SINGLE MODE FIBER TO PLANAR WAVEGUIDE COUPLING WITH BALL LENSES

by: R. van Aken

Supervisor: Prof. Ir. G.D. Khoe
Coach: Dr. Ir. W. van Etten

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SUMMARY.

This report deals with the problem of coupling a single mode fiber to a planar waveguide. The coupling is performed with ball lenses. The coupler is designed for a wavelength of 1550 nm. In order to design a coupler, the spotsize parameters $W$ of the fiber light-beam and the planar waveguide light-beam are determined. The fiber has a circular geometry. The light-beam, emitted by the fiber, has thus a circular cross-section. The planar waveguide has a rectangular geometry. The lightbeam, emitted by the waveguide, has an elliptical cross-section. The half beam width $W_F$ of the fiber is measured using the transverse offset technique for a misaligned fiber splice. $W_F$ is 5.05 $\mu$m. The spotsize parameters $W_X$ and $W_Y$ (in the two orthogonal directions x and y) of the planar waveguide are both measured and calculated. $W_X$ and $W_Y$ are calculated using the effective index method for dielectric waveguides. $W_X$ and $W_Y$ are measured using the transverse offset technique for a misaligned fiber planar waveguide splice. The measured and calculated values of $W_X$ and $W_Y$ agree well. Their values are: $W_X = 1.2 \mu$m and $W_Y = 0.5 \mu$m.

There are two possible coupling configurations: the single ball lens coupler and the two ball lens coupler. The single ball lens coupler consists of a 2 mm diameter ball lens with a focal distance of 1.11 mm. The distance between the fiber and the center of the ball lens is approximately 8.31 mm, the distance between the planar waveguide and the center of the ball lens is however only approximately 1.24 mm. The coupler has small alignment tolerances, which cause packaging problems with respect to reliability and stability. The calculated coupling loss is 1.8 dB. The coupling loss is also measured using an experimental setup. The measured loss is 4.1 dB, which is larger than the theoretical coupling loss. This extra loss is mainly caused by misalignments and scattering of the light, which is caused by rough and irregular endfaces of the planar waveguide. The two ball lens coupler has relatively large alignment tolerances, but can not be realised, because there are no ball lenses available with the desired ratio of focal distances ($f_2/f_1 = 6.52$).
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1. INTRODUCTION.

In order to introduce coherent optical communication systems in a competitive way, it is necessary to integrate the receiver of the communication system on a few chips. On these semiconductor chips, various optical and electrical devices are monolithically integrated (e.g. multiplexers, photodetectors, demodulators, etc.). Some signal processing is performed optically, other signal processing is performed electrically. The optical devices are interconnected by means of optical planar waveguides.

A major problem in this field is the coupling of optical fibers to these electro-optic chips. Nowadays, most long haul optical communication systems are single mode systems. The coupling problem is then reduced to the coupling of a single mode fiber to a single mode planar waveguide. The coupling can be performed in several ways, such as:

- Butt joint coupling. This is not the most effective way of coupling.
- The use of lenses, such as: cylindrical lenses, ball lenses, GRIN-rod lenses, etc.

Some lens systems consist of one lens, other systems consist of multiple lenses.

In this graduation project, the coupling will be performed with ball lenses. The coupler will be designed for a wavelength of 1550 nm. In chapter 2, an introduction to the coupling problem is given. The fiber has a circular geometry and the planar waveguide has a rectangular geometry. This means that the light-beams, emitted by both waveguides have different geometrical cross-sections. This causes extra loss in the coupler. This loss is calculated. Two coupler configurations are introduced: The single ball lens coupler and the two ball lens coupler.

In order to design a coupler, the waist parameters of the fiber light-beam and the planar waveguide light-beam must be determined. This is done in chapter 3. The two coupling configurations are discussed in detail in the chapters 4 and 5. The coupling efficiency is calculated and the influence of misalignments and spherical aberration(s) of the ball lens(es) on the coupling efficiency is calculated. Chapter 4 deals with the single ball lens coupler and chapter 5 deals with the two ball lens coupler.

An experimental setup of the single ball lens coupler is discussed in chapter 6. With this setup the power coupling efficiency is measured. At the end of the chapter, a packaging method for the single ball lens coupler is presented. In chapter 7, couplers consisting of other lenses (micro-lenses and graded-index lenses) are discussed. Finally, in chapter 8, the general conclusions will be presented.
2. THE USE OF BALL LENSES IN A COUPLER.

2.1. Introduction.

The coupling between a single mode fiber and a planar waveguide can be realised in several ways. One way is to make use of lenses. The lenses in a lens coupler are used to focus the light beam, which is emitted by the fiber (or vice versa by the planar waveguide), in such a way that maximal power is coupled into the planar waveguide. The problem of coupling light of a fiber into a planar waveguide (or vice versa) is depicted in figure 1. The coupling problem is now reduced to the problem of matching the lightbeam, emitted by the fiber, to the lightbeam, which is emitted by the planar waveguide.

fig. 1. Coupling problem of two optical waveguides.

The emitted lightbeam of both optical waveguides can be approximated by a Gaussian function, if a cross-section is taken perpendicular to the direction of propagation [1,2]. The lightbeam, emitted by the fiber, has a circular cross-section. The waist of the Gaussian beam is represented by the parameter $2W_F$. The planar waveguide has a rectangular geometry. The lightbeam emitted by the planar waveguide has an elliptical cross-section. The waist of the Gaussian beam, emitted by this waveguide, can be represented by the parameters $2W_x$ and $2W_y$. $W_x$ and $W_y$ are the waist parameters in two orthogonal directions (x and y, respectively).

By placing a lens system between the fiber and the planar waveguide, the fiber light-beam is transformed into another light-beam, which matches the beam of the planar waveguide. With use of a cylindrical lens, a circular light-beam can be transformed into an elliptical light-beam. In the x-direction, $W_F$ has to be translated into $W_X$. In the y-direction, $W_F$ has to be translated into $W_Y$. It is very difficult to design lenses, which can exactly perform both translations simultaneously. One option is to use lenses, which translate the lightbeam only in one orthogonal direction. If a combination of these lenses is used, the desired translations can also be performed. An example of the operation of these lenses is shown in figure 2.
fig. 2. Anamorphic imaging with two cylindrical lenses.

The circular lightbeam, emitted by the fiber, can also be translated into another circular beam, which matches the elliptical lightbeam as best as it can. In this situation, some loss has to be accepted, but the mathematical analysis and the design of the coupler is much easier. The alignment tolerances are also larger. In the next paragraph, the loss will be calculated, which is caused by matching a circular lightbeam to an elliptical lightbeam.

2.2. Calculation of the loss caused by matching two lightbeams with different geometrical cross-sections.

Assuming perfect fiber-waveguide alignment, the two attributes for fiber-waveguide coupling loss are reflection loss and the mismatch between the fiber and waveguide modes. Reflection loss can be reduced if not completely eliminated by using either index matching fluid or anti-reflection coatings. In this section, only the loss, caused by matching a circular beam waist to an elliptical beam waist, will be considered. All other losses will be assumed zero. It is assumed that the lens system images the fiber light-beam exactly at the planar waveguide. It is also assumed that only one ideal lens is placed between the two optical waveguides. This lens causes no extra loss and acts only as a phase shifter (the radius of curvature of the phasefront of the wave is changed).

