Fabrication and Analysis of an Optical Fibre with Nd:YAG Derived Core

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Abstract

In this study an optical fibre with a neodymium doped YAG core and silica cladding was fabricated. YAG derived core fibre is hard to fabricate as the fusion point differs between core and cladding. Therefore the core and cladding easily mix or break in the process.

In earlier studies, the core consists of 45% silica, which was reduced to around 10% in this study. Optical properties of the fibre such as numerical aperture, normalised frequency, and transmission spectrum were measured. The transmission of the fibre were not found to differ due to the silica found in the core, which is another indicator that the silica amount is low. As the difference of refractive index between core and cladding is large, the numerical aperture and normalised frequency of the study needs to be further explored.

Acknowledgements

First and foremost I want to express my gratitude towards Dr. Clarissa Harvey for her guidance and help. Additionally, I would like to thank my partner in this project, Arian Chimenson, for making my time at Albanova enjoyable. Thanks to Tuva Källberg and Klara Kiselman for reading the report and giving advice. I also want to thank Rays — for excellence, as well as their partners Beijerstiftelsen and Ekmansstiftelserna for giving me this opportunity.

Contents

1 Introduction

Optical fibres are heavily used in modern technology such as lasers, surgery and data communication [1]. The main advantages compared to electricity wires are the low loss of data and fast communication [1]. New methods of fibre fabrication has allowed other materials with different properties to be used in fibres. This study focused on a type of crystalline core fibre that has not been created successfully before.

1.1 Optics

There are two important phenomenons occurring in fibre optics - reflection and refraction.

Reflection describes how light changes direction when it hits the interface of two different mediums such that it returns into the same medium it originates from and can be seen in figure 1. The reflection law states that,

$$\theta_i = \theta_r \tag{1}$$

Where θ_i is the angle of incidence, and θ_r is the angle of reflection. [2]

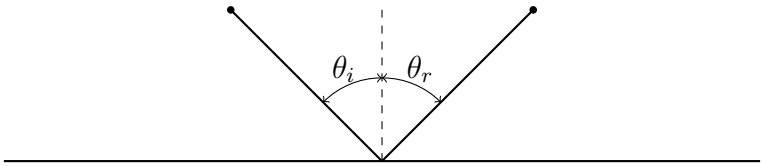


Figure 1: A reflection of a light beam that hits another medium.

Refraction describes how light bends when it passes through different transparent mediums, which can be seen in figure 2. Snell's law states that,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2, \tag{2}$$

where n_1 and n_2 are the refractive indexes of the mediums, θ_1 is the angle between the surface and the incoming ray, and θ_2 is the angle of the surface and the outgoing ray. [2]

Numerical Aperture (NA) describes the angular acceptance for a beam of light in an

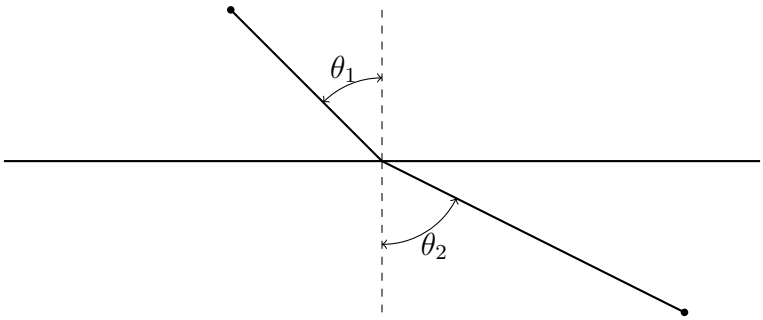


Figure 2: A refraction of a light beam that transverses into another medium.

optical system, and is defined as $n \sin\theta$, where n is the refractive index of the initial medium, and θ is the initial angle. As stated in equation 2, the NA will remain constant as the light emits through different materials. [2]

1.2 Laser Beams

If the intensity of a light beam can be described with a Gaussian function when the beam hits a perpendicular surface it is called a Gaussian beam. The divergence of a Gaussian beam is non-linear as the width depends on a Gaussian function. The width of a beam at the light source is called the beam waist and the how much the beam diverges depends on the beam quality factor. In general, a lower beam quality factor is better, with 1 being the lowest possible factor. To approximate the beam divergence angle in the far-field, the following equation can be used,

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

where θ is the beam divergence angle, λ is the wavelength of the laser, w_0 is the the beam waist, and M is the beam quality. Laser beams can be approximated to be Gaussian beams and to have a beam quality factor of 1, which makes it easy to calculate the beam divergence angle. [3]

When a laser with high energy intensity is emitted through a material it may change the molecular structure of the material. As the laws of optics and refractive indices of the materials may change in the process, the science of such optics is called non-linear

optics. [4]

1.3 Step-index Fibre

The most common type of optical fibre is step-index fibre, which is a core surrounded by a cladding with a slightly lower refractive index. If the difference in refractive index and incoming angle is small, the light is totally reflected off the sides of the core, which is called a total internal reflection. The fibre is usually made from silica which has a refractive index of 1.45, and is doped by some other material in either core or cladding to get the right difference in refractive index. [4]

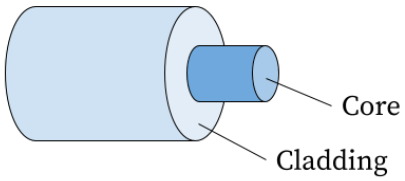


Figure 3: The different parts of a step-index fibre.

