 3.33\% \tag{12}$$

The total efficiency can also be measured by taking the power coming from the laser. Equations (13) and (14) show how to measure these efficiencies.

$$\eta_{single,tot} = \frac{P_{output,single}}{P_{laser}} = 0.71\% \tag{13}$$

$$\eta_{multi,tot} = \frac{P_{output,multi}}{P_{laser}} = 2.86\% \tag{14}$$

The result here above are found based on the values obtained during the experiments (see below). It seems trivial that the efficiency decreases as the path gets longer but this intuition is confirmed by the results. Note that the multi mode wasn't properly working during the lab so the power at the output of that fiber was found in the literature.

- $P_{laser} = 0.7\ mW$
- $P_{output,lens} = 0.6\ mW$
- $P_{output,single} = 0.005\ mW$
- $P_{output,multi} = 0.02\ mW$

C. Beam size measure of the single mode fiber

The same methodology is applied to find the beam size after going through the optical fiber. The first observation is that there is still a gaussian behaviour but it has been slightly impacted by the fiber.

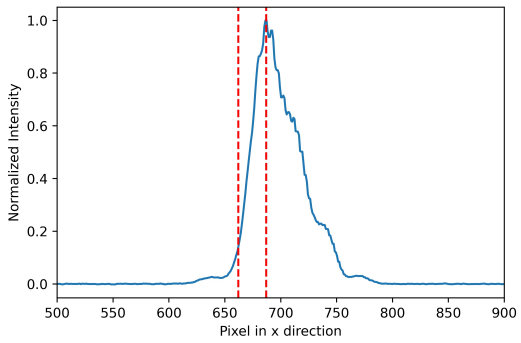


Fig. 11. Normalized output of the single mode fiber at a distance of 0 cm

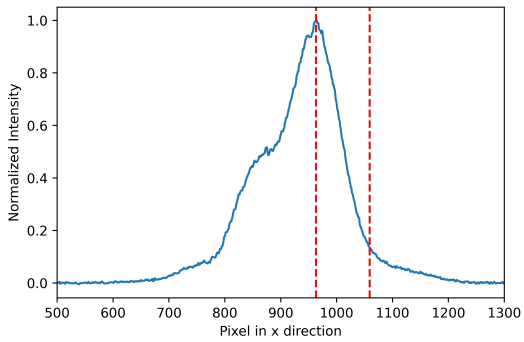


Fig. 12. Normalized output of the single mode fiber at a distance of 1 cm

The number of pixels between the maximum and the point where the curve as decreased by a factor of e^{-2} is 25 for a distance of 0 cm and 96 for a distance of 1 cm. The width of a pixel is 5.2 μm and therefore the beam radius are 0.13 mm and 0.5 mm respectively for distances of 0 cm and 1 cm. To obtain the diameter, the radius is multiplied by 2 under the assumption that the output of the fiber is symmetric (it is close to a gaussian).

Based on the diameter computed and the distance of the measurement, it is possible to obtain the numerical aperture and the MFD. Following formula's (15) and (16), the results

are found and put in Table V. The measurement at $0\ cm$ is problematic because it creates an infinite numerical aperture. If the experiment was to be done again, the measurement would be done at others distances and more samples would be taken (eg : $1\ cm$, $3\ cm$ and $5\ cm$).

$$NA = \sin\left(\arctan\left(\frac{D}{2L}\right)\right) \approx \frac{D}{2L} \tag{15}$$

In the expression above, D is the diameter measured and L is the distance between the output of the fiber and the place where the data was collected.

$$MFD = 2w_0 = \frac{2\lambda}{\pi NA} \tag{16}$$

TABLE V
RESULTS OF THE BEAM DIAMETER, NUMERICAL APERTURE AND MFD FOR THE SINGLE MODE FIBER

Distance	Beam diameter	NA	MFD
$0\ cm$	$260\ \mu m$	∞	$0\ \mu m$
$1\ cm$	$1\ mm$	0.05	$8.057\ \mu m$

D. Beam size measure of the multi mode fiber

During the laboratory, the multi mode fiber wasn't properly working. This may be due to misalignment between the fiber and the focused laser or to a intern problem in the fiber. To make the laser enter the fiber the cable was stripped and this procedure may have damage the material.

