Laser Physics and Non-linear Optics

Alignment in Integrated Optical Systems

Bachelor Assignment

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Summary

The goal of this research was to find a reliable method to couple light into an integrated optical system. In order to find such a method, experiments have been conducted to couple light of 1560 nm originating from a superluminescent diode, into two different waveguide chips: a silicon nitride (Si_3N_4) waveguide chip with silicon oxide (SiO_2) cladding and a indium phosphide (InP) waveguide chip. On this last one, also an MMI coupler was present.

Coupling into the silicon nitride waveguide succeeded manually by using a translation stage. For coupling into the indium phosphide waveguides a higher precision was needed. Therefore, a LabVIEW program was developed to move a piezo controlled stage with 5 nm precision and a traveling range of 20 μm. Mounting a light guiding fibre on the stage, the program can be used to move the fibre in such manner that an area of 20 μm x 20 μm can be scanned. During the scanning the program records data from a camera in order to analyse if coupling has been accomplished during the scan sequence.

The program has yet to be proved working, because no light was observed in any of the experiments to be coupled into the used MMI coupler. However experiments using a beam profiler indicated that this is caused by the experimental set-up and not by the program.

Contents

Introduction

Light as a physical phenomenon has been an interest of humanity since ages. Already in the time of the ancient Greek philosophers tried to uncover its origin and answer the question what light exactly is. Since then, many great minds boggled about light and came to different conclusions. Sir Isaac Newton, for example, was convinced light consisted out of particles, where on the other hand Christiaan Huygens thought of light as a wave phenomenon. It would take until the twentieth century before Albert Einstein gave the answer we use these days when we talk about light: light is a wave, but is also quantised in so called photons.

Of course this conclusion led to great turmoil: how could something be a particle and a wave at the same time? Nowadays a whole branch of physics, quantum mechanics, is based on this principle and though complications of this conclusion are still uneasy, most people have come to accept this answer to the question what the behaviour of nature is at the smallest scales.

Experimental goal

Light at these small scales has become a great interest of modern science. For if one could control light at such levels, new optical devices could be fabricated, which may lead to data processing at a much higher speed than with electronic devices. However, many problems arise when working with those systems, because light has to be coupled effectively in and out. Correspondingly, alignment in in- and output coupling is one of the central problems. When looking at possible applications where large number of devices are involved, this problem is also commonly known in the context of so-called packaging of integrated optical ssytems. This is due to the extreme small scales of the devices: waveguides of only a couple of micrometers are no exception. Also detection can be considered one of the main problems, since intensities of the light such devices use are to low for many detection methods. Moreover, for a lot of applications in integrated optical systems, light outside of the visible spectrum is used because visible light is absorbed. This makes detection even more difficult.

In our bachelor assignment we have tried to find a reliable way to couple light into such an integrated optical system and detect the guided light. This goal was divided in the following sub goals:

- Finding reliable methods to **detect** infrared light at low intensities;
- Achieving **coupling** by manual alignment in integrated optical systems;
- Constructing a method allowing for reliable coupling by **alignment**.

This report

About this research, we first will give an overview of the theoretical side of the experiments, in which waveguide optics are the most important. In the second part of this report we will elaborate on the experimental side of the assignment. Brief preliminary experiments will be explained, after which we will tell in more detail about the experiments conducted to solve the given problems.

Reinout Nonhebel & Bob Stienen
June 28th, 2013

Chapter 1

Waveguides and Integrated Optical Systems

1.1 Waveguide basics

In essence, a waveguide is a thin piece of material that is transparent for certain wavelengths. Because of its transparency, light can travel through it in accordance with the Maxwell Equations. This means that this light is subject to all properties of light as expected, i.e. interference, reflection and refraction. Since the used material has a lower refractive index than the air around it, light traveling through the waveguide can be guided by total internal reflection inside it and hence be forced to travel along the strip. In a way, a waveguide can be seen as an extremely thin glass fibre.

The guided light can be seen as a wave, with maxima of the electric and magnetic fields spaced a wavelength apart in the direction of propagation. After two internal reflections, the wave travels in the same direction as before the reflection. If the wave after two reflections is in phase with the light before (i.e. the maxima coincide) the light will persist. If it is not in phase, the light will gradually die out because of destructive interference. Therefore, the ray of light (the wave vector) can only exist at certain angles for a given wavelength. These angles correspond to the different *modes* that a waveguide can support. In order for light to be coupled, it therefore must satisfy the condition that it will not vanish due to destructive interference.

The allowed modes for a certain waveguide can be found by solving the Maxwell Equations for the boundary conditions given by the physical size of the waveguide. This gives multiple solutions across the width of the waveguide, called modes. Physically, this means that there fit n half wavelengths in the width of the waveguide in the $n-1^{th}$ mode. This is shown in figure 1.1.

When the dimensions of a waveguide are small compared to the wavelength of the light (a width of several times the wavelength is already con-

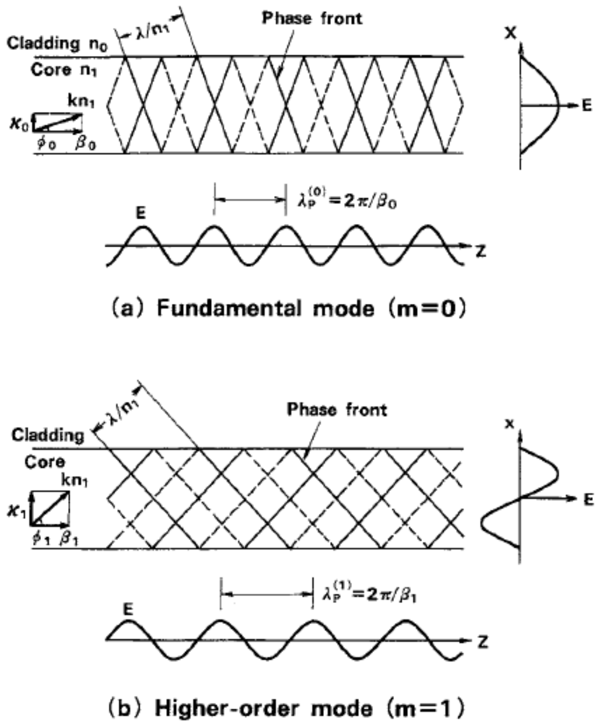


Figure 1.1: Formation of fundamental and higher-order modes in a waveguide compared to the lowest order (fundamental) mode. [1]

cerned small), only one mode is allowed, which is called the fundamental mode. Such a waveguide is said to be *single-mode.* [1, 4]

1.2 Used waveguides

For the conducted experiments, we have made use of two waveguide layouts to test the alignment with. These are simplified examples of integrated optical systems (IOS)[1]

The first system used was a silicon nitride (Si_3N_4) waveguide with silicon oxide (SiO_2) cladding. This chip, deposited on a silicon wafer, consisted only of straight waveguides and was used in order to test the alignment while avoiding the complications of more elaborate systems.

The second system used were indium phosphide waveguides.In figure 1.2 the cross-section of such waveguides can be seen. They are surrounded by an etching trench. The waveguides themselves have a width of 2 μm and are directly surrounded by air. This, and the fact that indium phosphide is

[1]These are also known as Photonic Integrated Circuits (PIC).

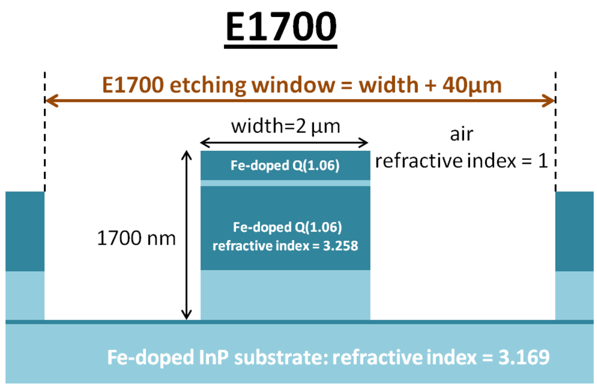


Figure 1.2: Cross-section of the waveguides on the second chip. [2]

brittle, makes them very fragile, so working with these waveguides asks very delicate handling. Any direct contact with the waveguides could damage them permanently.

1.3 Multimode-interference coupler

The indium phosphide chip also contained a so-called multimode-interference (MMI) coupler. The layout of this device can be seen in figure 1.3. The light coming from the incoming single-mode waveguide (in the image marked by *in 0*) spreads in the MMI coupler, by which multiple modes become available. This induces interference of multimodes in the device. Normally spoken, light will then constructively interfere at the connecting points for the outgoing waveguides (in the figure marked by *out 0* and *out 1*).