For a step-index fibre, the NA is defined as the maximum input angle of a light beam for which total internal reflection is possible at the core-cladding surface. The NA can be obtained by the difference in refractive index between core and cladding as,

$$\mathrm{NA} = n \sin \theta_{max} = \sqrt{n_{core}^2 - n_{cladding}^2}. \tag{4}$$

If the equation does not have a solution for the refractive indices of the core and cladding, the NA cannot be obtained by looking at the angle of the beam going through the fibre. [5]

Optical fibres can support several guided rays at the same time if the core radius is big and the NA value is high. Guided rays are generally called guided modes in the context of optical fibres. The number of modes supported is determined by the normalised

frequency, also called the V number, and obtained by,

$$V = \frac{2a\pi}{\lambda} \cdot \mathrm{NA}, \tag{5}$$

Where a is the core radius and λ is the wavelength. [6] If $V < 2.405...$ the fibre can only support one mode. For larger amount of modes, it is determined by $\frac{V^2}{2}$. [6]

During fibre transmission the signal can be attenuated due to absorption. Absorption occurs because of low material quality, water vapors, or trace materials that are present in the fibre. The rate of absorption depends on which wavelength the signal is emitted with, and some wavelengths are known to emit signal better for a certain material. Transmission, emission, and absorption can be measured by sending a laser beam through the laser as the difference in intensity measures how much of the beam that is absorbed by the fibre. Data loss over distance can be measured by repeating the process for different lengths of fibre. [7]

1.4 Nd:YAG

YAG ($Y_3A_5O_{12}$) is a synthetic crystal made from yttrium, aluminium, and garnet. It is a suitable material for optical fibre cores as it is transparent, has a low internal stress, and is highly heat resistant. It has a refractive index of 1.83. In order to enhance the properties of YAG it can be doped with other elements such as ytterbium (Yb) or neodymium (Nd). Generally, the YAG is doped with 1% of the other material. [8]

1.4.1 Crystalline core fibre fabrication

The method used to fabricate crystalline core fibre is called the molten core method. The core and cladding preforms are made seperately and put together while cold. The core material is chosen so that it melts at a lower temperature than the silica. When the silica is heated to a suitable consistency to draw fibre from the core becomes fluid and follows along into the fibre. The core solidifies as the fibre cools down. [9]

The problem when drawing fibre with a Nd:YAG core is that YAG has a greater thermal expansion than silica. If the preform is heated too much the core expands and the cladding cracks. Additionally, when the fibre is cooled down, the core shrinks faster than the cladding and the silica fuses into the core. When the core shrinks it deforms which makes it uneven and drippy in the fibre. Therefore, the optical properties of it may be weakened and air bubbles may occur. On the other hand, if the preform is heated too little the core does not melt properly and the core will crack instead. [10]

A solution would be to heat up the preform at a higher temperature, but for a shorter time. Then the cladding absorbs more heat than the core as the heat do not have time to spread. Therefore, the core do not expand as much, while the core still is fluid enough to draw the fibre. [11]

A fibre that is not made of 100% YAG core may not be called a YAG core fibre, instead it must be called a YAG derived core fibre. [11]

1.5 Energy Dispersive Spectroscopy

Energy dispersive spectroscopy (EDS) is used to detect different elements in a material sample. An electron beam is focused on a point on the surface of the sample. When the electron beam hits an atom it excites an electron from an inner shell and forces an electron in an outer shell to fill the empty spot. As the energy level of the electron is lowered, the excess energy is emitted and can be detected. The amount of energy emitted is unique for each chemical element. To determine the chemical composition of the sample the process can be repeated for each point on the surface. However, the amount of energy emitted overlaps a little bit for atoms with similar mass. Therefore, EDS should not be used for exact measurements. To get better results, the sample is put in a vacuum chamber to minimalise contamination from surrounding air. [12]

[12]

1.6 Scanning Electron Microscope

A scanning electron microscope (SEM) is used to visualise the chemical composition of a surface in an image. A electron beam is accelerated towards the surface. As the electrons collide with atoms in the material secondary electrons are scattered back and and measured. This process is repeated for each point on the measured surface. As heavier elements scatter electrons better it will produce an brighter image. SEM cannot detect different elements more precisely than that, and only produces black and white pictures. [13]

1.7 Aim of Study

The aim of this study was to create a glass fibre with a core of Nd:YAG such that the cladding does not mix into the core. Furthermore the optical properties of the fibre were to be explored.