Light propagation in single mode waveguides can be described simply by means of electromagnetic fields. If the assumption is made that the electromagnetic field is linearly polarised, the power coupling efficiency can be calculated by just using electric fields. The power coupling efficiency can now be written as [1]:

\[
\eta = \frac{2}{\left( \frac{W_F}{W_X} + \frac{W_X}{W_F} \right) 2} \cdot \frac{2}{\left( \frac{W_F}{W_Y} + \frac{W_Y}{W_F} \right) 2}
\]
The power coupling efficiency is at its maximum if:

\[
\frac{d\eta}{dW_F} = 0 \tag{2}
\]

This means that:

\[
W_F = \sqrt{W_X W_Y} \tag{3}
\]

The maximal power coupling efficiency is in this case:

\[
\eta_{MAX} = \frac{4}{2 + \alpha + \frac{1}{\alpha}} \text{ with } \alpha = \frac{W_X}{W_Y} \tag{4}
\]

This means that the maximal coupling efficiency depends on the ellipticity of the planar waveguide. In figure 3, \( \eta_{MAX} \) is depicted as a function of \( \alpha \).

\[
\eta_{MAX} \quad \alpha
\]

fig. 3. \( \eta_{MAX} \) depicted as a function of \( \alpha \).

2.3. Possible lens systems.

Ball lenses can be used to perform the desired beam transformation. A major advantage of ball lenses is the spherical shape. The ball lens can easily be described mathematically. There are two possible options for the lens system. One option is the use of a single ball lens in the lens system. Another option is the use of two ball lenses in the lens system. Both options are depicted in figure 4.
fig. 4. Two possible options for the lens system.

With the single lens system, the desired change in beam parameters of the lightbeam can be obtained by adjusting the distance between the fiber and the lens, and the distance between the lens and the planar waveguide. Advantages of this system are its simplicity and the lower loss, caused by the use of only one lens. The small alignment tolerances are a disadvantage of this system. This will be shown in section 4.3.

Advantages of the two lens system are the relatively large alignment tolerances (see also section 5.3.). An disadvantage is the enhanced loss, caused by the use of two lenses.

Both systems will be mathematically analysed in chapters 4 and 5. Also the influence of misalignments on the coupling efficiency will be calculated.
3. MEASUREMENTS OF THE FIBER FIELD AND THE PLANAR WAVEGUIDE FIELD.

3.1. Measurement of the single mode fiber field.

In order to determine the Gaussian parameters of the lightbeam emitted by the fiber, the fiber field has to be measured. There are two fibers selected to perform the coupling to the planar waveguide. In a later stage, one of the two fibers will be selected to perform the coupling. These two fibers are selected because the spotsizes were already measured by Philips N.V. The code numbers of these fibers are: SE8161A and AK3679A.

The fiber SE8161A is a single mode fiber with a depressed cladding. The mode field diameter is measured by Philips N.V. (with use of the far-field inversion integral technique [2]). The results are depicted in figure 5.

The other fiber (AK3679A) is a single mode fiber with a matched cladding. The mode field diameter is measured by Philips N.V. The results of the measurements are depicted in figure 6.
In order to get some experience with spotsize measurements, the mode field diameter of the fiber AK3679A is measured again (at the Eindhoven University of Technology). As measurement technique is used the transverse-offset technique [2]. This technique is based upon the loss of a misaligned fiber splice. If two pieces of the same fiber with spotsize $W$ are butt jointed with no angular misalignment or end separation, but with a transverse offset $d$, the power coupling efficiency becomes [1,2]:

$$\eta = \eta_0 \exp \left( -\frac{d^2}{W^2} \right)$$  \hspace{1cm} (5)

$\eta_0$ is a constant factor and is independent of $d$.

By measuring the transmission coefficient as a function of the transverse offset and fitting the measurement results to equation (5), the spotsize of the fiber can easily be determined. The measurement setup is designed by R. Maessen [3].

The theory, where the measurements are based on, assumes that there is no angular misalignment or end separation. Angular misalignment can be very easily reduced to less than a few degrees. The effect of end separation can be modelled using the Gaussian beam theory. For less than 1 percent increase in $W(z)$, $z$ has to be: $z < 18 \, \mu m$ ($\lambda = 1500 \, \text{nm}$, $W_0 = 5.5 \, \mu m$). A 18 $\mu m$ gap can easily be achieved in practice. The measurement results are depicted in figure 7.
fig. 7. Result of the transverse-offset measurements.

The measured mode field diameter is $2W_o = 11.0 \, \mu m$. This value agrees well with the measured value (by Philips N.V.) of $10.91 \, \mu m$.

3.2. Calculation of the planar waveguide field.

In this section, the Gaussian beam parameters $W_X$ and $W_Y$ of the light-beam emitted by the planar waveguide are calculated. The used planar waveguide is a so-called ridge type waveguide. The geometry of this waveguide is shown in figure 8. It consists of a 5 layer structure:

- A $N^+$ substrate.
- A InP buffer layer (thickness: 1.2 $\mu m$). This layer has to be thick enough to isolate the guided light optically from the substrate.
- The InGaAsP waveguide layer (thickness: 0.4 $\mu m$). The ridge guide is created by etching a step $\Delta d$ in the film ($\Delta d = 0.2 \, \mu m$).
- A sputtered InP cover layer (thickness: 0.4 $\mu m$).
- Air superstrate.
A ridge type waveguide has several advantages to a strip-loaded waveguide [4]:
- The edge roughness of the strip, which is due to the micro-structure of the sputtered film, introduces scattering losses.
- The strip-loaded waveguide is sensitive to contamination because part of the light flux travels through the uncovered region next to the strip.
- Prism coupling can be performed much easier with ridge type waveguides.

A disadvantage of the ridge type waveguide is the more laborious fabrication technique. In many computations the waveguide structure is considered to be a three-layer structure [4]:
- The buffer layer and substrate with refractive index $n_0$.
- The film with refractive index $n_1$.
- The InP layer with air superstrate above the actual waveguide.
  The refractive index is $n_0$.

The planar waveguide is a single mode waveguide for a wavelength of 1.55 μm. Thus only the fundamental mode propagates along the waveguide. The Gaussian beam parameters $W_x$ and $W_y$ can be calculated with use of the Effective Index Method (EIM) for dielectric waveguides. The transverse beam parameter $W_y$ can be calculated very easily, only the transverse structure of the waveguide should be considered. In this calculation, the waveguide consists of an InP top layer, the InGaAsP film and an InP bottom layer. In order to calculate the lateral beam parameter $W_x$ the Effective Index Method is used. The waveguide is separated into a number of regions in which the structure is invariant in lateral direction (see also figure 9). In each of these regions the effective index $\tilde{N}$ is computed as if the regions were infinitely extended in the longitudinal direction. The propagation constant of the waveguide can be computed by considering it as a 2-dimensional waveguide, in which each region is represented as a film having the lateral width of the region as film-thickness and its effective index as actual refractive index. The effective index $\tilde{N}$ is related to the propagation constant $\beta$ of the waveguide mode according to:
\[ N = \frac{\beta}{k_0} \]  
\[ (6) \]

\( k_0 \) is the propagation constant in vacuum. In the next paragraphs, \( W_x \) and \( W_y \) are calculated.

fig. 9. The Effective Index Method illustrated for a ridge-guide geometry.

**Calculation of \( W_y \).**

In this paragraph, the effective mode indices and \( W_y \) are calculated.

The refractive index of InP is: \( n_0 = 3.1693 \) (wavelength 1.55 \( \mu \text{m} \)).

The refractive index of InGaAsP is: \( n_1 = 3.2836 \) (wavelength 1.55 \( \mu \text{m} \)).