Theoretically, and based on the data of Prof. Donald C. O'Shea (Georgia Institute of Technology) in its book *Elements of Modern Optical Design* [17], we would have obtained the Figure 13 with our software.

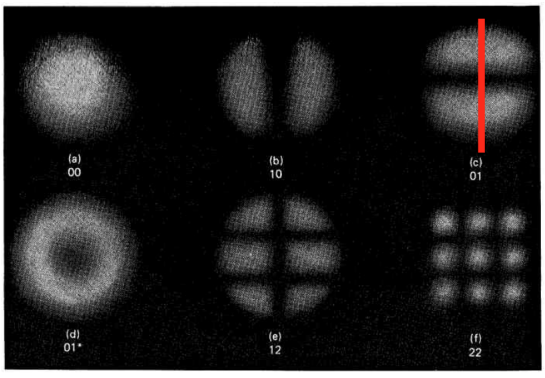


Fig. 13. Transverse mode distributions

Along the red line of Figure 13, the intensity of the light is given in the same book by Figure 14.

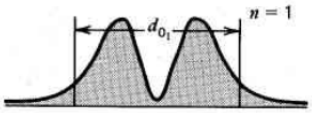


Fig. 14. Profile for a 1-order mode

It is clear that the global shape can be approximated to a product of a Gaussian distribution and a polynomial (Hermite) function. Two peaks means two modes are propagating in the multi-mode fiber.

Like it has been done for a single mode fiber, this graph allow to compute the numerical aperture of this fiber. It is given by the formula of Equation (15) with $D = d_{0_1}$ in the image. To get the actual $NA = 0.39$ of the data sheet, for $L = 1\,\mathrm{cm}$ a good value of D would be $D = 0.78\,\mathrm{cm}$.
It can also be interesting to verify the indices of refraction for the core and the cladding, to see if the NA of the data sheet is coherent. According to the script [3], we have Equation (17) for a step index structure and a small angle of incidence:

$$NA \approx n_1\sqrt{2\frac{n_1 - n_2}{n_1}} \tag{17}$$

where $n_1 = 1.46$ is the core index and $n_2 = 1.39$ is the cladding index. We should have:

$$NA \approx 1.46\sqrt{2\frac{1.46 - 1.39}{1.46}} \approx 0.45 \tag{18}$$

This value of $NA = 0.45$ is very close to the theoretical one of 0.39.

V. CONCLUSION

This optics laboratory work allowed us to put a finger on some specific characteristics of a data transmission through fiber, from the physics behind the creation of light by the laser to the outcome of this light transmitted.

We understood that different optical fibers can be used for communications, depending on the type of service we want it to perform: whether for long-reach data transmission (single mode fibers) or shorter distances (multi-mode fibers). Indeed, multi-mode fibers can guide light with poor beam quality and high optical power, which is interesting for short distance transmissions ; but a smaller core and a moderate numerical aperture (e.g. single mode) is better if one needs a good beam quality of a light source with higher radiance. About the efficiencies, we could see that the multi-mode fibers have better efficiency than the single mode fibers (about a factor 4 between the results of Section IV-B) even if the values obtained are really low. Our first intuition is a none perfect alignment of the laser with the fiber.

Practically, it was the first time for us using a laser and we scrupulously applied the appropriate safety measures. We also had the opportunity to truly feel the beam radius profile,

with the immediate perception of the size of the light spot with the software.

An interesting aspect that we did not measure is the influence of bending the fibers in the transmission. This could be done in another practical work or in later other works.

References

[1] Allied Market Research, *Global Optical Fiber Market by Mode: : Opportunity Analysis and Industry Forecast, 2018 - 2025* [Internet]. https://www.alliedmarketresearch.com/optical-fiber-market

[2] Wikipedia, *Helium–neon laser* [Internet]. https://en.wikipedia.org/wiki/Helium\OT1\textendashneon_laser

[3] Hans G. Limberger, (2019) *Optics Laboratory Work: Fiber Optics and Gaussian Laser Beams* [PDF]

[4] Wikipedia, *Numerical aperture* [Internet]. https://en.wikipedia.org/wiki/Numerical_aperture