2 Method

The method used in this study consisted of two parts, fabrication of the fibre and and measurements of optical properties of the fibre.

2.1 Fabrication

A preform was made of Nd:YAG and silica with a ratio of 1:3. Two centimeters on each end of the rod were made of solid Nd:YAG to avoid the core from flowing out of the cladding when heated. The preform was heated in an oven with a temperature of 2100° until the silica had the same consistency as honey. It was then drawn into a fibre that was 130 μm in diameter.

2.2 Fibre Analysis

Samples were cut from the fibre. The samples were analysed under a microscope to measure the width of the fibre and the quality of the core.

2.2.1 EDS and SEM

The samples were polished using fine grain sandpaper and run through EDS and SEM. In the scan, the occurrence of oxygen(O), silicon(Si), yttrium(Y), aluminium(Al), and neodymium(Nd) was examined to determine how sharp the edge between the core and cladding was and how much the cladding had spread into the core.

2.3 Measurements of Optical Properties

Three different optical properties were measured in the fibre, the NA value, the transmission spectra, and the emission spectra. A sample of Nd:YAG derived core fibre that was around 50 mm long was used for all experiments.

2.3.1 Setup for NA and transmission measures

A white laser was connected to a SMF-28 optical fibre. The laser was guided through the air using a collomating lense and a focusing lense, to focus it to the same width as the examined fibre. The laser went through a beam splitter in order to make it easier to couple the beam. Then it went through the fibre that was put on a fibre undertest translation stage (FUT stage). The FUT stage was used to couple the laser on 3-axis.

2.3.2 NA measurements

A CCD camera was mounted in front of the fibre. Between the camera and the laser a white paper was mounted. The full setup can be seen in figure 5 and figure 7. Initially the camera was mounted approximately 50 mm from the fibre. A series of images were taken, and the camera was moved 2 mm between each image.

The images were analysed in the program ImageJ Fiji. For each row, the average light level of all columns were calculated. The laser beam was approximated to be a gaussian beam and a python script was used to make a gaussian regression of each image data. A linear regression was made based on the width of each gaussian regression and the angle of the laser beam was determined. The far-field approximation for Gaussian beams was used as well to get another approximation for the angle of the beam. The NA was calculated using equation (13), such that

$$\mathrm{NA} = n_{air} \cdot \theta_{beam} \tag{6}$$

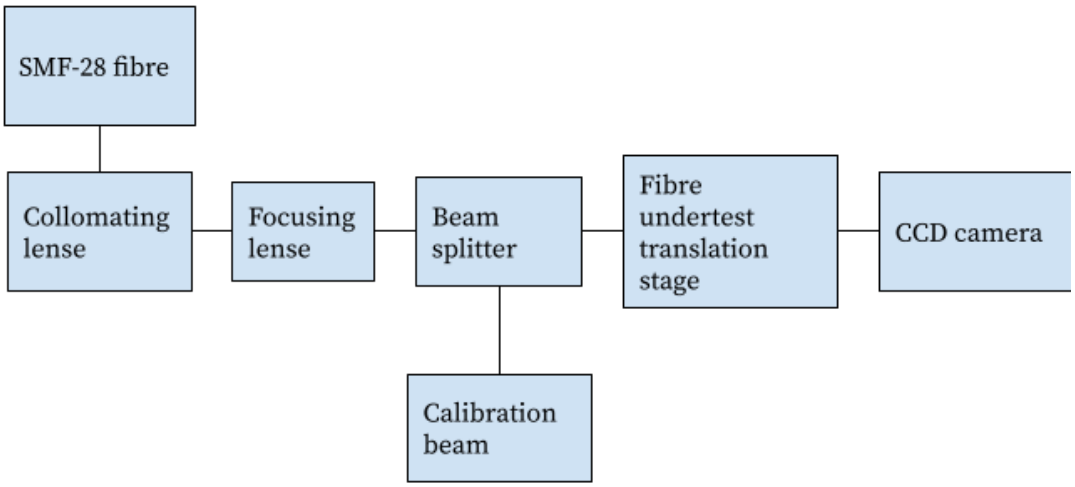


Figure 4: Schematic of the setup used to measure NA.