It is assumed that the waveguide is a lossless waveguide. The normalised film parameter \( V \) is defined as:

\[ V_i = \frac{2\pi}{\lambda} d_i \sqrt{n_i^2 - n_0^2} \]

\[ i = \text{the region number}. \]

\( V \) can be calculated in the three regions. In region 2 and 3 \( d \) is 0.2 \( \mu \text{m} \). This means that \( V_2 = V_3 \). With use of \( V \) and figure 10, the normalised propagation constant \( b \) can be calculated in the two different regions. \( b \) is defined as:

\[ b = \frac{\beta^2 - n_0^2 k_0^2}{n_i^2 k_0^2 - n_0^2 k_0^2} = \frac{N^2 - n_0^2}{n_i^2 - n_0^2}, \quad 0 < b < 1 \]  
\[ (8) \]
The integer \( m \) is called the mode number, for the fundamental mode it equals zero. The parameter \( a \) is the so-called asymmetry parameter. For symmetrical waveguides it equals zero. The mode effective index \( N \) can be calculated with use of equation (8):

\[
N_i = \sqrt{n_0^2 + b_i(n_i^2 - n_0^2)}
\]

\( N_i \) and \( N_{II} \) can be calculated with use of the two different values for \( b \):
\( N_i = 3.206 \)
\( N_{II} = 3.183 \)

Next, the effective mode width will be used. The effective mode width is defined as the width of a uniform intensity distribution having the same maximum intensity and the same power content as the mode profile \( U(y) \) (see also figure 11):

\[
W_E = \frac{\int U^2(y) \, dy}{U^2_{\text{MAX}}}
\]
fig. 11. The definition of the effective mode width of a mode profile.

For a Gaussian beam profile $\exp(-x^2/W_0^2)$, an effective mode width $W_0\sqrt{\pi/2}$ can be found, so that a mode can now be approximated by a Gaussian beam with beam waist:

$$W_0 = W_E \left[ \frac{2}{\pi} \right]$$

For TE-polarised modes, equation (10) can be calculated analytically in a 3 layer waveguide [4]:

$$W_E = \frac{1}{2} d \left[ 1 + \frac{1}{v} + \frac{1}{w} \right]$$

with:

$d = \text{the film thickness.}$

$v = \text{the normalised transverse attenuation constant in the substrate:}$

$$v = k_0 d \sqrt{N_2^n - n_0^2}$$

$w = \text{the normalised transverse attenuation constant in the cover layer:}$

$$w = k_0 d \sqrt{N_2^n - n_0^2}$$

$W_Y$ can be calculated, using the mode effective index in region 1 ($N_1$) and equation (11):

$$W_Y = 0.48 \ \mu m.$$

**Calculation of $W_X$.**

In order to calculate $W_X$, the same calculations must be made. Instead of the actual refractive indices $n_0$ and $n_1$, the mode effective indices $N_1$ and $N_2$ are used. $V$ can now be written as:

$$V = \frac{2\pi}{\lambda} w \sqrt{N_1^2 - N_2^2}$$
Using equation (15) and figure 10, the normalised propagation constant $b$ can be found. Now, the mode effective index in horizontal direction can be found:

$$N = \frac{\sqrt{N_{ii}^2 + b\left(N_{i}^2 - N_{ii}^2\right)}}{\sqrt{N_{i}^2}}$$  \hspace{1cm} (16)

$W_E$ can be calculated using equation 12 ($d$ has to be replaced by $w$). $W_x$ can be found using equation (11). This means that:

$$W_x = 1.18 \, \mu m.$$

### 3.3. Measurement of the planar waveguide field.

The planar waveguide field is also measured, in order to determine the Gaussian beam parameters. The transverse offset technique is used as measurement technique [2]. This measurement technique can also be used for asymmetrical light-beams. $W_x$ and $W_y$ will be determined using a misaligned single mode fiber planar waveguide splice. Two separate measurements are needed, one to measure $W_x$ and one to measure $W_y$. In the first case, the fiber has an offset $x_0$ in the x-direction, in the latter case, the fiber has an offset $y_0$ in the y-direction. It is assumed that no angular misalignment and end-separation occurs. In appendix A, the power coupling efficiency is calculated for a misaligned fiber planar waveguide splice with offsets $x_0$ and $y_0$. The power coupling efficiency is:

$$\eta = \frac{4W_F^2 W_x W_y}{W_F^2 + W_x^2} \exp \left(-\frac{2x_0^2}{W_F^2 + W_x^2}\right) \exp \left(-\frac{2y_0^2}{W_F^2 + W_y^2}\right)$$  \hspace{1cm} (17)

It can be seen from equation (17) that if $y_0 = 0$, the power coupling efficiency is only a function of $x_0$ and vice versa. Thus $W_x$ and $W_y$ can be measured separately. The fiber AK 3671A is used to perform the measurements. The mode field diameter of the fiber is $10.91 \, \mu m$ ($\lambda = 1.55 \, \mu m$). The measurement setup is depicted in figure 12.

fig. 12. Diagram of the measurement set-up.
The fiber is fixed on two piezo-elements, which can be moved in two orthogonal directions (x and y). These piezo-elements are controlled by a personal computer. The accuracy of the piezo-elements is 50 nm/V. The piezo-elements are fixed on x,y and z micro-positioners in order to perform the initial fiber-waveguide alignment. This is depicted in figure 13.

![Diagram of the fiber-holder.](Image)

fig. 13. Diagram of the fiber-holder.

The planar waveguide is fixed in a holder, which is depicted in figure 14.

![Diagram of the planar waveguide holder.](Image)

fig. 14. Diagram of the planar waveguide holder.

The 632 nm laser is used to track the lightbeam in the circuit. Using this laser, visual inspection of the splice is possible. The actual measurements are performed with the 1550 nm laserdiode. The measurement results are depicted in figures 15 and 16.
fig. 15. Result of the transverse offset measurement with offset $x_0$.

fig. 16. Result of the transverse offset measurement with offset $y_0$.

$W_x$ and $W_y$ can be determined from figures 15 and 16 using equation (17). This means for $W_x$ and $W_y$:

$W_x = 1.4 \, \mu m$.

$W_y = 0.6 \, \mu m$. 
3.4. Conclusions.

The measured and calculated values of $W_x$ and $W_y$ agree very well. In table 1 the influence of the different values of $W_x$ and $W_y$ on the power coupling efficiency is shown.

Table 1: The influence of the calculated and measured values of $W_x$ and $W_y$ on the coupling efficiency ($\alpha = W_x/W_y$).

<table>
<thead>
<tr>
<th>$W_x$ (in $\mu m$)</th>
<th>$W_y$ (in $\mu m$)</th>
<th>$\alpha$</th>
<th>Coupling efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>measured values</td>
<td>1.4</td>
<td>0.6</td>
<td>2.3</td>
</tr>
<tr>
<td>calculated values</td>
<td>1.18</td>
<td>0.48</td>
<td>2.46</td>
</tr>
</tbody>
</table>

As well the calculated values, as the measured values of $W_x$ and $W_y$ have a certain inaccuracy. The calculated values of $W_x$ and $W_y$ are probably more accurate. Therefore, these values will be used in the calculations made in chapters 4 and 5. Thus:

$W_x = 1.2 \, \mu m$.

$W_y = 0.5 \, \mu m$.

This means that $\alpha = 2.4$. The maximal coupling efficiency is 0.83. The theoretical coupling loss is 0.8 dB.
4. THE SINGLE LENS COUPLER.

4.1. Introduction.

In this chapter, a coupling system consisting of a single lens will be considered. A diagram of the coupler configuration is given in figure 17.

fig. 17. Diagram of the coupler configuration.

Firstly (in section 4.2.) the ray transfer matrix is calculated, assuming paraxial rays. With this assumption, the change in waist parameters, which is caused by the lens, can easily be calculated.