In theory, this device could be used to make a so-called optical switch. When the refractive index of the MMI coupler could be locally altered, the interference pattern would change. This can lead to destructive interference at the connection point of one outgoing waveguide and constructive interference at the connection point of the second, and therefore sending all the incoming light through only one waveguide. This optical equivalent of the transistor could give rise to a whole new technology of ultra-fast signal processing. This however is beyond the scope of our report.

The reason such an IOS was nevertheless used was because it gives rise to a possible detection method. When no changes are made to the local refractive index in the MMI coupler, both outgoing waveguides will guide light at the same ratio. This would mean that two separate intensity spots could be seen in the detection if the light was coupled. Initially, this is what an MMI coupler was meant for: splitting incoming light into two channels.

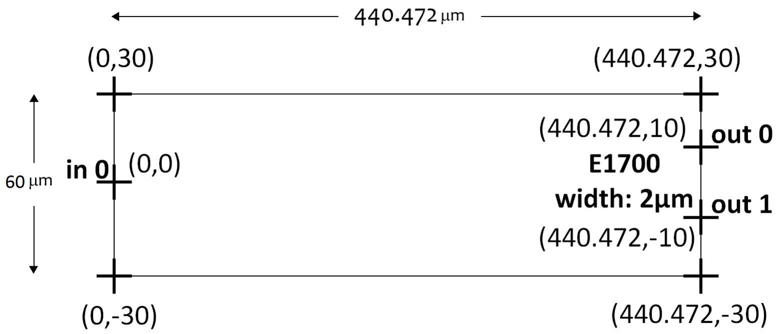
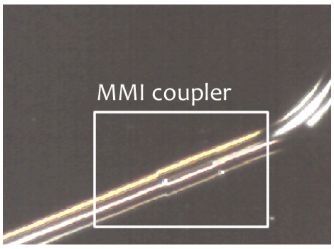
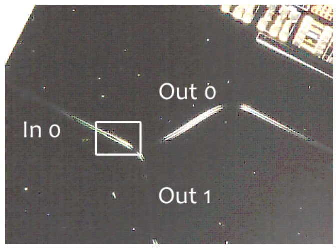


Figure 1.3: Schematic representation of the MMI coupler. The input waveguide (in 0) on the left side and the outputs on the right (out 0 and out 1) side have been indicated. [2]



(a) MMI coupler



(b) The general structure of the waveguides on the indium phosphide chip

Figure 1.4: Detail photographs of the used indium phosphide chip. In the left photograph. Marking in the pictures is in accordance with figure 1.3.

1.4 Characterisation of the MMI coupler

Documentation on the used MMI coupler chip only gave details on the layer structure and the dimensions of MMI coupler itself. This composition of the MMI coupler was equal to the one of the waveguides, as shown in figure 1.2. The dimensions of the MMI coupler can be seen in figure 1.3. This MMI coupler was specifically designed for 1550 nm light.

This available documentation was, on the other hand, lacking information about the exact form of the waveguides (i.e. eventual bending, curves etc.). Pictures were therefore taken using a CCD camera. This camera was able to zoom in on the chip. These photographs can be seen in figure 1.4.

In figure 1.4, the waveguides are labeled as in figure 1.3 and the MMI coupler is surrounded by a white box. As can be seen, the waveguides leading the light away from the MMI coupler diverge from each other just after the coupler.

In the second photograph (figure 1.4(b)), a more detailed image of the MMI coupler is shown. The actual coupler can be recognised as a thickening of the incoming waveguide. Also, the place the two outgoing waveguides diverge can be seen in the right side of the image. The reflections around the waveguides and MMI coupler are due to the width of the etching window, as specified in figure 1.2.

Chapter 2

Experimental aspects

2.1 Infrared Detection

2.1.1 Infrared spectrum

Before doing any alignment in waveguide set-ups at all, a proper knowledge about the lightsource is necessary. With this knowledge, the appropriate detection method can be chosen. For the conducted experiments, we eventually had to use infrared (IR) light with a low photon energy, since indium phosphide is a semiconductor with a bandgap of 1.06 eV, in which light with higher photon energies (e.q. visible red light) would be absorbed.

Measuring the spectrum was done by aligning two fibres with each other: this set-up is shown in figure 2.1. The first fibre is connected to a superluminescent diode (SLD) and the second to an optical spectrum analyser (OSA). Aligment was done using two 3-axis translation stages, as can be seen in figure 2.1. In this photo light can be seen being emitted from one of the fibres. This is because at the moment the photo was taken, red light from a laser diode was used for pre-alignment.

The two fibres were first aligned using a microscope, after which only small adjustments had to be made to couple the light from one fibre into the other. When the measured spectrum by the OSA was strong enough for the visible red light, the laser source was switched from the laser diode to the IR SLD.

The recorded spectrum can be seen in figure 2.2. The centre frequency of the laser is placed around 1560nm, so the photons of this light source have an energy equal to 0.795 eV. The light of this laser can therefore be used in experiments involving the indium phosphide waveguides, since it is not absorbed by the waveguide material.

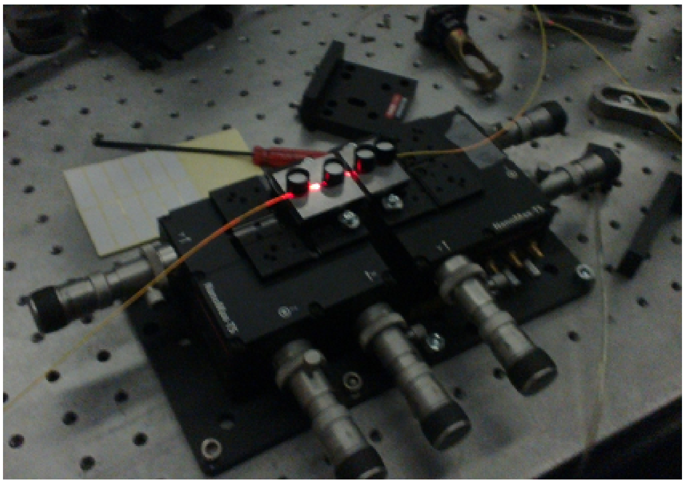


Figure 2.1: A photograph of the measurement set-up of the spectrum of the used IR SLD. As can be seen, two 3-axis translation stages have been used to align the two fibres.

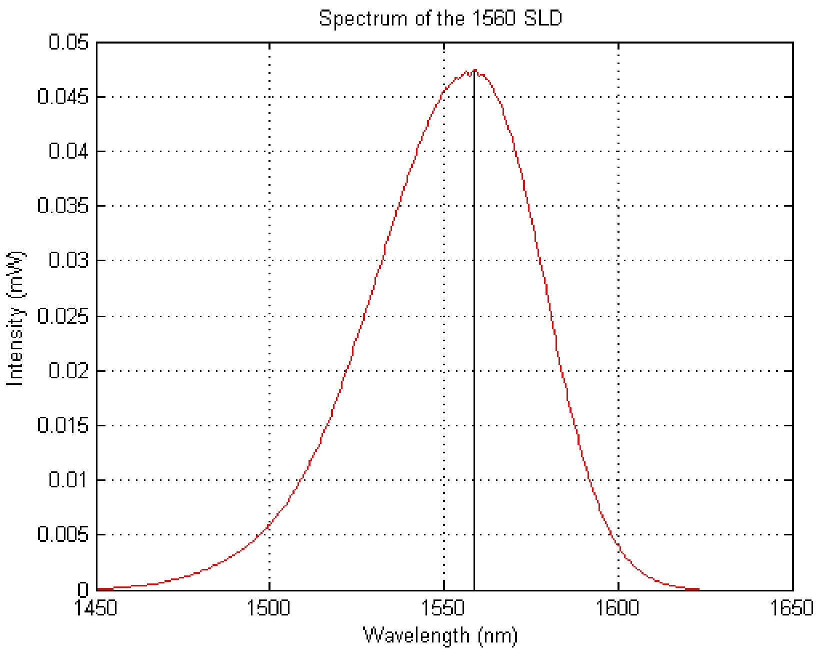


Figure 2.2: The spectrum of the IR SLD with a centre frequency of 1560 nm.