2.3.3 Transmission measurements

A multi mode fibre was coupled in front of the FUT stage and was connected to a optical spectral analyser (OSA). The Nd:YAG core derived fibre sample was run four times through the OSA, each time the power of the laser was increased by 25 %. A pure

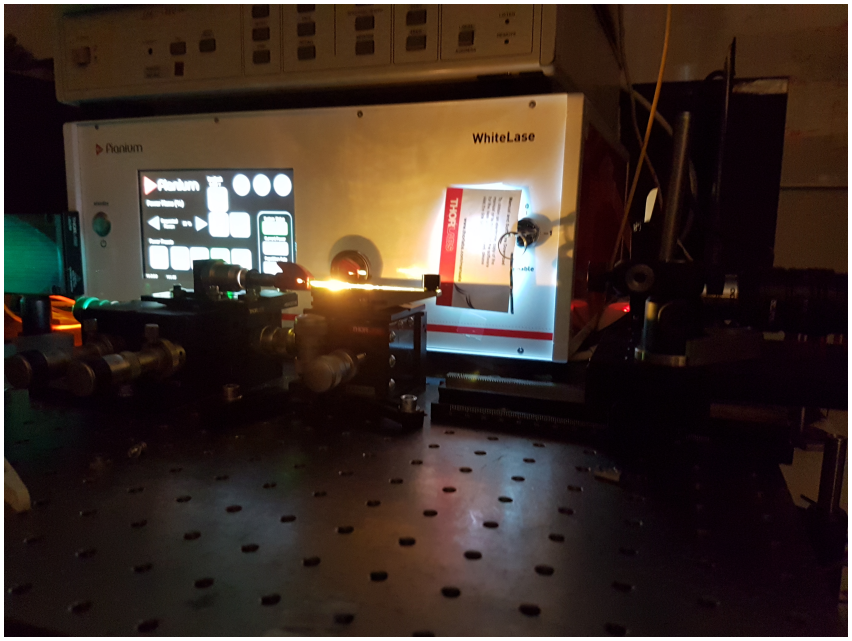


Figure 5: Setup for the laser, fibre and camera.

Nd:YAG rod was run through the OSA once. The data was plotted and compared.

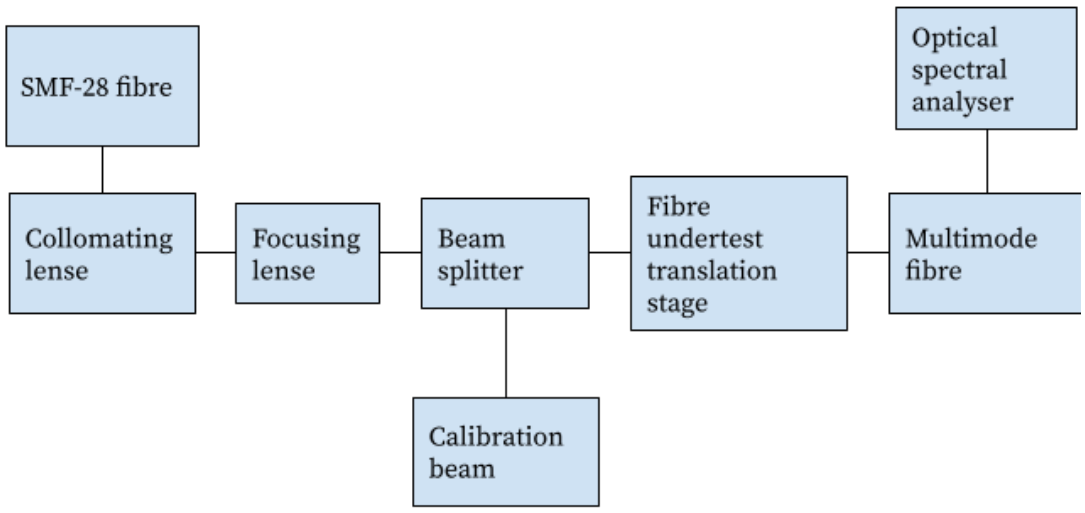


Figure 6: Schematic of the setup used to measure transmission spectra.

2.3.4 Emission measurements

A 808 nm diode pump laser was setup and connected to a 100/140 µm patch cable. It was then guided through the examined fibre with a collomating lense. IR viewer and IR detecting cards were used to couple the laser through the fibre. Long pass filters with a wavelength of 1050 nm and 1100 nm were used to transmit only those wavelengths. Outgoing laser was coupled to a multi mode fibre connected optical spectral analyser to detect the emission sprectra of the fibre. The experiment was done with 1.4 V and 2.0 V voltage in the incoming laser and wavelengths between 600 nm and 1500 nm. The data was plotted and compared.