In section 4.3, the influence of misalignments on the coupling efficiency is calculated. In this section, the rays are assumed to be paraxial. There is also assumed that the lens is located within the Fraunhofer diffraction region of the fiber output beam. This means that the distance between the fiber and the lens is so large that the fiber behaves as a point source with respect to the lens.

In section 4.4. the influence of the spherical aberration of the lens on the coupling efficiency is considered. A practical lens is never free of optical aberration. Optical aberrations are faults or defects of the image. In general they are described in terms of amount by which a geometrically traced ray misses a desired location in the image formed by an optical system. The most important form of optical aberration is the so-called spherical aberration. Spherical aberration can be defined as the (longitudinal) variation of focus with aperture. In this case, the rays are assumed to be not paraxial. Under paraxial approximation, all rays emitted from the fiber converge at the planar waveguide endface. It appears that the point, where a ray (emitted with angle \( \theta \)) crosses the optical axis again, depends on \( \theta \). This is depicted in figure 18.
The influence of spherical aberration can also be expressed in a blur circle. The place at which the light-beam has the smallest diameter (waist) is not the focal point, but this occurs just before the focal point. This means that the focal point degenerates into a circle, if a cross-section is taken perpendicular to the direction of propagation. This circle is called the blur circle, which is depicted in figure 19.

This means that the distance between the lens and the waveguides has to be shortened somewhat [5]. The effect of this shortening of the distances on the coupling efficiency is also considered.

4.2. Calculation of the ray transfer matrix.

In this section, the ray transfer matrix is calculated. The ball lens can easily be described mathematically. The ray path through the lens depends on the optical properties of the lens and the input conditions. These are represented by \( x_1 \) and \( x_1' \). \( x_1 \) represents the position of the ray (the distance from the optical axis). \( x_1' \) represents the angle or slope of the ray with respect to the optical axis. For paraxial rays, the corresponding output quantities \( x_2 \) and \( x_2' \) are linearly dependent on the input quantities. This can be written in matrix form [1]:

\[
\begin{pmatrix}
 x_2 \\
 x_2'
\end{pmatrix} = \begin{pmatrix}
 a & b \\
 c & d
\end{pmatrix}
\begin{pmatrix}
 x_1 \\
 x_1'
\end{pmatrix}
\]
The matrix is called the ray transfer matrix of the lens. Although the ball lens is considered to be a thick lens, the principal planes are located at the geometrical center of the lens [6]. A ball lens therefore can be described as a thin lens. Using the thick lens formula, the ray transfer matrix \( L \) of the ball lens can be written as [1,6]:

\[
\begin{pmatrix}
  x_2 \\
  x_2'
\end{pmatrix} =
\begin{pmatrix}
  A & B \\
  C & D
\end{pmatrix} \cdot
\begin{pmatrix}
  x_1 \\
  x_1'
\end{pmatrix}
\]

\[ L = \begin{pmatrix}
  1 & 0 \\
  \frac{-1}{f} & 1
\end{pmatrix} \]  

There is a connection between the focal distance \( f \), the radius \( r \) and the refractive index \( n \) of the ball lens [7]:

\[
\frac{f}{r} = \frac{n}{2(n-1)}
\]  

The coupling configuration is depicted in figure 20.

![Diagram of the lens configuration.](image)

fig. 20. Diagram of the lens configuration.

The ray transfer matrix is called \( M \). \( M \) can be written as:

\[
M = T_2 \cdot L_1 \cdot T_1
\]  

(Light transmission is chosen from left to right in figure 20.)
$T_1$ is the ray transfer matrix for the space between the fiber and the principal plane of the lens. $L_1$ is the transfer matrix for the ball lens. $T_2$ is the transfer matrix for the space between the principal plane of the lens and the planar waveguide. The following equations can be used for $T_1$, $T_2$ and $L_1$ [1]:

$$T_1 = \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix}, \quad T_2 = \begin{pmatrix} 1 & d_2 \\ 0 & 1 \end{pmatrix}$$  \tag{22}

$$L_1 = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$$  \tag{23}

This means for $M$:

$$M = \begin{pmatrix} 1 - \frac{d_2}{f} & d_1 + d_2 - \frac{d_1 d_2}{f} \\ -\frac{1}{f} & 1 - \frac{d_1}{f} \end{pmatrix}$$  \tag{24}

If the following relations are chosen for the distances $d_1$ and $d_2$, the ray transfer matrix reduces to a simple matrix [8]:

$$d_1 = (1 + m)f$$  \tag{25}

$$d_2 = \left(1 + \frac{1}{m}\right)f$$  \tag{26}

$m$ is called the magnification factor. A new planar waveguide waist can be defined, in order to maximise the power coupling efficiency (see also equation (3)):

$$W_{\text{PLANAR WAVEGUIDE}} = \sqrt{W_x W_y}$$  \tag{27}

The fiber light-beam waist $W_F$ has to be transformed to $W_P$ for maximum power transfer. $m$ is chosen such to maximise the power coupling efficiency between the fiber light-beam and the new planar waveguide light-beam waist:

$$m = \frac{W_{\text{FIBER}}}{W_{\text{PLANAR WAVEGUIDE}}} = \frac{W_F}{W_P}$$  \tag{28}

This means for $M$:

$$M = \begin{pmatrix} -\frac{1}{m} & 0 \\ -\frac{1}{f} & -m \end{pmatrix}$$  \tag{29}
This means that the fiber waist $W_f$ is reduced to $W_f/m$. This waist is the desired waist, which matches the planar waveguide waist as good as possible. The Philips fiber SE8161A is chosen to perform the coupling with. This fiber has a waist parameter $W$ of 5.05 $\mu$m. The other Philips fiber has a larger spotsize (see also section 3.1.), which enhances $m$ (see also equation (28)). For a practical coupler, $m$ has to be as small as possible. A ball lens with a diameter of 2 mm will be used in the coupler. This lens has a focal distance of 1.11 mm (1550 nm). The coupler will remain compact if the ball lens has a small focal distance. ($d_1$ and $d_2$ will remain small) and the spherical aberration causes little loss if a small ball lens is used. In chapter 3 $W_f$, $W_x$ and $W_y$ are determined. They have the following values:

$W_f = 5.05 \mu$m.
$W_x = 1.2 \mu$m.
$W_y = 0.5 \mu$m.

$m$ can be calculated using equation (28):

$m = 6.52$

This means for $d_1$ and $d_2$:

$d_1 \approx 8.33$ mm.
$d_2 \approx 1.26$ mm.

**4.3. The influence of misalignments on the coupling efficiency.**

In this section, the influence of misalignments is considered. In practice, optical coupling arrangements are never perfectly aligned. It is therefore useful to extend the coupling theory to include misalignments.