(a) IR-viewers (b) Detector cards

Figure 2.3: Devices for IR detection (source: http://www.thorlabs.de/navigation.cfm)

2.1.2 Methods of detection

Now that the spectrum of the light for the experiments is known, an appropriate detection method has to be chosen. This method would then be used to detect whether or not light had been coupled into a waveguide. The detection of 1560nm is in general very difficult, since silicon based detectors cannot be used.

The device we wanted to use for detection was an IR-viewer. This camera-like detector as seen on the right of figure 2.3(a) should, according to the documentation, be able to detect light of 1560 nm. However, the sensitivity of the detector was to low at 1560 nm, even direct exposure to light from the fibre was not strong enough to be detected by the viewer.

The method we eventually chose to image the IR light was a fluorescent screen formed by a detector card (figure 2.3(b)). These fluorescent cards light up when shone upon by IR wavelenghts and emit light in the visible spectrum. In contrast with the IR viewer however, the detector cards cannot be used to detect if IR light is being emitted from (an edge of) an object, they can only be used at the end of an set-up, or in a free laser beam, to detect if IR light is present or not. On the other hand: the card lights up strong enough to see it at the backside of the card, which makes permanent placing in a set-up for detection easier.

The set-up built in this way included a detector card approximately 2 to 3 mm from the end of the waveguide.

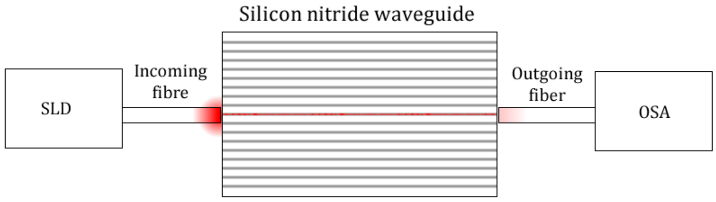


Figure 2.4: A schematic representation of light being coupled into the silicon nitride waveguide.

2.2 Coupling by Manual Alignment

2.2.1 Silicon nitride waveguide

Having a defined detection method, we wanted to couple light into the silicon nitride waveguide. Like the spectrum measurement pre-alignment was done using red light from a laser diode. The setup for this experiment is shown in figure 2.4.

When light was coupled into the waveguide, it could be seen that light was coupled in by only looking at the silicon chip. Red light was scattered from the waveguide in which light was coupled in, possibly due to imperfections in the waveguide (like sidewall roughness of the waveguide). When the light was also, after that, coupled in into the outgoing fibre, the spectrum could be measured with the OSA. When the signal was optimised, the lightsource was switched to the SLD. The measured spectrum can be seen in figure 2.5.

In this spectrum a high frequency modulation can be seen on top of the spectrum (compared to figure 2.2). The peaks could be due to interference in the set-up. For this to happen, there must be a sort of cavity somewhere in which this interference could take place. In order to determine this cavity, we calculated the free spectral range (FSR). With this quantity, the width of the cavity can be determined with

$$d = \frac{c}{2 \cdot fsr} \tag{2.1}$$

where c is the speed of light, d the cavity width and fsr the free spectral range. With that information, we could determine where the light is exactly interfering with itself. To retrieve the FSR, the location of the peaks must be calculated in the frequency domain, as is done in figure 2.6. The vertical spacing of those peaks is then equal to the FSR, which turned out to be 0.36 THz, so by using formula 2.1 the length of the cavity was calculated to be 0.41 mm.

This could correspond to the spaces between the fibres and the waveguide

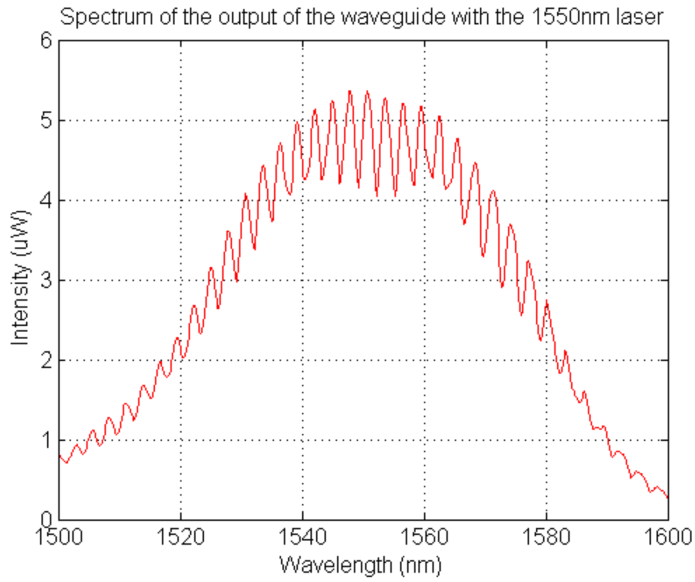


Figure 2.5: Spectrum measured of the light that was coupled in the silicon nitride waveguide.

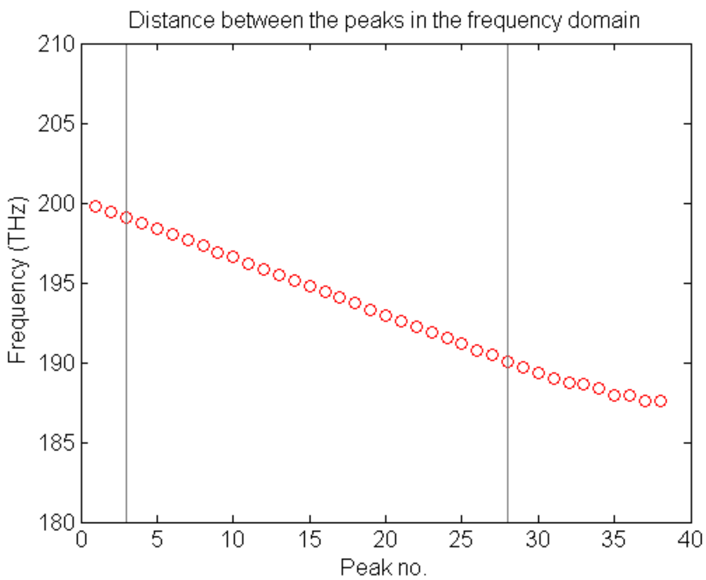


Figure 2.6: Distance between the peaks in figure 2.5 in the frequency domain.

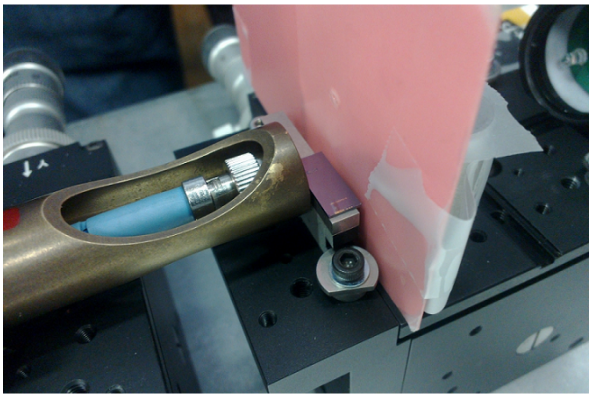


Figure 2.7: Detail of the setup. The fibre can be seen (centre / left), just as the pink detection card (centre) and the webcam (top right) to record the fluorescent light.

or to the space between the two fibres in the used fibre coupler. A decisive conclusion about the exact location of the cavity can however not be made.

2.2.2 Indium phosphide waveguides

The next step was to couple light into the indium phosphide waveguides. In contrast with the silicon waveguides, using this waveguide we were not able to use red light for pre-alignment, since the would be absorbed by electron excitation. There would be no coupling at all in that case, so we directly had to use the IR light. We detected coupling using the detector card, which was placed perpendicular to the direction of the propagation of the light. The exact set-up used for detection can be seen in figure 2.7. An webcam is used to record the light emitted by the fluorescent card.

However, it turned out we were not able to couple light into the waveguide in this manner. In contrast to the earlier measurements, the coarse placement of the fibre as far more difficult to do when the used light cannot be detected directly. Moreover, the precision of manual alignment is still rather coarse: the waveguide has a width of 2μm and when one has no idea of how close he is to coupling light into the waveguide, the exact fibre position to do this is quickly missed.

