Loss of Power in Dielectric Optical Waveguides

Paulina Ibek
paulina.ibek@hotmail.com

under the direction of
Prof. Katia Gallo
Amin Baghban
Department of Applied Physics
KTH Royal Institute of Technology

Research Academy for Young Scientists
July 11, 2018
Abstract

Waveguides have become an essential part of our society and everyday life. They are used for lasers, sensing, communication and provide households with internet. The Bragg waveguide is one type of waveguide which can separate different wavelengths. A lot of research is done on the components of the waveguide, but there are no separate studies focusing on the losses themselves. In this paper the thickness, length and curvature of waveguides were altered to determine the loss. The experiment was conducted by transmitting light through the waveguides with optical fibers and analyzing the data with an optical spectrum analyzer. The reflection in the different components of the system were also determined and an experiment with a circulator was conducted. The results showed that thicker waveguides are more efficient, that thickness affects curved waveguides with bigger radii more than those with smaller radii and that waveguides with the biggest radii were the least efficient. It was also shown that straight waveguides had higher efficiency. In the future, loss experiments could be conducted on waveguides with disconnected components, other structures and materials.
Acknowledgements

First and foremost I would like to thank my mentors Amin Baghban and Katia Gallo for guiding me through this research project until the finish line and helping me understand complex concepts I have never heard of before. I really enjoyed every minute with you at AlbaNova and appreciate all the time you spent supervising me. Thanks to you I now understand the importance of waveguides and caught a glimpse of the research world, which was a truly unique experience.

Thank you to Research Academy for Young Scientists and their collaborators AcadeMedia and Europaskolan for giving me this amazing opportunity.

I would also like to thank all the organizers at Rays who spent their time being with us and making sure that everything worked, staying up several nights planning for the days to come, correcting all the reports and making sure we all had a great time.
## Contents

1 Introduction

1.1 Theory

1.1.1 Light

1.1.2 Bragg Reflection

1.1.3 Through the Waveguide

1.1.4 Loss of Light in the Waveguide

1.1.5 Optimization

1.2 Previous Research

1.3 Aim of the study

2 Method

2.1 Fabrication

2.2 Construction

2.3 Experimental procedure

2.3.1 Circulator

2.3.2 Reflection

2.3.3 Loss

3 Results

3.1 Circulator

3.2 Reflection

3.3 Loss for Different Lengths

3.4 Loss in Curves

4 Discussion

4.1 Future research

4.2 Conclusion
1 Introduction

Modern physics permeates nearly every household in developed countries. One of the most recent additions is the optical fiber which has become a world wide source for internet and only after a few years in use, it would be hard to imagine our everyday life without it. The optical fiber is just one type of waveguide. Waveguides are structures that guide electromagnetic waves and are used in fields like lasers, communication and sensing. If a component called Bragg grating is added to a waveguide, some wavelengths will pass through it and the others reflect, leaving the system completely. Depending on different variables such as the shape, thickness or length of the grating, different wavelengths with varying intensities will be reflected. By studying these changes it will become possible to optimize and obtain the desired reflection. [1]

1.1 Theory

A Bragg waveguide has a Bragg grating in the very middle of it, which reflects and transmits different wavelengths, two components at the ends of the waveguide that catch and transfer the light called grating couplers and optical fibers, which are the elements pointed at the ends of the waveguides. There is also a light source, in the case of this study, a laser and a device that receives the light and determines the reflected wavelengths. [1]

1.1.1 Light

Light is an electromagnetic wave consisting of a magnetic and electric field oscillating perpendicular to each other and the direction of propagation, forming a transverse wave. One of the laws ruling light which plays a fundamental role in Bragg waveguides is Snell’s law

\[ \sin \theta_1 n_1 = \sin \theta_2 n_2. \]  

(1)

where \( n \) is the refractive index for the two materials and \( \theta \) the angle of incidence or the reflection angle. Depending on how fast the light propagates through materials, the
angles will vary. The refractive index exists for a couple of common materials like air or water, but the speed of light is also affected by the shape of the substance, which \( n \) does not include. For more complicated structures, like Bragg gratings, the refractive index is called effective index, \( n_{\text{eff}} \), and the main difference is that the geometry is also taken into account when calculating the speed of light in the material. [3]