Light propagation in single mode waveguides can be described by means of electromagnetic fields. If the assumption is made that the electromagnetic fields are linearly polarised, the power coupling efficiency can be calculated by just using electric fields. For the time being, it is assumed that there are no misalignments. A sketch of the coupler configuration is given in figure 20. The electric field vector of the fiber field is called $E_f$. The electric field vector of the planar waveguide field is called $E_p$. At the fiber endface (the waist) $E_f$ can be written as [1]:

$$E_f = E_{_{f_{\theta}}} \exp \left( - \frac{x^2}{W_f^2} \right) \exp \left( - \frac{y^2}{W_f^2} \right)$$

At the planar waveguide endface $E_p$ can be written as:

$$E_p = E_{_{p_{\theta}}} \exp \left( - \frac{x^2}{W_x^2} \right) \exp \left( - \frac{y^2}{W_y^2} \right)$$

Both fields have to be normalised to unity power. This means that:
The electric fields $E_f$ and $E_p$ can now be written as:

$$E_f = \sqrt{2} \exp \left(-\frac{x^2}{W_f^2}\right) \sqrt{2} \exp \left(-\frac{y^2}{W_f^2}\right)$$

$$E_p = \sqrt{2} \exp \left(-\frac{x^2}{W_x^2}\right) \sqrt{2} \exp \left(-\frac{y^2}{W_y^2}\right)$$

The ray transfer matrix of a ball lens is the same matrix as the ray transfer matrix of a thin lens, although the ball lens is considered to be a thick lens. The ball lens has a principal plane at the geometrical center of the lens [6]. This principal plane is chosen to be the coupling plane. The thin lens transfer matrix is considered to coincide with the principal plane. In fact, the coupling plane is situated at an infinite semal distance at the right side of the principal plane (see also figure 21). The power coupling efficiency will be calculated at this plane. The electric field of the fiber can be described at a distance $z$ of the fiber end face as [1]:

$$E_{fi}(r,z) = A \frac{W(0)}{W(z)} \exp \left(-\frac{r^2}{W^2(z)}\right) \exp \left(-j \left[kz + \frac{kr^2}{2R(z)} - \phi(z)\right]\right)$$

with:

$A = \text{a constant.}$

$r = \sqrt{x^2 + y^2}$

$W(z)$ is the half beam width at distance $z$.

$$W(z) = W_0 \sqrt{1 + \frac{z^2}{z_0^2}}$$

$R(z)$ is the radius of curvature of the wavefront.

$$R(z) = z + \frac{z_0^2}{z}$$

$$\phi(z) = \arctan \left(\frac{z}{z_0}\right)$$
For a fixed value of $z$ the fiber field is a Gaussian function of $r$. At the coupling plane $z$ is equal to $d_1$. The coupling plane is infinitely extended in transversal direction. Only the transversal ($r$) dependence of $E_{F1}$ is important for the time being (no misalignments are considered). $E_{F1}(r)$ can now be written as:

$$E_{F1}(r) = \frac{\sqrt{2}}{\sqrt{\pi} W(d_1)} \exp \left(-\frac{r^2}{W^2(d_1)}\right) \exp \left(-\frac{jk r^2}{2R(d_1)}\right)$$  \hspace{1cm} (37)

with:

$$W(d_1) = W_0 \sqrt{1 + \frac{d_1^2}{z_0^2}}$$

$W(d_1)$ can be approximated by:

$$W(d_1) \approx W_1 \frac{d_1}{k W_F} \quad \text{with} \quad k = \frac{2\pi}{\lambda}$$  \hspace{1cm} (38)

because $d_1 \gg z_0$ ($z_0 \approx 52 \, \mu m$ and $d_1 \approx 8.3 \, mm$).

$R(d_1)$ can be approximated by:

$$R(d_1) \approx d_1$$  \hspace{1cm} (39)

because $d_1 \gg z_0^2$. This means for $E_{F1}$ [8]:

$$E_{F1} = \frac{4\sqrt{2}}{\sqrt{\pi} \sqrt{W_{F1}}} \exp \left(-\frac{x^2}{W_{x1}^2}\right) \exp \left(-\frac{j k x^2}{2d_1}\right) \cdot \frac{4\sqrt{2}}{\sqrt{\pi} \sqrt{W_{F1}}} \exp \left(-\frac{y^2}{W_{y1}^2}\right) \exp \left(-\frac{j k y^2}{2d_1}\right)$$  \hspace{1cm} (40)

with:

$$W_{F1} = \frac{2d_1}{k W_F}$$

The electric field vector of the planar waveguide can immediately behind the lens (as seen from the left side of figure 21) be expressed as:

$$E_{F1} = \frac{4\sqrt{2}}{\sqrt{\pi} \sqrt{W_{x1}}} \exp \left(-\frac{x^2}{W_{x1}^2}\right) \exp \left(-\frac{j k x^2}{2d_2}\right) \cdot \frac{4\sqrt{2}}{\sqrt{\pi} \sqrt{W_{y1}}} \exp \left(-\frac{y^2}{W_{y1}^2}\right) \exp \left(-\frac{j k y^2}{2d_2}\right)$$  \hspace{1cm} (41)
with:
\[ W_{x1} = \frac{2d_2}{kW_x}, \quad W_{y1} = \frac{2d_2}{kW_y} \]

Now, misalignments are introduced. For reasons of simplicity, only misalignments in one orthogonal direction (the x-direction) are considered. Misalignments in the other orthogonal direction can be calculated by changing the x parameters into y parameters and vice versa. The following misalignments are considered [9]:
- The distances between the waveguides and the lens are not optimal (longitudinal misalignments). They are given by the following relations:
  \[ L_1 = d_1 + a = (1 + m)f + a \] (42)
  \[ L_2 = d_2 + b = \left(1 + \frac{1}{m}\right)f + b \] (43)
  
  a, b are the parameters that represent the misalignments.
- The influences of the transversal offsets \( x_{of} \) and \( x_{os} \) of the waveguides are considered.
- The influences of the tilt angles \( \theta_f \) and \( \theta_s \) of the waveguides are considered.

A sketch of the coupling configuration is given in figure 21.

fig. 21. Sketch of the coupling configuration with the various misalignments.

In the next paragraph, the influence of the described misalignments on the coupling efficiency is calculated. The principal plane of the lens is chosen as coupling plane. For the angular misalignments, also the axial (z) dependence of \( E_{r1} \) (equation (36)) is important. The electric field vector of the fiber field, immediately before the lens, (equation (40)) is now changed into [9,10]:
\[ E_{F1} = \frac{4\sqrt{2}}{\sqrt{\pi} \sqrt{W_{F1}}} \exp \left[ -\frac{y^2}{W_{F1}} \right] \exp \left[ -\frac{jky^2}{2L_1} \right] \frac{4\sqrt{2}}{\sqrt{\pi} \sqrt{W_{F1}}} \exp \left[ -\frac{(x-x_{of} - L_1 \theta_F)^2}{W_{F1}^2} \right] \cdot \] 

\[ \cdot \exp \left[ -\frac{jk(x-x_{of} - L_1 \theta_F)^2}{2L_1} \right] \exp \left[ -jk\theta_F [x-x_{of}] \right] \] (44)

with:

\[ W_{F1} = \frac{2L_1}{kW_F} \]

The last term of equation (44) is the term \( \exp(-jkz) \) of equation (36). In order to calculate the power coupling efficiency, the axial component of \( E_{F1} \) is needed (the axial component of \( E_{F1} \) is given in equation (44)). \( E_{F1} \) can now be written as:

\[ E_{F1} = \frac{4\sqrt{2}}{\sqrt{\pi} \sqrt{W_{F1}}} \exp \left[ -\frac{(x-x_{of} - L_1 \theta_F)^2}{W_{F1}^2} \right] \exp \left[ -\frac{jk}{2L_1} \left[ (x-x_{of})^2 + L_1 \theta_F x \right] \right] \cdot \] (45)

The lens changes the electric field vector \( E_{F1} \) into \( E_{F2} \). The influence of the lens on the electric field can easily be derived from the ray transfer matrix of the ball lens. \( E_{F2} \) can be written as:

\[ E_{F2} = E_{F1} \cdot \exp \left[ \frac{jkx^2}{2L} \right] \exp \left[ \frac{jky^2}{2L} \right] \] (46)