2.3 Alignment using piezo elements

A method that is more precise if the use of three piezo elements that are installed in one of the translation stages, one for each controllable axis. These elements have a positional resolution of 5 nm and a travel range of 20 μm, so when a coarse placement of the fibre is done, the piezo elements

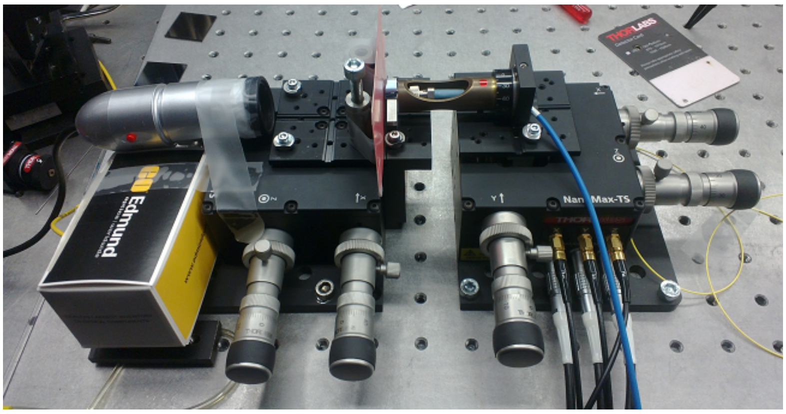


Figure 2.8: Full set-up with the piezo controlled stage. On the bottom right, the cables used to control the piezo elements with can be seen.

could be used to move the fibre more precise to a certain location. The full set-up for this piezo-controlled alignment experiment can be seen in figure 2.8. On the bottom right, the cables used to control the piezo elements with can be seen. However, the piezo controller that can be used to control these piezo elements can be programmed used LabVIEW.

2.3.1 Automated scanning

A LabVIEW program, able to change the position of the fibre step by step in such a manner that the whole area in front of the waveguide can be scanned, was implemented to make alignment easier. An example of this path can be seen in figure 2.9. The exact path depends on the step size in both the x- and y-direction[1]

2.3.2 Data processing

During the scanning, the program records in each step a photo of the detector card with the webcam. To detect coupling, the photo is analysed, for when light is coupled, two light spots should be visible on the detector card due to the two outgoing waveguides.

The program makes an intensity profile of each image by averaging the measured intensities in each column of the image. The resulting array is then saved into a matrix as a new row, together with the position of the stage relative to its starting position. This is done for each single step, which

[1]The prorgam was built in such way that also the z-direction, the direction perpendicular to the scanning area, could be changed during the scanning proces, but we never used this feature, because it could possibly damage the chip when the fibre touches it.

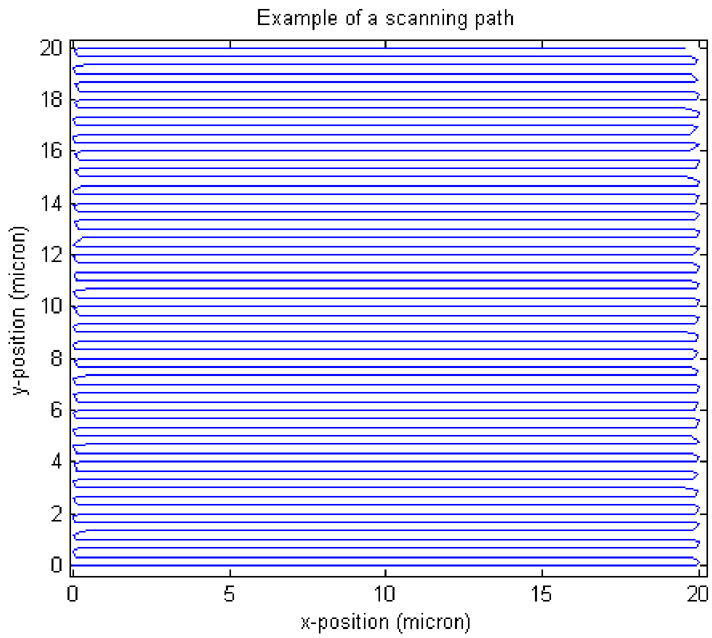


Figure 2.9: Example of the path the scanning program follows during scanning. The start position is defined as (0,0).

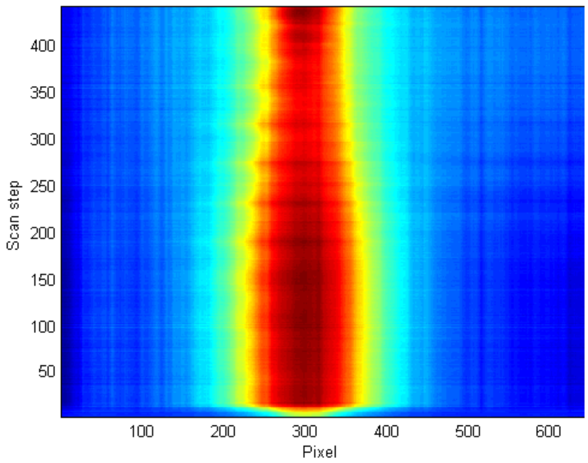


Figure 2.10: Plane plot of an intensity profile matrix. The part of the matrix used to save the position of the fibre is excluded from the plot.

results in an intensity profile matrix (IPM) that can be analysed afterwards on abnormalities in the intensity profile at certain positions.

The program is explained in detail in appendix B. There the program structure is explained and a manual is given on how to use the program.

2.3.3 Results

Moving the fibre

The output of the program is shown in 2.10. For this measurement, the fibre was mounted on the translation stage.

As can be seen in this image, there was no position at which the intensity plot showed two (or three[2]) peaks instead of one, but there is a periodic behaviour in the width of the intensity maximum. Analysis of the intensity of a certain column in the picture, including taking the moving average and taking the Fourier transform, was done using a self written routine (see appendix C.1). Results of this routine are shown in figure 2.11.

When coupling would have occured, the plane plot (the upper left image in figure 2.11) would have shown a split of the intensity maximum to two (or three) maxima. The chance that coupling would be accomplished in the center of the scanning range is negligible, so the peaks would be separated not equally, but would by alternating close and far apart. The fourier

[2]It is possible that, when light is coupled, it would result in an image of the main beam (the part that travels along the waveguide and MMI coupler) and the intensity spots made by the waveguides

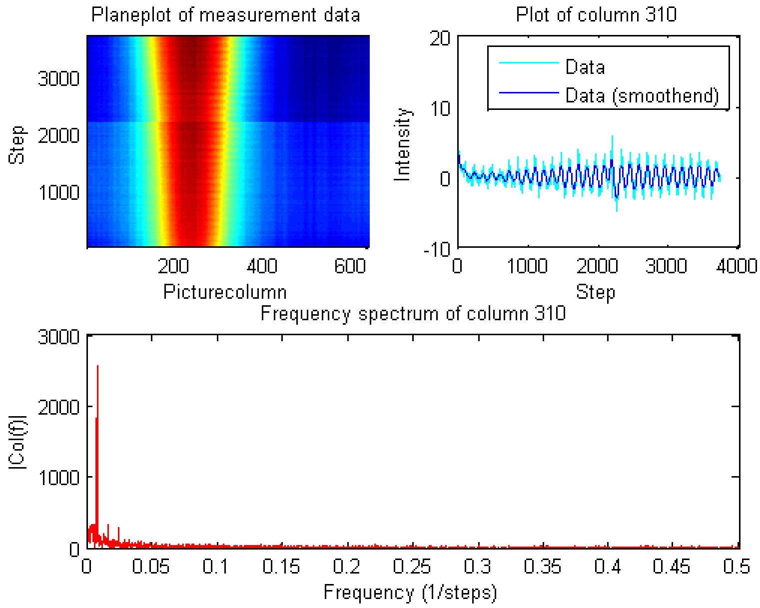


Figure 2.11: Output of the Fourier analysis program.

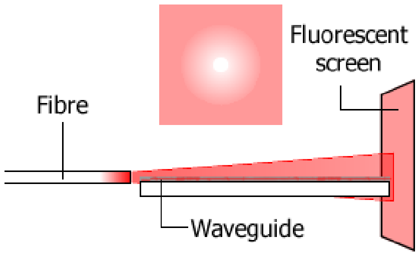
spectrum would then show two peaks.

It can be seen that there is indeed a very strong periodic behaviour. Its period turns out to be exactly the number of steps in taken in one row of the scanning plat. The width of this period indicates that more light is captured by the detector card when the fibre is at its minimum (or maximum) than when it is at the other side (the other x-position), which could be caused by the waveguide lying not precisely perpendicular to the incoming beam of light. However, the Fourier spectrum shows only a single peak, indicating there was indeed no coupling.