1.1.2 Bragg Reflection

Bragg reflection describes the reflection of light in crystals. It is based on the principle that crystals can be seen as pancakes stacked on one another. When light hits the crystal, it will penetrate different number of layers of the material, depending on its angle of incidence, and then get reflected. If the distance between two layers is the wavelength times a positive integer and normal reflection occurs, the light will remain in phase, meaning the light will undergo constructive interference. The path difference between the waves is \( 2d \sin \theta \), where \( d \) is the distance between the layers and \( \theta \) the scattering angle. The constructive interference is intensified by the fact that crystals have many layers. This results in the Bragg equation which describes the condition on \( \theta \) for constructive interference

\[
2d \sin \theta = m\lambda. \tag{2}
\]

The Bragg grating in a dielectric optical waveguide has the structure of a crystal and can therefore, after some modifications, be described with Bragg reflection. The difference between the two is that for Bragg gratings, light can only propagate in one direction, the direction of the waveguide. Since the crystal structure of the material is somewhat bothered by the rugged sides of the Bragg grating, the \( n_{\text{eff}} \) is added. In equation (3) the distance, \( d \), is replaced with the period of the structures on the sides of the grating, \( \Lambda \). This gives the Bragg equation for Bragg gratings, equation (3). It is important to note that light only can propagate through the waveguide if constructive interference occurs.

\[
2\Lambda n_{\text{eff}} \sin \theta = m\lambda \tag{3}
\]
Conducting experiments on the Bragg grating, most of the variables above are constant. The period of the structures on the sides of the grating is the same unless samples are changed, and the angle of the light pointed at the couplers remains the same (the angles inside the waveguide do not change because normal reflection is assumed). The only variable is therefore the wavelength, which will determine what light will scatter and leave the waveguide and what wavelengths will be transmitted. This means that different Bragg gratings and angles (which only move the spectrum sideways) transmit specific wavelengths. [2]

1.1.3 Through the Waveguide

A few conditions must be fulfilled for the light to get into the waveguide and propagate through it. First and foremost the light must be contained in the waveguide. This is achieved with encircling the waveguide by a material with a higher effective index. Since light prefers to move as fast as possible, most of it will stay in the waveguide. It is also important that the light has the right angle inside the waveguide. According to Snell’s law, the angle of the light in a material with a higher $n$ is smaller than that for a material with a smaller $n$. This means that if the angle in a waveguide, increases sufficiently, the angle in the other material will be $90^\circ$, meaning that the light will not leave the waveguide. This is called the critical angle, and is the smallest angle light must have to propagate through a waveguide. If the angle increases further, the light will be reflected on the inside of the waveguide and proceed forward bouncing on the inner walls. This is called total inner reflection. The critical angle, $\theta_{\text{critical}}$, is described with

$$\sin \theta_{\text{critical}} = \frac{n_1}{n_2},$$ (4)
where \( n_1 \) is the index of the surrounding material and \( n_2 \) the index of the waveguide. This means that the condition for total inner reflection is

\[
\theta > \theta_{\text{critical}}.
\] (5)

The second requirement for light to stay in the waveguide is related to the phase of light. Constructive interference has to occur for the light to proceed through the waveguide, which happens when light has the same properties, or phase, \( \phi \), in the same latitudinal spots in the waveguide. That means that the change in phase between two positions has to be a positive integer times \( 2\pi \). The phase shift can be explained with spatial angular velocity, \( k \), which describes how many oscillations a wave makes per space unit and is related to the wavelength of the light by \( k = \frac{2\pi}{\lambda} \). If this value is multiplied with the distance travelled of the light, which in this case is \( 2L \) (to the other side and back), one will obtain the phase shift. It is important to use the effective index, since the light travels in a waveguide. The final equation for phase change will be

\[
\Delta \phi = 2\pi m = 2L \frac{2\pi n_{\text{eff}}}{\lambda}.
\] (6)

From this, one can derive at what angle the light must hit the waveguide to match the phase. \( L \) is the same as the height of the waveguide times \( \cos \theta \), so the new equation will be

\[
2 \frac{d \cos \theta}{\cos \theta} \cdot \frac{n_{\text{eff}}}{\lambda} = m \to \cos \theta = \frac{2dn_{\text{eff}}}{m\lambda}.
\] (7)

Using geometry, one can obtain which angle \( \beta \) fulfills the requirements of phase and position

\[
\sin \beta = \frac{4d^2n_{\text{eff}}^2}{m\lambda}.
\] (8)

Light can only enter and leave the waveguides through the grating couplers set on the ends of the waveguides. The couplers are shaped like vertical lines to compensate for their higher effective index compared to air and match the wave vector from the outside so
that light can enter, according to the following formula:

\[ n_0 \frac{2\pi}{\lambda} = n_{\text{eff}} \frac{2\pi}{\lambda} + \frac{2\pi}{\Lambda_c} \]  

(9)

where \( n_0 \) is the refractive index, \( \lambda \) the wavelength, \( n_{\text{eff}} \) the effective index in the grating coupler and \( \Lambda_c \) the period of the vertical lines.