The electric field vector of the planar waveguide field, immediately behind the lens, (equation (41)) is now, because of the misalignments, changed into (analogous with equations (44) and (45)) \[9,10\]:

\[ E_{F1} = \frac{4\sqrt{2}}{\sqrt{\pi} \sqrt{W_{x_1}}} \exp \left[ -\frac{(x-x_{os} - L_2 \theta_S)^2}{W_{x_1}^2} \right] \exp \left[ +\frac{jk}{2L_2} \left[ (x-x_{os})^2 + L_2 \theta_S x \right] \right] \cdot \] (47)

\[ \cdot \frac{4\sqrt{2}}{\sqrt{\pi} \sqrt{W_{y_1}}} \exp \left[ -\frac{y^2}{W_{y_1}} \right] \exp \left[ +\frac{jky^2}{2L_2} \right] \]

with:

\[ W_{x_1} = \frac{2L_2}{kW_x} \quad , \quad W_{y_1} = \frac{2L_2}{kW_y} \]
Since both the fiber field and the waveguide field are explicitly given as a product of two functions, the power coupling coefficient can be written as:

\[ \eta = |C_x C_y|^2 = |C_x|^2 |C_y|^2 \]  (48)

with:

\[ C_x = \int_{-\infty}^{\infty} E_{p2}(x) E_{p1}^*(x) \, dx \]  (49)

\[ C_y = \int_{-\infty}^{\infty} E_{p2}(y) E_{p1}^*(y) \, dy \]  (50)

Now, the influence of the various misalignments on the coupling efficiency can be evaluated using equations (48), (49) and (50). The computer program MATLAB is used to perform the simulations. The influence of the longitudinal misalignments of the fiber (parameter a) and the planar waveguide (parameter b) is depicted in figures 22 and 23.

![fig. 22. η as function of a.](image)

![fig. 23. η as function of b.](image)

It can be seen that the longitudinal misalignment between the fiber and the lens has very little influence on the coupling efficiency (figure 22). However, the longitudinal misalignment between the lens and the planar waveguide has much influence on the coupling efficiency (figure 23). The influence of the transversal fiber offsets in the x- and y-direction is depicted in figures 24 and 25.
fig. 24. $\eta$ as function of $x_{OF}$, the fiber offset in the $x$-direction.

fig. 25. $\eta$ as function of $y_{OF}$, the fiber offset in the $y$-direction.

The influence of the tilt angles $\theta_F$ of the fiber in the $x$ and $y$-direction on the coupling efficiency is depicted in figures 26 and 27.

fig. 26. $\eta$ as function of $\theta_F$ in the $x$-direction.

fig. 27. $\eta$ as function of $\theta_F$ in the $y$-direction.

The influence of the transverse offsets of the planar waveguide in the $x$ and $y$-direction on the coupling efficiency is depicted in figures 28 and 29.
It can be seen that the transverse offsets of the planar waveguide have much influence on the coupling efficiency. The influence of the tilt angles $\theta_s$ of the planar waveguide in the x and y-direction is depicted in figures 30 and 31.

It can be seen that the longitudinal misalignment of the fiber has little influence on the coupling efficiency. Also the influence of the tilt angles $\theta_F$ and $\theta_s$ of the fiber and the planar waveguide on the coupling efficiency is little. The other misalignments have much influence on the coupling efficiency.
4.4. The influence of the spherical aberration on the coupling efficiency.

In this section, the influence of spherical aberration on the coupling efficiency is considered. The coupler configuration is depicted in figure 32.

The distance parameters $L_1$ and $L_2$ are now changed into:

$$L_1 = d_1 - \alpha = (1 + m)f - \alpha$$  \hspace{1cm} (51)

$$L_2 = d_2 - \alpha = \left(1 + \frac{1}{m}\right)f - \alpha$$  \hspace{1cm} (52)

Because of spherical aberration, the waist of the lightbeam behind the lens is not located at the focal point, but just before this point. This is already explained in section 4.1. Parameter $\alpha$ expresses the shortening of the distances between the waveguides and the lens. It will be demonstrated that the optimum coupling efficiency is a function of $\alpha$. The coupling efficiency is at its maximum if $\alpha > 0$. Here a problem arises.

The power coupling efficiency depends also on the distances between the waveguides and the lens. If the distances $L_1$ and $L_2$ change, the magnification factor $m$ also changes. Thus a trade-off has to be made between the influence of the spherical aberration and the influence of the magnification factor $m$ on the coupling efficiency. The influence of the lens on the electromagnetic field can be described as (see also appendix B) [9,11]:

$$\exp \left\{ \frac{jkr^2}{2f} + \frac{jkr^4}{32f(d \_1 - \alpha)^2} \left( \frac{n}{(n-1)^2} - 1 \right) \left[ \left( \frac{d_1 - \alpha}{f} \right)^2 + 4 \left( \frac{d_1 - \alpha}{f} \right)^{-4} \right] \right\}$$  \hspace{1cm} (53)
Under paraxial approximation, equation (53) is reduced to:

\[
\exp \left( \frac{j \kappa r^2}{2f} \right) \tag{54}
\]

The principal plane of the ball lens is chosen to be the coupling plane. The E-vector of the electromagnetic field, emitted by the fiber, can just before the lens be written as:

\[
E_{F1} = \frac{\sqrt{2}}{\sqrt{\pi} W_{F1}^2} \exp \left( - \frac{r^2}{W_{F1}^2} \right) \exp \left( - \frac{j \kappa r^2}{2(d_1 - \alpha)} \right) \tag{55}
\]

with:

\[
W_{F1} = \frac{2(d_1 - \alpha)}{k W_F}
\]

The field immediately after the lens can be described as:

\[
E_{F2} = E_{F1} \cdot \exp \left( \frac{j \kappa r^2}{2f} + \frac{j \kappa r^4}{32 f (d_1 - \alpha)^2} \left( \frac{n}{(n-1)^2} - 1 \right) \left( \frac{d_1 - \alpha}{f} \right)^2 + 4 \left( \frac{d_1 - \alpha}{f} \right)^4 \right) \tag{56}
\]

The E-vector of the electromagnetic field of the planar waveguide, just after the lens, can be written as:

\[
E_{P1} = \frac{\sqrt{2}}{\sqrt{\pi} W_{P1}^2} \exp \left( - \frac{r^2}{W_{P1}^2} \right) \exp \left( \frac{j \kappa r^2}{2(d_2 - \alpha)} \right) \tag{57}
\]

with:

\[
W_{P1} = \frac{2(d_2 - \alpha)}{k W_P} \quad \text{with} \quad W_p = \sqrt{W_x W_y} \quad \text{(see also equation (3))}
\]

The coupling efficiency can be expressed as:

\[
\eta = \left| \int_{-\infty}^{\infty} E_{F2}^* E_{P1} \, dr \right|^2 \tag{58}
\]

The optimum value of \( \alpha \) can be determined by evaluating the coupling efficiency. This is done with use of the computer program MATLAB. The result of the simulation is shown in figure 33.
It can be seen from figure 33 that the optimum value of $\alpha$ is: $\alpha = 18 \, \mu m$. The maximum coupling efficiency is 0.8. These calculations are made with the assumption that the planar waveguide light-beam is circular. However the planar waveguide lightbeam is elliptical. This introduces another loss of 17%. The maximum power coupling efficiency is:

$$\eta = 0.8 \times 0.83 = 0.66.$$  

This means that the single ball lens coupler has a coupling loss of 1.8 dB. This loss is caused by spherical aberration of the ball lens and by different geometrical cross-sections of the fiber light-beam and the planar waveguide light-beam.
5. THE TWO LENS COUPLER.