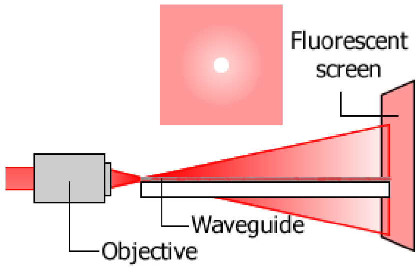
Moving a microscope objective

Because solely moving the fibre showed no results, the set-up was altered to focus the light on the waveguide. In that way, more light is likely to be coupled into the waveguide and light passing the waveguide will cause less background noise (see image 2.12). In order to achieve this: light from the fibre was collimated and led through an objective mounted on the translation stage, so that fine adjustments could be made, in order to let the light go exactly through the centre of the objective.

To prevent spherical aberration, two mirrors were used to focus the light through the centre of the microscope objective. These mirrors were mounted on an optical table. However, since only the objective could be moved in



(a) Previous set-up



(b) Set-up including the objective

Figure 2.12: Schematic representations of two different set-ups, the first without a microscope objective, the second including it.

this way - using the translation stage - automatically spherical aberration will occur, but can this hardly be prevented.

It turned out also this approach did not deliver the expected results. One of the possible explanations for this is that the method of detection is not sensitive enough after all. The divergence of the light out of the waveguides might just be to great to be detected, or the two peaks are still relative to weak to tell apart from the background noise in the intensity profile caused by the original beam.

2.4 Detection using a Beam Profiler

In order to check if it is the detection method that fails in this context, we replaced the detection card with a so-called beam profiler (Thorlabs BP104-IR). This device, as shown in figure 2.13(a) can to measure the intensity of a incoming beam across a given area. This data can be collected using an accompanying program, which is shown in figure 2.13(b).

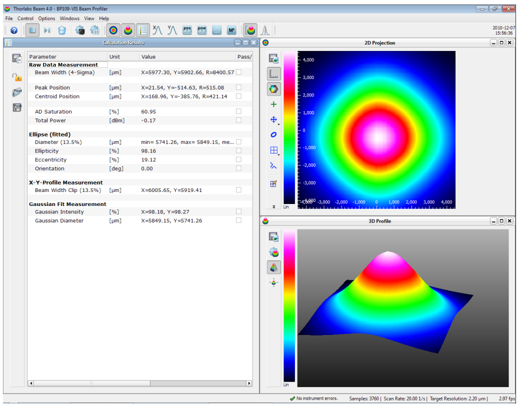
In this set-up, the beamprofiler was placed directly behind the waveguide, with still the microscope objective mounted on the piezo element controlled stage. Because the LabVIEW program works only when the camera is attached, it could only be used to move the microscope objective [3].

Also the beamprofiler did not give images in which coupling was observed. A selection of those results can be seen in figure 2.14. Each of these images was taken with a fixed x-position for the microscope objective, but with a different height relative to the waveguide. What can be seen in image 2.14(c) is that there is constructive interference, possibly in the waveguide base.

In these images can be seen that the beamprofiler gives some sort of

[3] The beam profiler did in fact have an ActiveX component which made it, in theory, possible to actually make such a program, but this could not be finished due to time.

(a) Beamprofiler

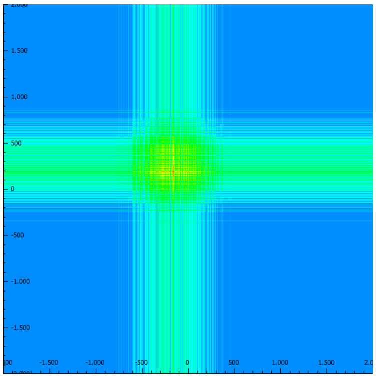


(b) Beamprofiler program

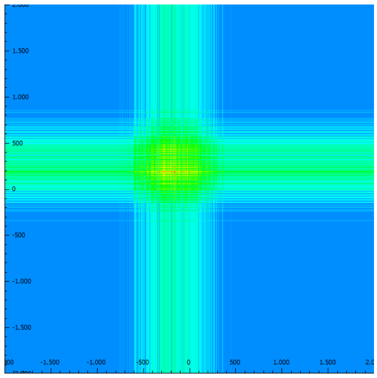
Figure 2.13: The beamprofiler and its program

crosses instead of clear spots like expected (compare these images for instance with figure 2.13(b)). The reason for this behaviour is unknown, but nevertheless intensity profiles can be made of the measurements. Using the accompanying program, such profiles can be made for both averaged columns and averaged rows. This gives images like in figure 2.15.

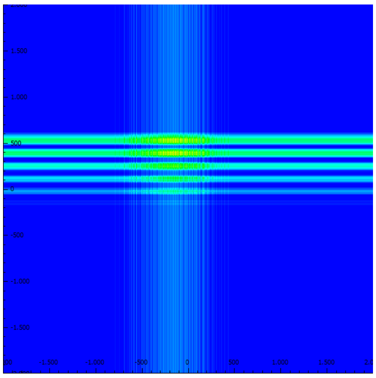
From this figure we can conclude also here the beam was not splitted, for in that case there would be two peaks in the x-direction (left graph in figure 2.15). This could however be caused by the distance between the waveguide chip and the actual powerdetector in the detector itself.



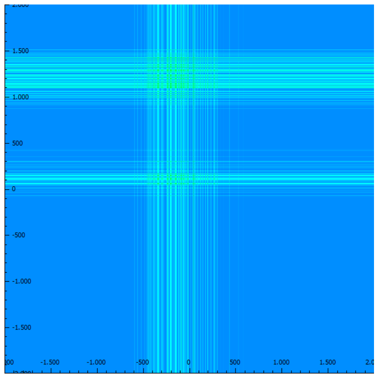
(a)



(b)



(c)



(d)

Figure 2.14: Results of measurements with the beam profiler. Each image was taken with a different microscope objective position relative to the waveguide

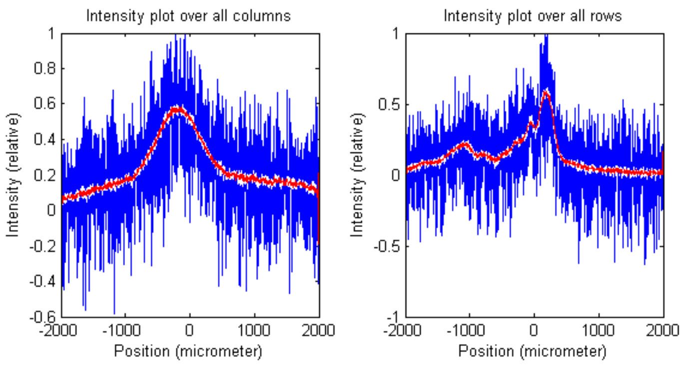


Figure 2.15: Intensity profiles recorded with the beamprofiler program. The white and red lines use the same dataset as the blue line, but they are filtered using the moving average.

Chapter 3

Discussion

Waveguides

The reason coupling was not detected with the indium phosphide chip could be caused by the waveguide chip itself. Detecting defects on the chip is only possible when they are sufficiently large, but also small defects have effects on the light output. We can therefore be not sure the waveguide chip was damage free.

Furthermore: the choice of using an MMI coupler to detect coupling was maybe not the best choice we could have made, for it gives rise to the problem that incident light that misses the waveguide automatically is background noise in the detection. Making use of a unsplitted waveguide with a bend in it would have solved this problem.

Detection

Detection cards

In many of the conducted experiments detection cards were used as a fluorescent screen to detect the IR light. This, however, turned out to be a possible reason the experiments were not able to detect coupling. It could be possible the cards diverge the light to much or that detection at the backside of the card is not a very reliable method to control if on the front of the card two (or three) intensity maxima are formed.

Beamprofiler

The beam profiler used in the last experiments gave cross-like intensity profiles where it should give just intensity spots. The reason for this is unknown, but since this behaviour was independent of the tilt of the detector, it is possibly either a feature in the analysis program we did not find (for example:

an method to find maxima) or a hardware problem we are not able to solve at all.

Coupling

Microscope objective

Using a microscope objective to focus light into a waveguide does make it more likely for light to be coupled into the waveguide it is focussed at, but when used in combination with our LabVIEW program induces spherical aberration. In our experiments we neglected this effect because the stage only has a travel range of 20μm. Nevertheless could it be that this is enough to make coupling impossible.

Furthermore, it turned out to be difficult to align a beam exactly at the centre of the objective using two mirrors. Mounting the fibre with collimator on the stage would have solved both these problems.