The last property of light which has to be taken into account when travelling through a waveguide is the mode. Modes are different sets of properties of light like the speed, angle, shape of distribution and so on. A mode is obtained with Maxwell equation, equation (10), where values for relative magnetic permeability, relative electric permittivity and the conductivity of the waveguide, as well as the wave vector in air, are included.

\[ \nabla \times \mu_r^{-1}(\nabla \times \vec{E}) - k_0^2(\varepsilon_r - i\sigma/\omega\varepsilon_0)\vec{E} = 0 \]  

(10)

The solution is the electric field for the light, which consists of an amplitude which determines the shape of the mode and a wavefunction, which gives the phase of the light, (11). A mode shows what the electric field of light will look like; it gives the information about where light will travel and with what intensity.

\[ \vec{E} = \vec{E}_{0(x,y)} \cdot e^{-i(\omega t - k_z z)} \]  

(11)

It is because of the second part of the solution that the travelled distance in the waveguide has to match the phase and be an integer times \( 2\pi \). The solution and thus the mode, is the distribution of the electric field and therefore the distribution of light in the waveguide. Often the mode is not contained by the waveguide, but extends to the outer parts as well. The wider the waveguide, the more light is contained. The mode does not have to be equally strong everywhere. Usually when conducting experiments on waveguides, it is the strongest in the middle and weaker in the outskirts of the waveguide. If one changes the variables included in the Maxwell equation (10), the field could for instance be strong
on just one side of the waveguide and weak in the other so that light only travels through half the waveguide. This is not very common though, and does not occur in this study. [4]

1.1.4 Loss of Light in the Waveguide

As light travels through the waveguide, loss is inevitable. One of the reasons is related to mode. As said before, mode does not have to be exclusively in the waveguide, so some of the light is outside of it. Since the sides of the waveguides are not smooth, which is a consequence of the fabrication not being precise enough, some of the light will scatter against the roughness. If the light has to travel through a long waveguide, more light will scatter. For the same reasons there will be less loss if the waveguide is wide. For curved waveguides, some of the light is also lost in the bendings of the waveguide. The angle of light in a straight waveguide does not change because of normal reflection, but in a bent waveguide light will hit the other side of the waveguide with different angles, depending on the curvature and angle of incidence. Some of these angles might not solve equation (6) and therefore leave the waveguide. The more curved a waveguide, the bigger the losses will be. On the other hand, if one wants a waveguide to begin and end in specific places, and instead of a sharp curve builds a more rounded one, the waveguide will become longer and therefore the scattering losses will be more extensive. There should also be some loss even before light enters the waveguide. Some reflection should happen as light leaves the optical fiber and some should also be reflected from the grating couplers. The reflection, and therefore loss, of the light moving from one material with the refractive index $n_1$ to a material with a refractive index of $n_2$ is

$$ R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 $$

(12)

where reflection (R) gives the percentage of reflected light. [4]
1.1.5 Optimization

It is important to have as much power as possible when conducting experiments to receive the most distinct results. As said before, the waveguide requires the light to have specific properties for it to enter, and one of those properties is the polarization of light. Polarization is the ratio between the B-field and E-field of the light. When light is transmitted from the laser, the polarization of the light might change due to the position and bend of the cables, thus not matching the waveguide and weakening the signal of the transmitted light. This can be solved with the polarization controller which light goes through after the cables from the laser and before the waveguide. By changing the position of the controller (which consists of three moving discs) one can change the polarization of the light so that it matches the requirement of the waveguide. It is also important to have the right angle when pointing the optical fiber at the grating couplers. When the angle changes, the spectrum of transmitted light will shift (but not change in shape), so that the nadir will end up on another wavelength according to the following equation:

$$\Lambda_{\text{coupler}} = \frac{\lambda_0}{n_{\text{eff}} - \sin \alpha}$$  \hspace{1cm} (13)

where $\Lambda_{\text{coupler}}$ is the period of the patterns on the Bragg grating, $\lambda_0$ the nadir and $\alpha$ the angle of the light. If one notices that the spectrum only moves up with bigger wavelengths, it might be a good idea to make the angle of the fibers bigger. [1]