5.1. Introduction.

In this section, a coupling system consisting of two ball lenses is considered. A diagram of the coupler configuration is given in figure 34.

fig. 34. Diagram of the coupler configuration.

In this chapter, the same calculations are made as in chapter 4. In section 5.2., the ray transfer matrix is calculated. In section 5.3., the influence of misalignments on the coupling efficiency is calculated and in section 5.4., the influence of the spherical aberration of the lens system on the coupling efficiency is calculated.

5.2. Calculation of the ray transfer matrix.

With the ray transfer matrix, the influence of the distances between the waveguides and the lenses on the magnification factor \( m \) can be calculated. The coupler configuration is shown in figure 35.

fig. 35. Sketch of the coupler.
The ray transfer matrix is called $M$. Light transmission is from left to right in figure 35. $M$ can be written as:

$$M = T_3 T_2 L_2 L_1 T_1$$

(59)

with $[1]$:

$$T_1 = \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix}, \quad T_2 = \begin{bmatrix} 1 & d_2 \\ 0 & 1 \end{bmatrix}, \quad T_3 = \begin{bmatrix} 1 & d_3 \\ 0 & 1 \end{bmatrix}$$

$$L_1 = \begin{bmatrix} 1 & 0 \\ \frac{-1}{f_1} & 1 \end{bmatrix}, \quad L_2 = \begin{bmatrix} 1 & 0 \\ \frac{-1}{f_2} & 1 \end{bmatrix}$$

If the following relations are chosen for the distances $d_1$, $d_2$ and $d_3$, the ray transfer matrix reduces to a simple matrix:

$$d_1 = f_1, \quad d_2 = f_1 + f_2, \quad d_3 = f_2$$

(60)

This means for $M$:

$$M = \begin{bmatrix} \frac{-f_2}{f_1} & 0 \\ 0 & \frac{-f_1}{f_2} \end{bmatrix}$$

(61)

If $m$ is chosen to be: $m = \frac{f_1}{f_2}$, then the fiber waist $W_F$ is reduced to $W_F/m$, which is the desired waist and matches the planar waveguide waist as good as possible. Here a problem arises. The measured values of $W_F$, $W_X$ and $W_Y$ are (Philips fiber SE8161A):

$W_F = 5.05 \mu m.$

$W_X = 1.2 \mu m.$

$W_Y = 0.5 \mu m.$

This means that $m = 6.52$ (see also equation (28)).

There are no ball lenses available with the desired ratio of focal distances. This means that the two lens system can not be used in the coupler. May be, in future, ball lenses will be available with the desired ratio of focal distances. Therefore, the influence of misalignments on the coupling efficiency will be calculated in section 5.3. The influence of the spherical aberration on the coupling efficiency will be calculated in section 5.4. Simulations are not made of the various calculations.
5.3. The influence of misalignments on the coupling efficiency.

In this section, the influence of misalignments is considered. The rays are assumed to be paraxial. Like chapter 4, only misalignments in one orthogonal direction (the x-direction) are considered. A sketch of the coupler configuration is given in figure 36.

![Sketch of the coupling configuration with various misalignments.](image)

The following misalignments are considered [9]:
- The distances between the waveguides and the lenses are not optimal (longitudinal misalignments). They are given by the following relations:

\[ L_1 = f_1 + a \]  \hspace{1cm} (62)
\[ L_2 = f_1 + f_2 + b \]  \hspace{1cm} (63)
\[ L_3 = f_2 + c \]  \hspace{1cm} (64)

\( a, b \) and \( c \) are the parameters that represent the misalignments.
- The influence of the transversal offsets \( x_{of} \) and \( x_{os} \) are considered.
  The offset between the lenses is not considered, because the lenses are very large compared to both waveguides. This means that this offset has very little influence on the coupling efficiency.
- The influence of the tilt angles \( \theta_F \) and \( \theta_S \) are considered.

In the next paragraph, the influence of the described misalignments on the coupling efficiency is calculated. The principal plane of ball lens 1 is chosen as coupling plane. The ray transfer matrix of lens 1 is considered to coincide with this principal plane. In fact, the coupling plane is situated at a infinite semal distance at the right side of the principal plane (see also figure 36). The power coupling efficiency will be calculated in this plane. The ball
lenses are assumed to be ideal. Both electromagnetic fields, emitted by both waveguides, are power normalised to unity. The field emitted by the fiber, can just before lens 1 be expressed as (analogous with equations (44) and (45)) [9,10]:

\[
E_{F1} = \frac{\sqrt{2}}{\sqrt{\pi W_{F1}}} \exp \left\{ -\frac{(x-x_{OF} - L_1 \theta_F)^2}{W_{F1}^2} \right\} \exp \left\{ -\frac{jk}{2L_1} \frac{(x-x_{OF})^2 + L_1 \theta_F x}{W_{F1}^2} \right\}.
\]

with:

\[ W_{F1} = \frac{2L_1}{kW_F} \]

The field, emitted by the fiber, can just behind lens 1 be expressed as:

\[ E_{F2} = E_{F1} \cdot \exp \left\{ \frac{jkx}{2f_1} \right\} \exp \left\{ \frac{jky}{2f_1} \right\} \]  (66)

The electric field vector of the planar waveguide field (immediately behind lens 2) can be expressed as (analogous with equations (44) and (45)):

\[
E_{p1} = \frac{\sqrt{2}}{\sqrt{\pi W_{X1}}} \exp \left\{ -\frac{(x-x_{os} - L_3 \theta_S)^2}{W_{X1}^2} \right\} \exp \left\{ +\frac{jk}{2L_3} \frac{(x-x_{os})^2 + L_3 \theta_S x}{W_{X1}^2} \right\}.
\]

with:

\[ W_{X1} = \frac{2L_3}{kW_X}, \quad W_{Y1} = \frac{2L_3}{kW_Y} \]

The electromagnetic field, emitted by the planar waveguide, can just behind lens 1, be expressed as [10]:

\[
E_{p3} = \frac{\sqrt{2}}{\sqrt{\pi W_{X3}}} \exp \left\{ -\frac{(x-x_{os} - L_3 \theta_S)^2}{W_{X3}^2} \right\} \exp \left\{ +\frac{jk}{2L_2} \frac{(x-x_{os})^2 + L_2 \theta_S x}{W_{X3}^2} \right\} \exp \left\{ -\frac{jk}{2L_2} \frac{1 - \frac{L_{LE}}{L_2} \frac{W_{Y1}^2}{W_{EX}^2 + W_{X1}^2}}{W_{Y3}^2} \right\}.
\]

with:
\[ W_{EX} = \frac{2L_{LE}}{kW_{X1}}, \quad W_{EY} = \frac{2L_{LE}}{kW_{Y1}} \quad \text{with:} \quad L_{LE} = \left[ \frac{1}{L_1} + \frac{1}{L_2} - \frac{1}{\ell_2} \right]^{-1} \]

\[ W_{X3} = \left[ \left( \frac{2L_3}{kW_{X1}} \right)^2 + \left( \frac{L_2W_{X1}}{L_{LE}} \right)^2 \right]^{\frac{1}{2}} \]

\[ W_{Y3} = \left[ \left( \frac{2L_3}{kW_{Y1}} \right)^2 + \left( \frac{L_2W_{Y1}}{L_{LE}} \right)^2 \right]^{\frac{1}{2}} \]

The coupling efficiency \( \eta \) can now be calculated with the following relation:
\[
\eta = |C_X|^2 \cdot |C_Y|^2 \tag{69}
\]

with:
\[
C_X = \int_{-\infty}^{\infty} E_{F2}(x)E_{F3}^*(x)dx \tag{70}
\]

\[
C_Y = \int_{-\infty}^{\infty} E_{F2}(y)E_{F3}^*(y)dy \tag{71}
\]

There are no ball lenses available with the desired ratio of focal distances. Thus no simulations can be made of the various misalignments.