LabVIEW program

The LabVIEW program we wrote seems to work, but we were not able to test it properly. Using it on the silicon nitride waveguide chip led to the conclusion there was to much background noise and the indium phosphide waveguide chip was not detected to be coupled at all at any point during the experiments. However, the results of the program indicate it actually works, such that the negative results were only due to the set-up.

Chapter 4

Conclusions

The goal of the research was to find a reliable way to couple light relatively easy into an integrated optical system. We found such a way in a LabVIEW program we wrote, which was able to both control a piezo controlled translation stage and process data from a webcam at the same time. In this research, we were not able to properly prove the working of this program, but experiments indicate this is not caused by the LabVIEW program, but by defects in the design of the set-up.

4.1 Recommendations for future research

If one would continue research towards reliable alignment in integrated optical systems, we give the following recommendations:

- **Choice of IOS** In our experiments, we almost solely used a waveguide connected to an MMI coupler. In hindsight, it had been more useful to test the program at an easier system, like a unsplitted waveguide with a bend in it. In this way, light that initially misses the waveguide will not become background noise in the measured result.

- **Detection with the beam profiler** The potential of the beam profiler is much higher then the measurement potential of the detection cards we used for most of our experiments. It would therefore be recommendable to find out why the beam profiler gives the unexpected cross-like structure in the results and rewrite the LabVIEW program so that it uses the data from the beam profiler instead of the data from a webcam.

Dankwoord

Met dit verslag kijken we terug op een drietal jaren waarin we de bachelor Technische Natuurkunde hebben gevolgd en die we hiermee hopen af te sluiten. We zijn dan ook van mening dat het afronden van de bachelor opdracht in een groter licht moet worden gezien dan alleen de periode van 10 weken waarin we er actief aan hebben gewerkt. Stellen dat dat wel het geval zou zijn, zou een ontkenning zijn van het belang van die andere 140 weken van de bachelor, zonder welke dit verslag er nooit zou zijn geweest.

Er zijn een heleboel mensen zonder wie dit verslag er nooit zou zijn geweest en het zou ondoenlijk, zo niet onleesbaar, worden als we iedereen hier zouden gaan noemen. Echter willen we wel graag van de gelegenheid gebruik maken om een aantal specifieke mensen te bedanken voor hun steun en hulp, niet zozeer enkel tijdens deze opdracht, maar over de gehele drie jaar.

Reinout Nonhebel

For starters, I would like to thank all the people of the LPNO group for their help in the labs when we were totally new there. In particular Jörn Epping, our tutor, thank you for your feedback, assistance, enthusiasm and patience.

Verder aan iedereen die ik lastig heb gevallen met frustraties en overdreven enthousiasme een welgemeend dankjewel voor een luisterend oor, nieuwe ideeën en een frisse kijk op alles wat wel en niet lukte.

En last but not least wil ik graag Bob bedanken. We hebben samen zowel opluchting als intense frustratie meegemaakt de afgelopen maanden, maar ik weet zeker dat ik er met veel plezier aan zal terugdenken. Het was geweldig om met je samen te werken, bedankt daarvoor.

Bob Stienen

Of all people, I think our tutor Jörn Epping deserves a lot of kudos. During the assignment there were a lot of setbacks which, time by time, made me think whether or not this assignment would eventually work out. Furthermore, his seemingly unlimited patience regarding the assignment and the internship I did alongside this concluding bachelor research was praiseworthy.

Ook zou ik graag Reinout hiervoor willen bedanken. Achteraf was het echt een heel slecht idee om een stage en een bachelor opdracht tegelijkertijd te proberen te doen, maar ik sta er echt van te kijken hoeveel geduld één persoon kan hebben. Dat samen met het feit dat je een toffe persoon bent om mee samen te werken, zorgt ervoor dat ik deze bachelor opdracht (of de vele zouteloze grappen) niet snel zal vergeten.

In het algemeen wil ik voor de hele bachelor de opleiding bedanken en in het bijzonder Brigitte Tel. Ik weet niet hoe het bij andere opleidingen is geregeld, maar van een dergelijke openheid en de bereikbaarheid van de mensen binnen opleidingen heb ik in mijn functie als voorlichtingscoördinator en van mensen buiten de UT maar zelden gehoord. Dat, tesamen met het niet alleen inzetten op ontwikkeling van studenten binnen de opleiding maar ook over de grenzen van de natuurkunde durven te kijken maken dat ik hierbij een diepe buiging maak voor Marloes, Brigitte, Jeroen en alle andere mensen die binnen de opleiding werkzaam zijn,.

Natuurlijk mag ik ook de docenten niet vergeten, van wie ik uit ervaring weet dat hun functie vaak wordt onderschat. Het overbrengen van kennis is een vak apart en het enthousiast maken van studenten al helemaal. Serge, Claudia, Bob, Wouter en al die anderen met wie ik de afgelopen jaren heb leren kennen: blijf enthousiasme overbrengen zoals jullie dat bij mij is gelukt!

Ten slotte vergeet ik natuurlijk ook niet familie en vrienden, die me uitzonderingsloos hebben gesteund tijdens de afgelopen jaren en me constant hebben voorgehouden mijn hart te volgen in lastige keuzes. Pap, mam, broertjes en zusje, Corine, Rianne, Lieke, Imre, Carolien, Liesbeth en alle anderen die ik hier niet kan noemen (sorry, jullie zijn met te veel): heel erg bedankt! Ik denk niet dat ik voor een betere omgeving zou kunnen - of überhaupt durven - wensen.

Appendix A

List of used equipment

Equipment	Details
Beam profiler	**BP104-IR** - Thorlabs Slit Scanning Beam Profiler, 700 - 1800 nm, 10μm - 4mm Beam
Detector cards	**VRC2** - Thorlabs Absorption: 400 - 640 nm and 800 - 1700 nm Emission: 580 - 750 nm **VRC4** - Thorlabs Absorption: 790 - 840 nm, 870 - 1070 nm and 1500 - 1590 nm Emission: 520 - 580 nm
IR detector	**SM-3R** - TOPAG Detection up to 2000nm
Lasers	**S5FC1550P-A2** - Thorlabs Fibre Coupled SLD Source 1550 nm, 2 mW, PM **S1FC635PM** - Thorlabs Fibre Coupled Laser Source 635 nm, 2.5 mW, PM
Moveable stage	**MAX313D** - Thorlabs 3-Axis NanoMax Stage, Differential Drives, No Piezos **MAX311** - Thorlabs Closed-Loop 3-Axis NanoMax Stage w/ Differential Drives and Piezos
Piezo controler	**BPC303** - Thorlabs 150V USB Closed-Loop Piezo Controllers

Appendix B

LabVIEW program

B.1 Goal of the program

The goal of this program is to allow automated movement of a piezo-controlled stage, so that a fibre, mounted to this stage, can be moved over a certain area. That way, you do not have to go over checking a lot of positions by hand. Controlling the platform with piezos is also more accurate than manipulating the stage by hand, as the piezo's have a higher precision (5 nm) than the screws (1 μm). This is necessary when light has to be coupled into a waveguide with (sub-) micrometer precision.

B.2 Usage

The interface consists of five tabs. The first tab is used for configuration. The serial numbers of the piezo drive units itself (not the 3-channel controller) have to be inserted. Clicking CONFIGURE tells the program to connect to the piezos. If this is successful, the green light will turn on and the piezo position will be set to zero when the automatic calibration is completed. The program is now ready for use.

> When finished with the program, use the STOP button in the configuration tab to disconnect the piezo controller.

The last three tabs will show the control panels of the individual piezos. These can be used for direct control.

The main part of the program is the AUTOMATED SCANNING tab. The left column shows the current position at the top and the desired position at the bottom. The target position can also be controlled directly by typing a position or using the up/down arrows. All distances are measured in microns.

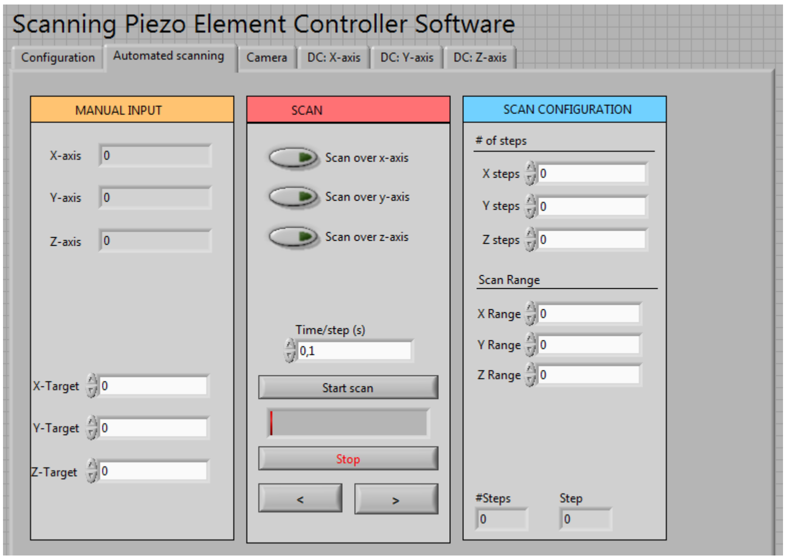


Figure B.1: The interface of the LabVIEW program where the movement of the stage can be controlled.