[5] Wikipedia, *Laser beam profiler* [Internet]. https://en.wikipedia.org/wiki/Laser_beam_profiler

[6] Newport, *Fiber Optic Basics* [Internet]. https://www.newport.com/t/fiber-optic-basics

[7] The Fiber Optic Association, *Optical Fiber Testing - Loss and Attenuation Coefficient* [Internet]. https://www.thefoa.org/tech/ref/testing/test/loss.html

[8] Newport, *Technical Note: Fiber Optic Coupling* [Internet]. https://www.newport.com/n/fiber-optic-coupling

[9] Thorlabs, *Step-Index Multimode Fiber Optic Patch Cables: SMA to SMA* [Internet]. https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=351#1508

[10] Thorlabs, *Single Mode Fiber* [Internet]. https://www.thorlabs.com/drawings/db0c93ef160ce47-2B2C8D29-E99F-9815-45AA2502675DDCA6/SM450-SpecSheet.pdf

[11] Thorlabs, *630nm single mode fiber: 3M* [Internet]. https://www.thorlabs.com/catalogpages/v16/512.pdf

[12] Thorlabs, *Scanning-Slit Optical Beam Profilers* [Internet]. https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=804

[13] Thorlabs, *Digital Handheld Optical Power and Energy Meter Console* [Internet]. https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=3341

[14] Thorlabs, *Three-Hole Fiber Stripping Tool* [Internet]. https://www.thorlabs.com/catalogpages/Obsolete/2016/T865.pdf

[15] Thorlabs, *M72L02 Fiber* [Internet]. https://www.thorlabs.com/thorproduct.cfm?partnumber=M72L02

[16] RP Photonics Encyclopedia, *Multimode Fibers* [Internet]. https://www.rp-photonics.com/multimode_fibers.html

[17] O'Shea, New York (1985) *Elements of modern optical design* [Wiley]

[18] ThorLabs, *FG010LDA Datasheet* [Internet]. https://www.thorlabs.com/drawings/94a295b1c6393f9-08DA24D0-A831-E9C2-22237B2C20CC602F/FG010LDA-SpecSheet.pdf

[19] Newport, (2016) *Gaussian Beam Optics PDF*

[20] Thorlabs, *HNLS008L-JP HeNe Laser* [Internet]. https://www.thorlabs.com/thorproduct.cfm?partnumber=HNLS008L-JP#ad-image-0

VI. Appendix

Fig. 15. Thorlabs Beam Profiler BP 209 VIS [12]

Specifications:

- Wavelength Range from 200 to 2700 nm
- For Near-Gaussian Beams from Ø2.5 µm to Ø9 mm
- Scanning-Slit and Knife-Edge Operating Modes

Fig. 16. Thorlabs Digital Optical Power and Energy Meter PM100D [13]

Specifications:

- Wavelength Range from 185 nm to 25 µm
- Optical Power Range from 100 pW to 200 W

Fig. 17. Thorlabs Slim Photodiode Power Sensor S132C [13]

Specifications:

- Aperture size of Ø9.5 mm
- Wavelength Ranges from 700 nm to 1800 nm
- Optical Power Range from 5 nW to 5 mW

Fig. 18. FTS4 Three-Hole Fiber Stripping Tool [14]

Specification:

- Three holes

Fig. 19. Thorlabs multimode fiber M72L02 [15]

Specifications:

- Numerical aperture of 0.39
- Diameter of $200\,\mu\mathrm{m}$
- Length of $2\,\mathrm{m}$

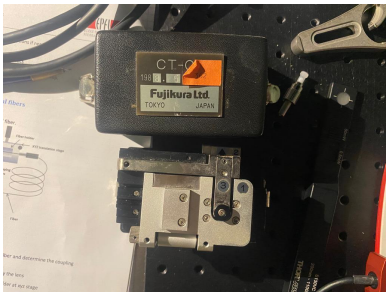


Fig. 20. Fujikura Fiber Cleaver

Fig. 21. Thorlabs HNLS008L-JP - Self-Contained HeNe Laser [20]

Specifications:

- Wavelength of $632.8\,\mathrm{nm}$
- Polarized
- Power Supply of $100\,\mathrm{V}$AC