1.2 Previous Research

Research done in the past on waveguides and Bragg gratings has shown that Bragg gratings with sinusoidal-sidewall modulations transmit more power than rectangular-sidewall modulations and that the transmission is stronger for narrow bandwidth corrugations. It has also been shown that low $\kappa$ values (low $\kappa$ means that the sidewall modulations are less extruded than the modulations of a Bragg grating with high $\kappa$ values) and that if a $\frac{\lambda}{4}$- shift is added in the modulations, no wavelengths will be transmitted, except for
a very narrow line around 1549 nm. What no one seems to have tested, however, is the actual loss of light/power in different types of waveguides. In most studies the loss for a specific waveguide is determined, but the subject is never in the centre of a study, where different variables are changed to see how that affects the loss. Most of the times the research is focused on the actual transmission instead. This is a downside to the entire area. Since there does not seem to exist a systematic determination of how loss is affected by different variables, it makes the optimization of the waveguides more difficult. [1] [5]

1.3 Aim of the study

The aim of this study is to change the length, curvature and thickness, to see when the losses of power are the most significant. The reflection will also be measured to see if it fits the transmission curve and if not, loss in other parts of the setup will be determined. By studying how different variables change the loss of power, it will be possible to find the most favourable features and create the most efficient waveguides.

2 Method

2.1 Fabrication

The starting point of the fabrication is a thin-film LNOI wafer, consisting out of a 300 nm thick LiNbO$_3$ piece, confined to silicon with a 2 μm SiO$_2$ layer. In the next step a Cr mask is placed on the structure and resistors in places where extruded pieces are wanted. After that the unfinished waveguide is bombarded with Ar$^+$ or F$^-$ ions in a so called E-beam Lithography. This results in the Cr being removed, leaving the parts with resistors untouched. The next steps are two types of etching, with first one eliminating the resistors and the LiNbO$_3$ around it (leaving the LiNbO$_3$ under the resistor). The second etching removes the Cr mask. After these six steps the waveguide is complete and ready for use. A silicon base is used for practical reasons, because many mini devices today also have
this semiconductor as base which means that the waveguide and device of choice could be put on the same chip. Lithium niobate is used because according to previous research it has been shown empirically that it is the material with the most reliable patterning. [1]

2.2 Construction

The experimental setup is the waveguide connected to optical fibers from both sides, a tunable CW laser, polarization controllers and an optical spectrum analyzer. The CW laser is connected to the polarization controllers and transmits light of different wavelengths throughout the experiment. On the CW laser one can change the setting for wavelengths, power and electric current. The polarization controllers change the electric field to obtain as much power as possible. Afterwards, the light travels from the polarization controllers through the fibers to the waveguide. It is crucial for the fibers to be precisely pointed at the ends of the waveguides, so that the light can hit it and then come out through the other fiber. From the couplers, light moves through the waveguides to the Bragg grating. It is in this stage that specific wavelengths are reflected. In the last step the transmitted wavelengths continue to the spectrum analyzer, which detects what light went through and summarizes the data in a graph, with the intensity on the y-axis and the wavelength on the x-axis.

The waveguide itself consists of smaller parts. Grating couplers are set on the ends of the waveguides and catch or transmit the light from or to the fibers. Afterwards the light travels to the Bragg grating, which is where the reflection of specific wavelengths takes place. Since the Bragg grating can be shaped in many different ways and have other varying properties, it is difficult to describe a typical Bragg grating. Gratings used in previous studies have been approximately 550 nm wide and shaped like periodic waves or squares at the edges with a period of 500 nm. The ones used in this study vary in shape and are described in a latter subsection (see Reflection). [1]
2.3 Experimental procedure

For the different experiments, a similar procedure was carried out. Firstly the CW laser was set to \( P = 10 \, \mu\text{W} \) and \( \lambda = 1570 \, \text{nm} \). These values were chosen because it is easier to detect the light with those when the fibers are placed over the grating couplers. It is known that none of the Bragg gratings reflect the wavelength 1570 nm so the signal would be strong, and the power of 10 \( \mu\text{W} \) is one highest the CW laser can produce. Afterwards, the fibers were directed at the waveguide with a computer program and a microscope. When the optical spectrum showed a value of at least a few nm (though it usually went up to a tenth of a \( \mu\text{m} \)), even more fine motions were used to place the fiber right. After that the polarization was changed to make the signal even stronger. When it seemed like a stronger signal could not be achieved, the settings on the CW laser were changed to \( P = 1 \, \mu\text{m} \) which gave the current \( I = 34 \, \text{mA} \). Since the different wavelengths have a limit of how much power they can contain, the power was set to SI1. The CW laser tests all wavelengths between 1550 - 1600 nm during the experiment, so they did not have to be changed manually. The electric current powers the laser which creates the emitted light and since it depends on the other variables (wavelength and power), it was not changed separately.