The right column is used for setting up a scan. You can select a range for the x, y and z axis and set the number of steps for that range. The step size is equal to the range divided by the number of steps. The program automatically adds one step per axis, so that both the zero and the final position (as set by range) are actually visited.

> Only even values should be used for the step size. Otherwise the platform will try to continue past the 20 microns instead of turning around.

The centre column can be used to perform a scan. Select the axes that should be used with the buttons and set a step time. Finally, press start to run the scan. The piezos will now move the platform according to the desired parameters. The progress is shown in the red bar. If you want to abort the scan, use the STOP button.

> The next/previous buttons are not functional yet. Also the step counters at the bottom right are solely for debugging purposes.

Do not edit the target values when a scan is running. This will mess up the counting system, causing the piezo to try to reach positions it cannot do.

In addition, the program can use a webcam to take pictures during the scan. The intensity profile in the horizontal direction is saved for each position, so that the position at which a spot appears can be found later on. That way, the program can perform a scan autonomously and the data can be collected afterwards.

The data is saved in form of a matrix, where the rows are intensity profiles for different positions. The first 640 items of a row contain the profile; the last three columns are used to save the location data (x, y, z-positions in microns).

B.3 Program structure

The program consists out of four parts: initialisation, changing the position of the piezo- element controlled stage, changing the target position in such a way it scans a region and the video acquisition part. In this section, each of these program parts are discussed.

B.3.1 Initialisation

In the initialisation step (as seen in figure B.2), started by pressing the CONFIGURE button, the program creates references to the piezo drives from the serial numbers provided by the user. The target positions and the "scan progress" bar are set to zero. When the configure-button is pressed, the program tries to connect to the piezo controllers. If no error occurs (i.e. the connection is successful), it moves on to the main part of the program.

B.3.2 Changing positions

Figure B.3 shows the part of the program where the errors and references from the initialisation stage go. If the connection is successful (i.e. no error occured during initialisation), the piezos are zeroed and the main update loop is started. At a maximum frequency of 100 Hz the target positions are communicated to the controller. The actual position is returned and shown in the three indicators. When the STOP button from the configuration panel is pressed, this loop ends and the connection to the controller is closed.

This part of the program is the only part of the program that directly changes the position of the stage. As can be seen in the figure, in the while loop an value of x-target, y-target and z-target are written to the first, second and third piezo drivers respectively. These values are originating

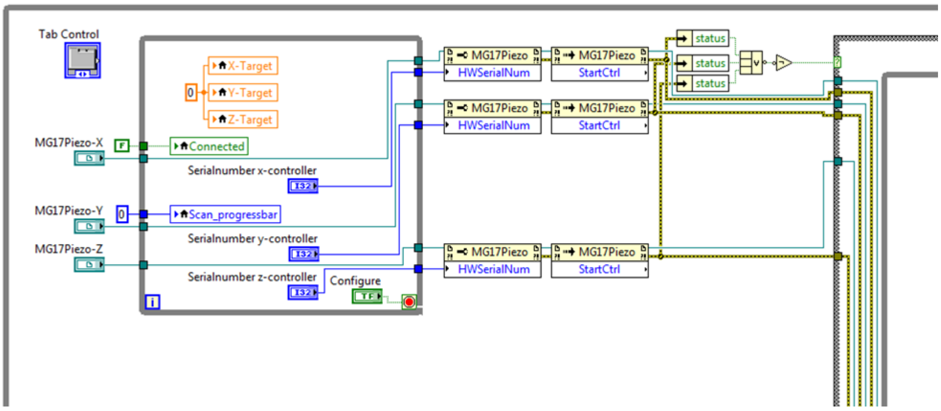


Figure B.2: Initialisation part of the program

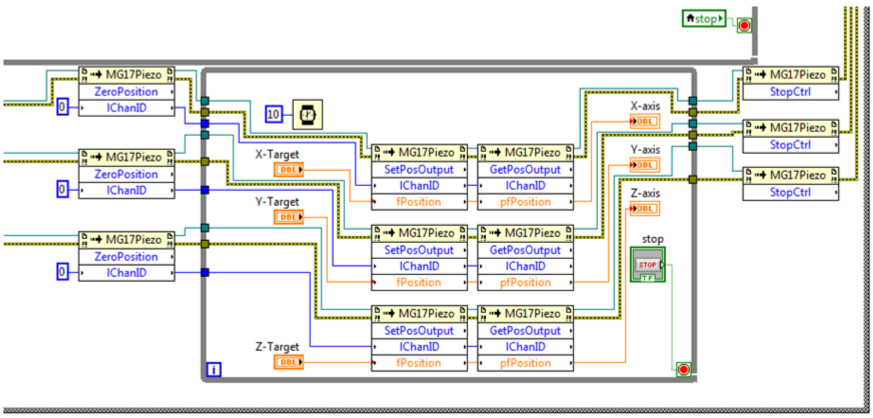


Figure B.3: Part of the program where the position of the stage is controlled.

from numeric controls at the frontpanel. Every $1/100th$ second the program tries to write the target values to the piezo driver. In this way, the rest of the program only has to change the value of these controls and not write directly to the drivers, which would end in data communication chaos.

B.3.3 Scanning

The main part of the program structure can be seen in figure B.4 and (in a part of) figure B.5. It is contained within an event structure coupled to the START SCAN button. From top to bottom it does the following: It sets the target positions to zero in all dimensions. It then creates a zero-sized array to save the intensity profiles, creates an empty image for the camera pictures and an x-axis (numbers 1 to 640) to show the intensity profiles in a graph. Finally, three sub-VI blocks are used to set the step size and number of steps. If for any axis scanning is disabled or the number of steps is set to zero, the step size for that axis is set to zero and the number of steps to one. That way only one value (zero) is scanned. The total number of steps is calculated at the top.

If the scanning is turned on, the step size is set as range/#steps and the number of steps is increased by one, so that both the zero and the final position are used in the scan.

What follows are three nested loops (one for each axis) that perform the scanning. The current position is read; the step size is added and then written to the piezo drives again. The inner loops (y- and x-axes) have an extra feature. To scan back and forth the step size is subtracted instead of added if the outer loop index is odd. These new positions are then writen to the numeric controls x-target, y-target or z-target, so that the new positions can be communicated with the piezo drivers, as discussed in the previous section.

Due to rounding errors it is possible to scan forth and back to a position like -3E-16, but the piezos cannot do positions less than zero. To eliminate this, any value less than zero is set to zero again.

B.3.4 Video Acquisition (VAQ)

The video acquisition part of the program, shown in figure B.5, shows two inner loops. The bottom part implements the scanning and timing, as well as the registration of the progress in the progressbar. The Vision Acquisition (VAQ) is used to capture images of a webcam. The intensity component is added to the placeholder mentioned before and displayed. The intensity profile is extracted and together with the positions of the peaks shown in a graph.

On the top right the current position data is added to the profiles and finally merged with the previously acquired data in a matrix. This data is eventually, when the scanning is ended, used to generate a .csv-file, which can in its turn be analysed using programs like Matlab.

If the scan is stopped with the stop button, the VAQ connection is closed and the loops are terminated one by one.