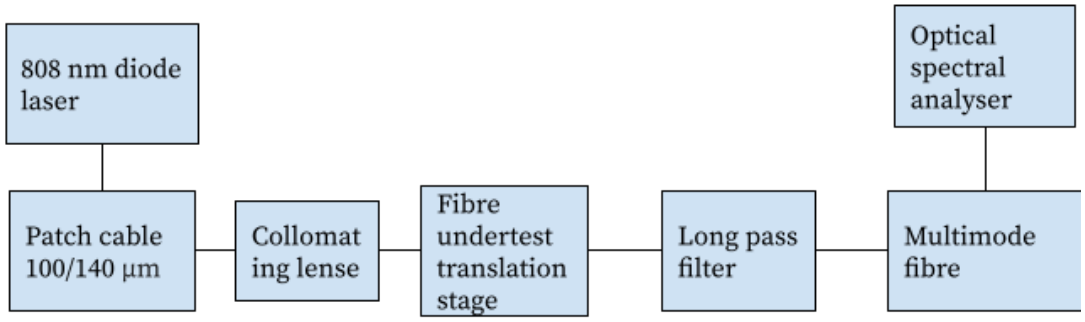
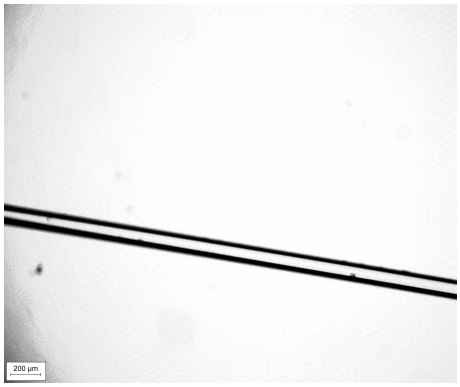


Figure 7: Schematic of the setup used to measure emission spectra.

3 Results

3.1 Quality of the fibre

The core structure of the fibre from a side-view can be seen in figure 8, showing that part of the core is replaced with air bubbles. The sample is lit from beneath.



(a) A fibre sample that is completely filled with core.

(b) An air bubble in the Nd:YAG core.

Figure 8: The examinated fibre sample seen from the side through a microscope.

In figure 9 the core-cladding structure of a polished cross-section of the fibre sample can be seen.

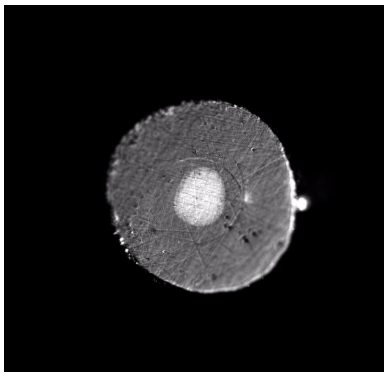
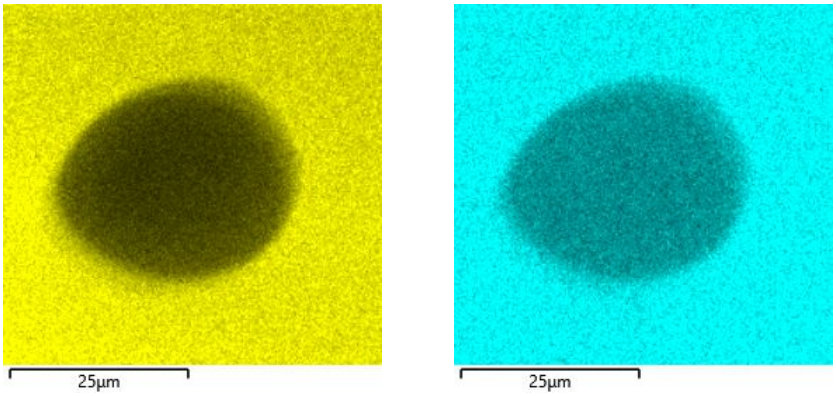


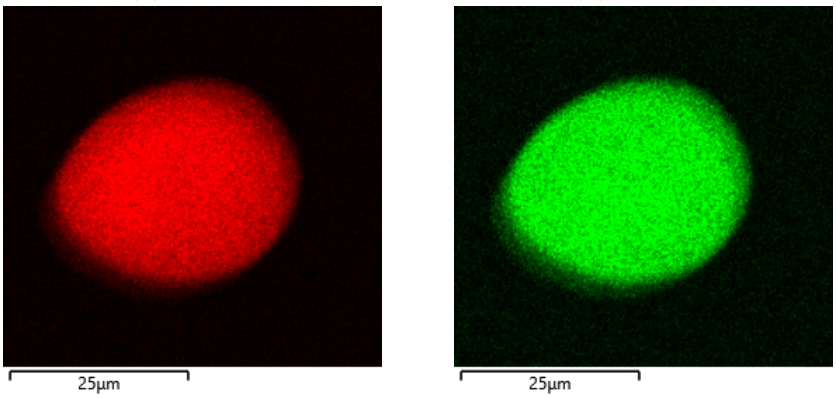
Figure 9: The polished cross-section of a fibre sample seen through a microscope.

3.1.1 EDS and SEM

In figure 10 illustrations of frequency of different elements in the core and the cladding can be seen, where brighter colour indicates higher occurrence of an element. The sample is lit from the top.



(a) Silicon (b) Oxygen



(c) Aluminium (d) Yttrium

Figure 10: Difference in frequency of atoms in core and cladding. Figure (a) and (b) show elements that were frequent in the cladding. Figure (c) and (d) show elements that were frequent in the core.

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In figure 11 the composition of elements on the radius of the fibre can be seen. The weight percentage of silica in the core was 9 %, while the weight percentage of Nd:YAG in the cladding was 0 %.