2.3.1 Circulator

A circulator is a device with three inputs. One of them is connected to the laser, the second to the waveguide and the third one to a detector. The purpose of the circulator is to check the reflected light. During experiments on Bragg gratings a spectrum of the transmitted light is received and the reflected light is expected to be complementary to it. The aim of this experiment was to see whether or not the actual reflection actually matched the expectations. The experiment started with the standard procedure described in section 2.3 and the circulator was plugged in. The experiment was conducted on a Bragg grating with a known spectrum of transmission. During the experiment the detector only detected the spectrum of reflection.
2.3.2 Reflection

As a follow up for the previous experiment, the reflection experiment was conducted, to test how much of the light was lost during other experiments. The standard procedure was followed except for a fiber which led the light to the detector being connected directly to the optical fiber so that none of the light travelled through the waveguide. The power was set to 5 mW. The point of this experiment was to see how much of the light got reflected in the optical fiber and never even got into the Bragg grating. The optical fiber was lifted so that no light would get reflected on the surface of the coupler. After this it was known how much light the fiber reflected, but it was also suspected that some light was lost due to reflection from the surface of the coupler. To measure this, the optical fiber was put closer to the coupler and then the reflection was measured. The result was the reflection from both the fiber and coupler together, but since the reflection from the fiber was known, it was easy to obtain the reflection from the coupler as well.

2.3.3 Loss

The last experiments were the experiments measuring the loss in the waveguide itself. For this, waveguides with different lengths, thicknesses and curvatures were tested. The normal procedure was followed for all of the experiments. Firstly a set of four waveguides was tested where all the waveguides were 1 \( \mu \)m thick with the lengths 125 \( \mu \)m, 250 \( \mu \)m, 500 \( \mu \)m, 500 \( \mu \)m. The same experiment was then conducted on an identical set of waveguides with the only difference being the smoothness of the surface and having a LN base instead of a Si base. Then two experiments were conducted on curved wavelengths with the radii 25 \( \mu \)m, 50 \( \mu \)m, 100 \( \mu \)m and one straight wavelength with the same thickness as a reference. The thicknesses of the waveguides were 800 nm and 500 nm.
3 Results

3.1 Circulator

When the reflection was measured for 1 mW, reflected power was almost 1 mW as seen in Figure 1.

![Reflection Transmission](image)

Figure 1: The Reflection and Transmission for a waveguide

This means that a lot of power was lost, either because of reflection from the fiber and grating or because of loss in the circulator.

3.2 Reflection

Table 1 shows how much power was put into the fibers, how much was transmitted after the circulator and how much was reflected from the fiber and the grating coupler.
Table 1: Power Lost and Transmitted when Measuring Reflection

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>5 mW</td>
</tr>
<tr>
<td>After circulator</td>
<td>120 µW</td>
</tr>
<tr>
<td>Total reflection from grating and fiber</td>
<td>5.5 µW</td>
</tr>
<tr>
<td>Reflected power from fiber</td>
<td>5 µW</td>
</tr>
<tr>
<td>Power transmitted to detector</td>
<td>150 nW</td>
</tr>
<tr>
<td>Power lost in circulator</td>
<td>4.9 mW</td>
</tr>
<tr>
<td>Power lost in waveguide and Bragg grating</td>
<td>0.13 µW</td>
</tr>
</tbody>
</table>

It is clear that the reflection from the different components does not contribute a lot to the total loss of power, compared to the loss of power after the circulator and after the Bragg grating. The values which were not directly received from the experiment were calculated.

3.3 Loss for Different Lengths

Figure 2 shows how much power the different waveguides transmitted depending on their length.

![Figure 2: Loss of Light for an Old 1µm Thick Waveguide](image)

Figure 2: Loss of Light for an Old 1µm Thick Waveguide
The waveguide which was 500 µm long seems to have the most power, while the rest of the results are not as clear.

For the new sample, the results are quite the opposite. Here it seems like the 500 µm long waveguide has the least power, while the others, just like in Figure 2, also override each other at multiple points.