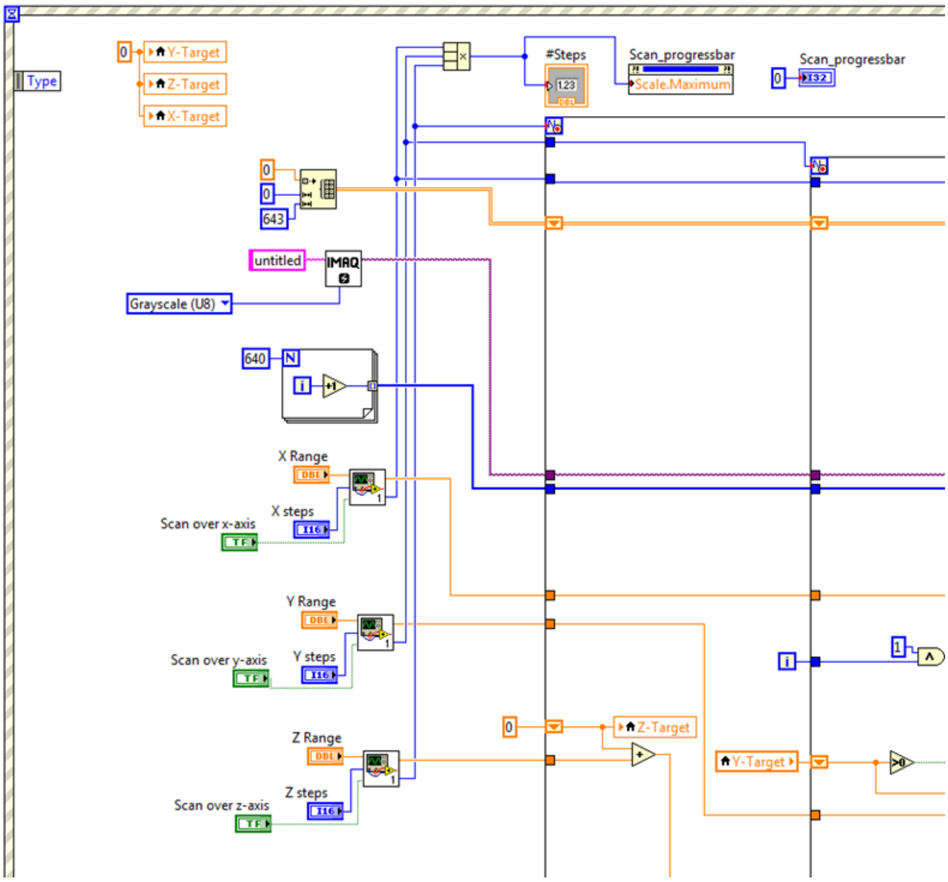


Figure B.4: Main part of the program

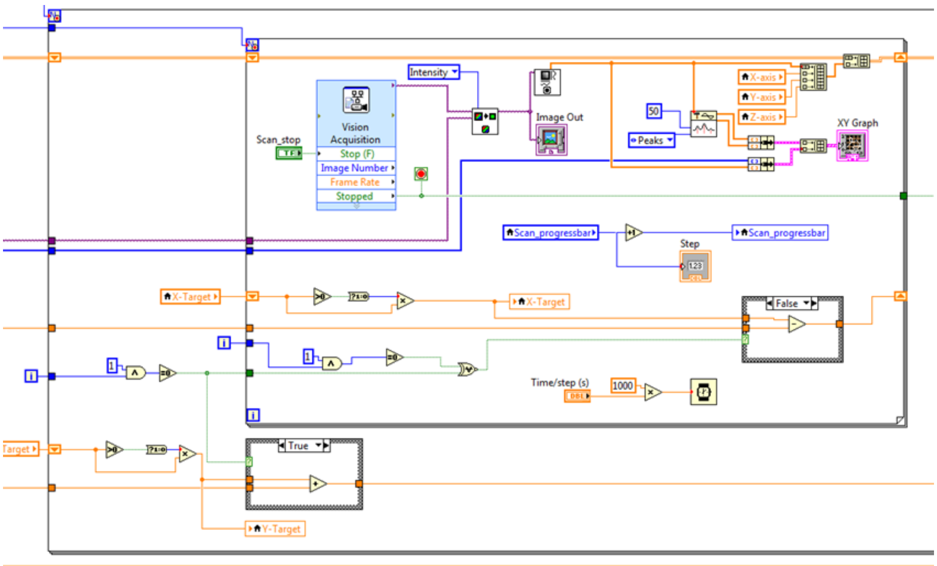


Figure B.5: VAQ-part and analysis of this picture of the program

Appendix C

Matlab code

C.1 Fourier analysis of oscillation in LabVIEW-output

```
close all;

% Load data
a = load('testrun12pol.csv');

% Show data (location data not included)
figure;
subplot(2,2,1);
pcolor(a(:,1:640)); shading flat;
xlabel('Picturecolumn');
ylabel('Step');
title('Planeplot of measurement data');

% Edit data for fourier transform and plot
data = a(:,1:640);
col = data(:,310) - smooth(data(:,310),240,'moving');
col_smooth_50 = smooth(col,50,'moving');

% Plot all (smoothened) data
subplot(2,2,2);
plot(col,'c');
hold on;
plot(col_smooth_50,'b');
legend 'Data' 'Data (smoothend)';
xlabel('Step');
ylabel('Intensity');
title('Plot of column 310');
```

```
% Configure data for FFT
fs = 1;
L = length(col);
NFFT = pow2(nextpow2(L)); % Next power of 2 from length of y

% FFT
Y = abs(fft(col,NFFT));
Y = Y(1:end/2);
f = (0:(NFFT/2-1))/NFFT;

% Plot single-sided amplitude spectrum.
subplot(2,2,[3 4]);
plot(f,Y,'r');
title('Frequency spectrum of column 310');
xlabel('Frequency (1/steps)');
ylabel('|Col(f)|');

% Get period
[~,i] = max(Y);
f_max = 1/f(i);
disp('The numer of steps between different peaks is:');
disp(f_max);
```

Appendix D

Beam profiler operation

This text and image originate from the beam profiler manual.

As shown in figure D.1, the BP104/BP109 uses the principle of scanning slits mounted on a rotating drum. This drum is equipped with a position encoder, which delivers exact information on the actual drum position to the analysing software.

The slits are oriented orthogonal at angles +45° and -45° with respect to the rotation axis. This scanning axis is tilted at 45deg so that the scanning directions of the slits appear as 0° (horizontal) and 90° (vertical), respectively. These scanning directions are marked as X and Y on the front of the instrument.

Using the rotation mount these scanning axes can be tilted to within +/- 60° in order to adapt it to the major and minor axes of an elliptical beam.

In addition there is a neutral density (ND) filter mounted on the drum which is used to take integral power measurements during every revolution. So this Beam Profiler can be used as a power meter, too.

Note that the power meter readout is the result of a separate integral measurement and is not a result of mathematical integration across the scanned beam profile.

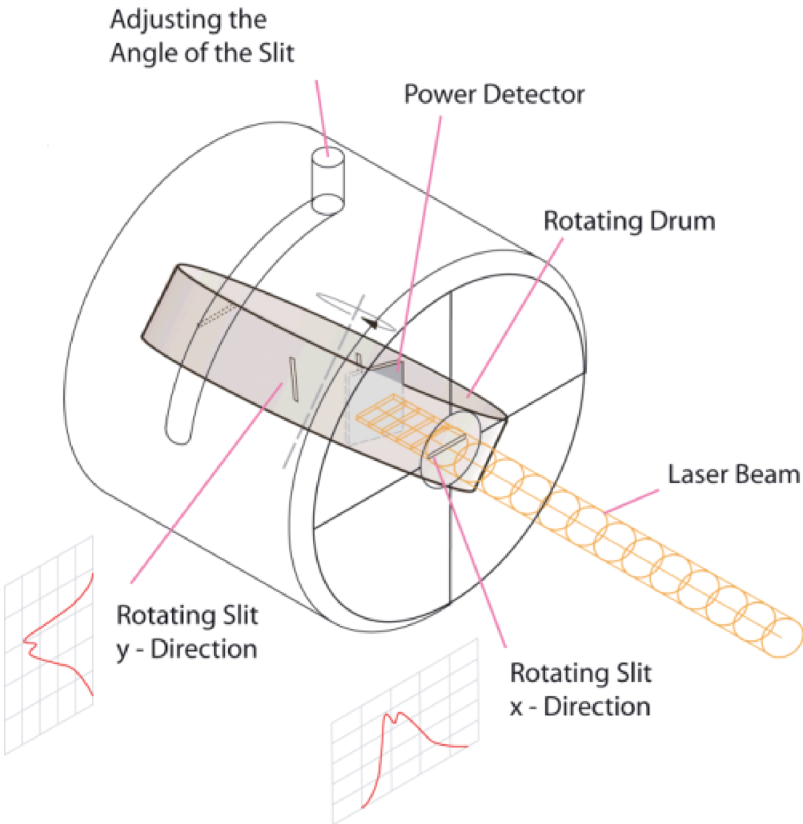


Figure D.1: Beamprofiler (inside view)

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