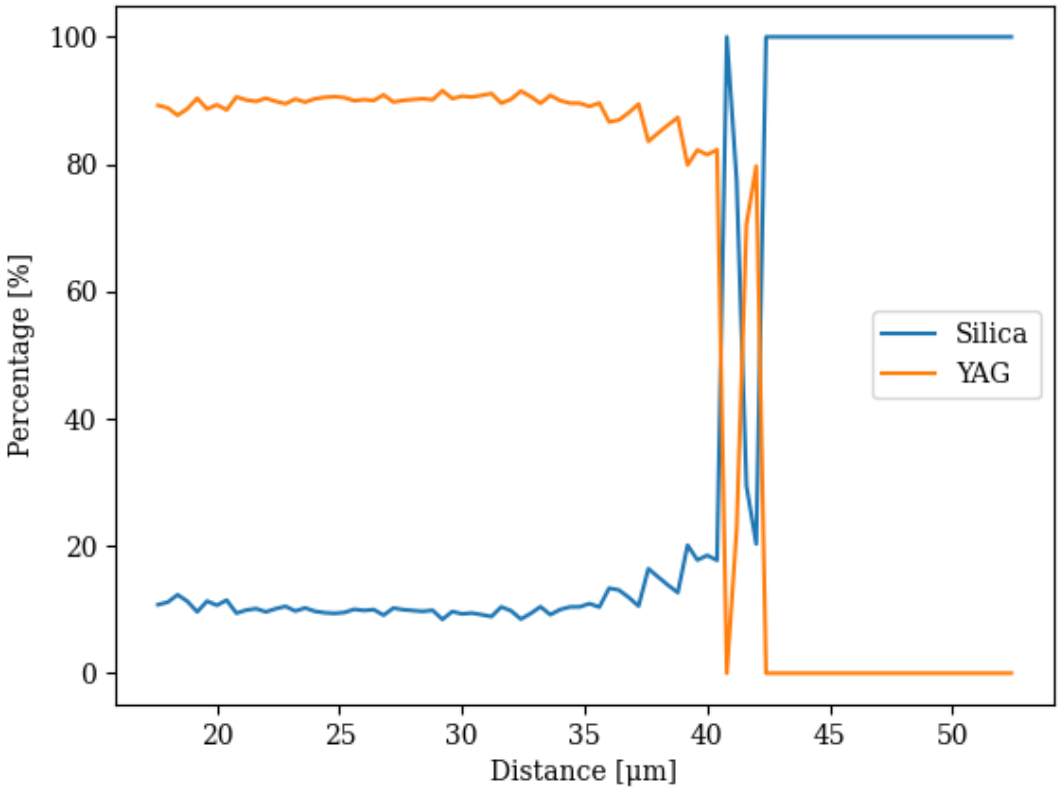
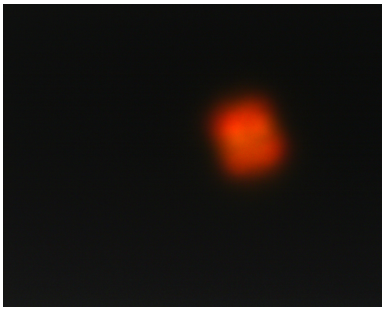


Figure 11: Composition of materials in the fibre corresponding to figure 10.

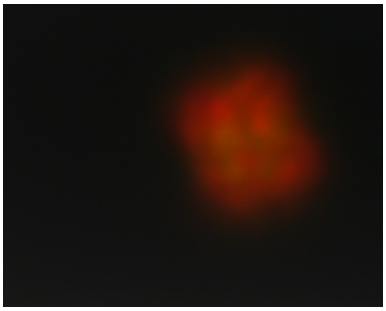
3.2 NA measurements

It can be seen in figure 12 how the width and intensity of the laser beam changed when the camera was moved. Figure 13 shows how the Gaussian regressions of the images of the laser beam increased in width over distance from the fibre. The maximum increase of the beam was used to calculate the maximum angle of the beam, which was approximated to be 0.22 rad and the NA was approximated to be 0.22

(a) The first image of the laser beam



(b) The camera was moved 4 mm.



(c) The camera was moved 8 mm.

Figure 12: How the laser beam diverged after it was transmitted through the fibre core.