![Figure 3: Loss of Light for a New 1 µm Thick Waveguide](image)

There are also some peaks at different points which should not exist because there are no Bragg gratings in the waveguides reflecting specific wavelengths.

### 3.4 Loss in Curves

Figures 4 and 5 show the loss of power for curved waveguides with different radii. For the 500 nm thick waveguide, the straight waveguide transmitted the most light, while the one with the largest radius, and therefore the longest waveguide had the most loss.
Figure 4: Loss of Light in a 500 nm Thick Curved Waveguide

Figure 5 shows the loss of light for a 800 nm thicker waveguide and like in Figure 4 the straight waveguide has the most power and the one with the largest radius has the least.

Figure 5: Loss of Light in a 800 nm Thick Curved Waveguide

4 Discussion

When adding another component, in this case the circulator, more loss is expected since light has to travel longer and because this type for circulator was not made for such
precise experiments as the ones conducted in this study. The reflection experiment was conducted to verify the hypothesis that most of the loss was due to the circulator and not because of the different parts of the setup e.g. the fiber or grating coupler. The expected value for reflected light from the fiber (which has the refractive index 1.5) is, according to the equation (12), 4%, while the actual loss from the fiber (which is after the light leaves the circulator) is 4.2%. That means there is no significant unexpected loss in the fiber. We expect the other loss between the optical fiber and grating coupler to be reflection from the coupler since there is no other reasonable explanation. It was not tested because the loss was rather insignificant. The power lost in the circulator was 4.9 mW, the reflected light from the grating coupler and the fiber corresponded to 5.5 µW and the power lost in the waveguide and Bragg grating was 0.13 µW, meaning most of the power was lost in the circulator.

The results from the waveguides with varying properties were quite unambiguous. The graph for the old straight waveguides shows that the 500 µm long waveguide has the most power in the middle of the spectrum, but has very little power at around 1500 – 1600 nm. If an average of the power for all the wavelengths was taken, the 500 µm long waveguide probably would not have been the strongest. If the yellow line is overlooked in that graph, it seems like the shortest waveguide has the most power on average and that the two other have approximately the same amount. The reason for the results not being clear might be because the waveguide was thicker. The 500 µm waveguide has more power in the middle of the spectrum because during the optimization stadium, the fibers were more precisely pointed at the couplers and the polarization controllers were better set. For the new straight waveguides the results were more rugged. All the dips can only be explained with outer disturbances like the construction work outside of AlbaNova. In Figure 3 a conclusion cannot be drawn, probably because of the waveguide being too thick.

As expected, the straight reference waveguide had the most power in the experiments for curved waveguides. What is interesting, however is that the waveguide with the largest radius, and therefore the longest was the one with the least power in both cases. This
means that the loss from bendings is smaller than that of a longer waveguide. In Figure 4 the waveguides with the radii 50 µm and 25 µm have approximately the same power, while in Figure 5 the one of the two with the bigger radius (and therefore longer) has more power than the one with a radius of 25 µm. One explanation might be that the latter waveguides are thicker because that leads to the mode being more contained and the light getting less scattered. That would mean that for those specific thicknesses and curvatures, the bend plays a bigger role than the length. The conclusion that can be drawn when comparing Figure 4 and Figure 5 is that the thicker the waveguide, the smaller the loss from the length. It can also be observed that the waveguides in Figure 5 have more power than those in Figure 4. This again indicates that thickness plays a crucial role in the loss of light. The loss from the new straight waveguide (Figure 3) is bigger than the loss from the old waveguide (Figure 2). The reason behind this might be that a new material was used in the new waveguide. If the transmitted light for the bent waveguides are compared, which were all made with the same material as the old straight waveguides, it is much greater than in the straight waveguides. The new straight sample might have less power because of the settings not being optimized.

4.1 Future research

For future studies it would be interesting to look at the reflection spectrum of a waveguide using a circulator which does not loose as much power as the one used in this study. One could also look at the loss in other types of waveguides, like the straight waveguides with disjointed circles on the sides. Loss in a waveguide with applied voltage could also be studied to see whether there is less or more loss.

4.2 Conclusion

Concluding, the circulator used in this study was not precise enough to measure the reflection spectrum. The light loss in the circulator was too significant for the result to be
taken into consideration. The conclusion that can be drawn from the wavelengths with
different variables is that, depending on the thickness, either the loss from long waveguides
or curves can be more dominant. To draw a more certain conclusion, experiments on more
variables have to be conducted.
References