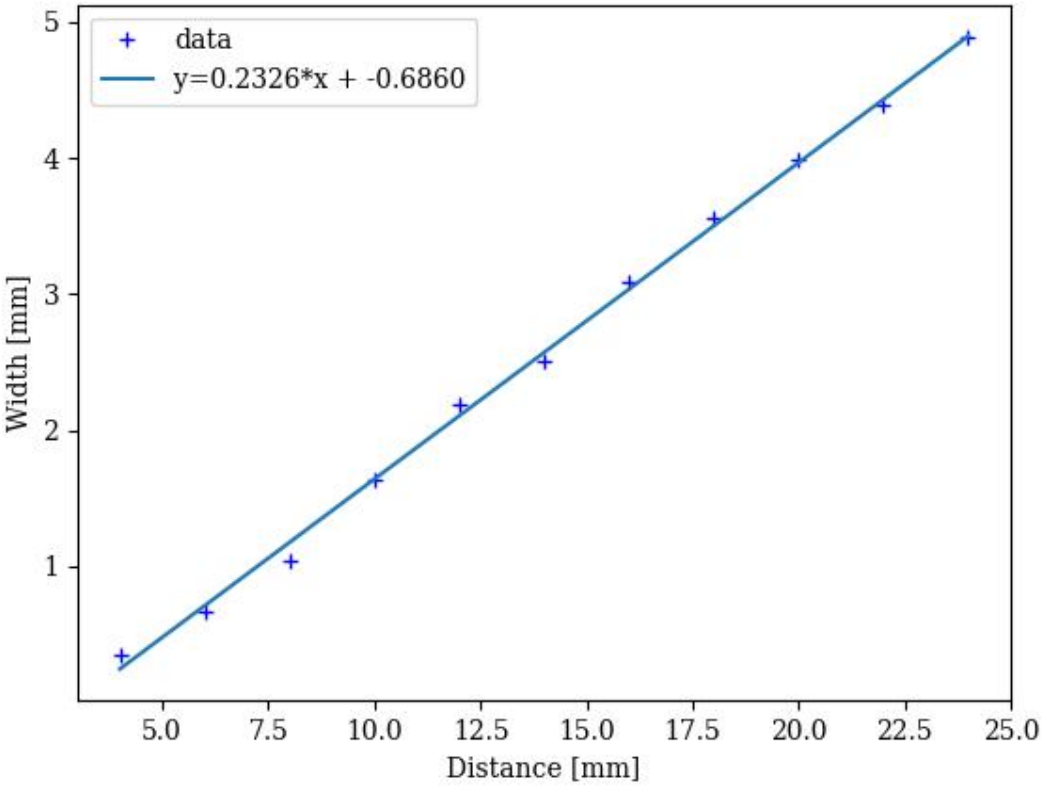


Figure 13: Width of the beam.

3.3 Emission measurements

Emission of the fibre for the wavelengths 600 nm to 1500 nm can be seen in figure 14.

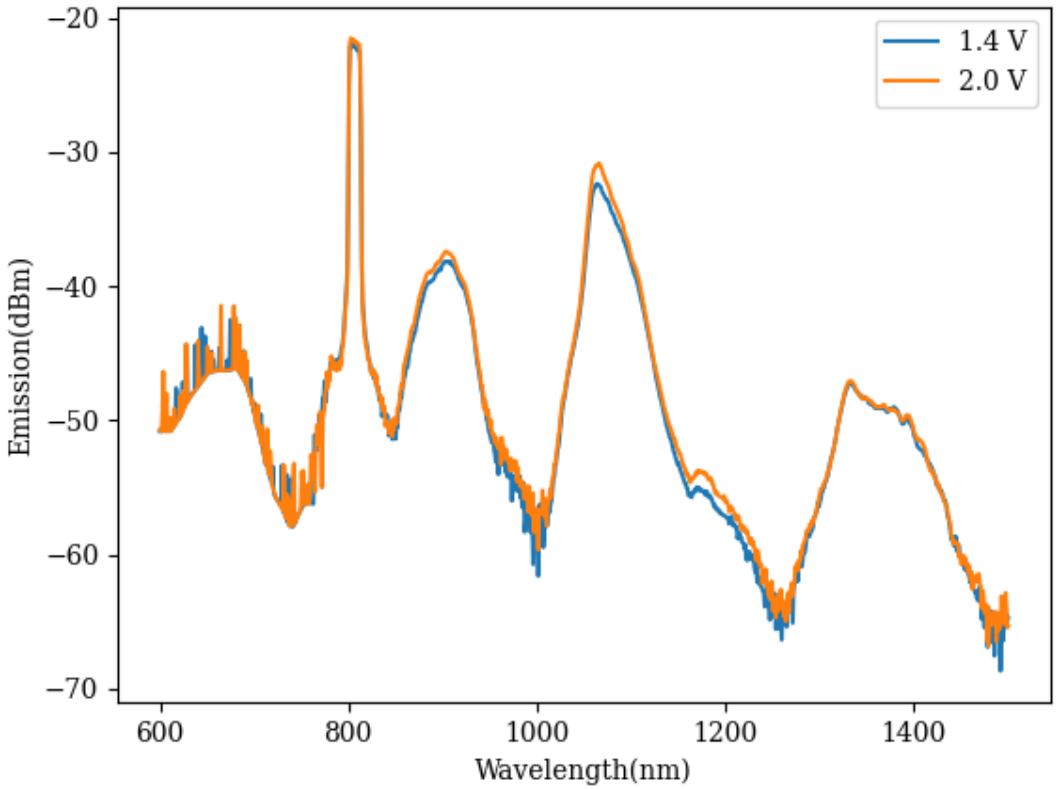


Figure 14: Emission of the fibre for different wavelengths.

3.4 Transmission measurements

Transmission of the fibre for the wavelengths 600 nm to 1800 nm can be seen in figure 15.

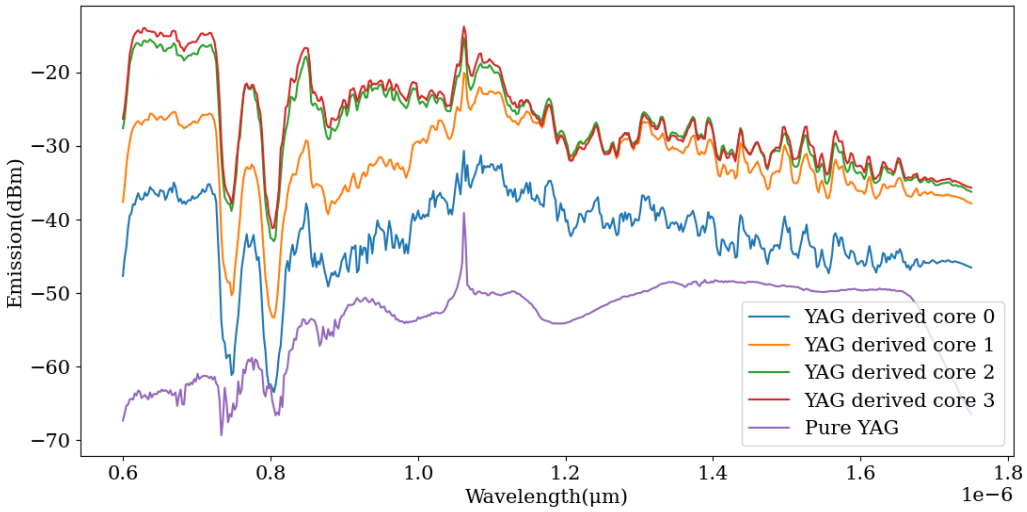


Figure 15: Transmission of the fibre sample and a pure Nd:YAG rod for different wavelengths.

4 Discussion

There are mainly two different aspects of the results to be discussed - the quality of the fabricated fibre, and how that influenced the optical properties of the fibre.

4.1 Quality of the fibre

Compared to earlier research, the amount of silica in the core was reduced from 45% to 10% according to the EDS and SEM scans [10]. This study suggests that it is possible to lower the amount of silica in the core by lowering how long the fibre is heated and instead heating it at a higher temperature during fabrication. However, as the fibre core was not filled with 100% Nd:YAG it is still a Nd:YAG derived core fibre.

The EDS scans were calibrated to heavier materials such as yttrium, neodymium and silicon. Therefore, as oxygen is a light element, the scan labeled a lot of noise as oxygen and almost 25 % extra oxygen was found compared to how much the ratios of the other elements indicated should have been there. However, as the chemical composition of the

materials in the fibre was known and the scan measured all the other elements more precisely, the extra oxygen could be ignored without consequences for the result.

The transmission spectra of the fibre was similar to the transmission spectra of pure Nd:YAG. For example, in figure 15 it can be seen that the transmission dips at around 750 nm and 820 nm, and peaks at 1050 nm. This is another indication that the fibre core contains mostly Nd:YAG.

As stated in the introduction, EDS only gives a rough estimation of the chemical composition and is not to be trusted. In this case, the transmission experiment confirmed the rough estimation given by the EDS scan. In order to know a more exact chemical composition of the fibre core, it would need to be further explored in the future.

Despite the successful decrease of silica in the core, the fibre fabrication was problematic. As seen in figure 8, the core had some imperfections. The core appeared drippy in the fibre and some air bubbles were stuck in there which influenced the optical properties negatively. To avoid that the temperature in the oven during fabrication of the fibre can be further explored in the future.

4.2 Optical properties

In the fibre, the refractive index step is 0.38 between core and cladding, which is too big to use the reduced formulas presented in the introduction to calculate the NA value. Therefore, V number and NA value needs to be studied further in the future.

The emission of the fibre only increased a few dBm when the amount of voltage applied was increased. The emission was expected to increase a little bit as the optical spectral analyser received a stronger signal. Therefore the small increase in emission does not imply that the molecular structure of the fibre core changed, which indicates that it is resistant to high energies.

4.3 Conclusion

A fibre made of a silica cladding and a Nd:YAG derived core was manufactured in this study. The EDS scan showed that the amount of fusion between the core and cladding decreased compared to earlier studies. In addition, measurements of the transmission spectra showed that the core contained mostly YAG.

There was a large difference in refractive index between core and cladding, as well as an uneven core structure. Therefore, other methods to calculate the NA value, as well as temperature during fabrication should be explored in the future.

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