5.4. The influence of the spherical aberration on the coupling efficiency.

In this section, the influence of the spherical aberration on the coupling efficiency is considered. The coupler configuration is given in figure 37.

fig. 37. Diagram of the coupler configuration.
The distances $L_1$, $L_2$ and $L_3$ are now changed into:

\[ L_1 = f_1 - \alpha \]  
\[ L_2 = f_1 + f_2 - 2\alpha \]  
\[ L_3 = f_2 - \alpha \]  

Parameter $\alpha$ expresses the shortening of the distances between the waveguides and the lens. In this lens system (consisting of two ball lenses), $\alpha$ has very little influence on the magnification factor. $m$ is determined by the ratio of $f_1$ and $f_2$. In this section, the third order spherical aberration theory is applied again. The E-vector of the field emitted by the fiber, can just before lens 1 be written as:

\[ E_{F1} = \frac{\sqrt{2}}{4\pi \sqrt{W_{F1}}} \exp \left( -\frac{r^2}{W_{F1}^2} \right) \exp \left( -\frac{jkr^2}{2(f_1 - \alpha)} \right) \]  

with:

\[ W_{F1} = \frac{2(f_1 - \alpha)}{KW_F} \]

The field immediately after lens 1 can be described as (see also appendix B) [9,11]:

\[ E_{F2} = E_{F1} \cdot \exp \left( \frac{jkr^2}{2f_1} + \frac{jkr^4}{32f_1^3(f_1 - \alpha)^2} \left( \frac{n_1}{(n_1 - 1)^2} - 1 \right) \left( \frac{f_1 - \alpha}{f_1} \right)^2 + 4 \left( \frac{f_1 - \alpha}{f_1} \right) - 4 \right) \]  

The E-vector of the electric field, emitted by the planar waveguide, can just behind lens 2 be written as:

\[ E_{P2} = \frac{\sqrt{2}}{4\pi \sqrt{W_{P2}}} \exp \left( -\frac{r^2}{W_{P2}^2} \right) \exp \left( -\frac{jkr^2}{2(f_2 - \alpha)} \right) \]  

with:

\[ W_{P2} = \frac{2(f_2 - \alpha)}{KW_P} \]

The E-vector of the electric field, emitted by the planar waveguide, can just behind lens 1 be written as [9]:
The coupling efficiency $\eta$ can now be calculated with:

$$\eta = \left| \int_{-\infty}^{\infty} E_{F2} E_{P2}^* \, dr \right|^2$$

(79)

Now, it is possible to determine the optimum value of $\alpha$ by evaluating the coupling efficiency. There are no ball lenses available with the desired ratio of focal distances. Thus the optimum value of $\alpha$ can not be determined.
6. MEASUREMENT OF THE COUPLING EFFICIENCY.

6.1. Description of the measurement setup.

In this chapter, the measurement of the power coupling efficiency of a single ball lens coupler will be discussed. The measurement setup is shown in figure 38.

A 632 nm laser is used for visual inspection of the coupling, whereas, a 1550 nm laser diode is used to perform the actual coupling with. The distance between the fiber and the center of the ball lens is approximately 8.31 mm, the distance between the center of the ball lens and the planar waveguide is however only approximately 1.24 mm. The Philips fiber SE8161A is fused into a ferrule, which is fixed into a holder. This holder is schematically depicted in figure 39. It consists of three micro-positioners (movable in x, y and z direction) and two positioners which can be used to adjust the angles \( \varphi \) and \( \theta \), \( \varphi \) is the angle in the x-y plane, whereas, \( \theta \) is the angle in the y-z plane.

fig. 38. Diagram of the measurement setup.

fig. 39. Diagram of the fiber holder.
The ball lens is fixed in a holder. The ball lens holder is schematically depicted in figure 40.

fig. 40. Diagram of the ball lens holder.

The planar waveguide is fixed into a holder, which can be moved in the x and y direction. The holder is schematically depicted in figure 41.

fig. 41. Diagram of the planar waveguide holder.


In section 6.1. the measurement setup has been given, whereas in this section, the measurement results are discussed. The ball lens is anti-reflection coated, but the single mode fiber and the planar waveguide are not. Firstly the optical power is measured without the ball lens and the planar waveguide. In this way, the optical power, leaving the fiber, can be determined. This power appears to be 54.8 $\mu$W.
Now, the optical power leaving the planar waveguide is measured. (The used measurement setup is depicted in figure 38). This power appears to be 9.8 μW. The power coupling efficiency is thus 0.18. There are however Fresnel reflections on both sides of the planar waveguide (two air-InGaAsP interfaces), also the light is slightly attenuated by the planar waveguide (approximately 0.5 dB). The refractive index of the InGaAsP waveguide is 3.2836 (wavelength of 1550 nm). It can be expected that the waveguide acts as a resonant optical cavity. The power transmission coefficient of the optical cavity is given by [12]:

\[ T = \frac{L(1-R)^2}{(1-LR)^2 + 4LR\sin^2(\theta)} \]  

\( L \) = the transmittance of the planar waveguide, \( L = 0.89 \).
\( R \) = the power reflectivity of the air-InGaAsP junction, \( R = 0.28 \).
\( \theta \) = the optical length of the planar waveguide. \( \theta \) is given by:

\[ \theta = \frac{2\pi nd}{\lambda} \]  

\( d \) = the length of the planar waveguide, \( d = 2 \text{ mm} \).
\( n \) = the refractive index of InGaAsP, \( n = 3.2836 \).

\( d \) is not exactly known. This means that the transmission coefficient \( T \) can’t be exactly calculated. It can be calculated that \( 0.29 \leq T \leq 0.79 \). The measured power coupling efficiency of the coupler is thus not exactly known. The power transmission coefficient \( T \) of the planar waveguide can be measured using a tunable laserdiode with a wavelength of approximately 1550 nm. If the wavelength of the laserdiode is slightly varied, the minimum and maximum value of \( T \) can be determined. It was measured that the difference between the minimum and maximum value of \( T \) was only 0.21 dB.

It can thus be concluded that the planar waveguide acts practically not as a resonant optical cavity, because the endfaces of the waveguide are rough, irregular and angled, which causes scattering of the light. One of the endfaces of the planar waveguide is depicted in figure 42.

fig. 42. Photograph of one of the endfaces of the planar waveguide (magnification: 500x).
The power transmission coefficient $T$ of the planar waveguide can now be calculated to be 0.46 (2 air-InGaAsP interfaces and a loss in the waveguide of approximately 0.5 dB). The measured power coupling efficiency of the single ball lens coupler is thus 0.39. In table 2 the various coupling losses are summarised.

Table 2: Summary of the various coupling losses.

<table>
<thead>
<tr>
<th>loss (in dB)</th>
<th>measured coupling loss of the coupler and the planar waveguide</th>
<th>calculated loss of the planar waveguide</th>
<th>measured coupling loss of the single ball lens coupler</th>
<th>theoretical coupling loss of the single ball lens coupler</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td></td>
<td>3.4</td>
<td>4.1</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The measured coupling loss is larger than the theoretical coupling loss because of several reasons:
- Misalignments of the waveguides.
- The endfaces of the planar waveguide are probably rough, irregular and angled. This causes some extra loss, which has not been taken into account.
- Not all the power, emitted by the fiber, reaches the lens surface.
- Losses due to polarisation effects. The influence of the state of polarisation of the electromagnetic light-wave on the coupling efficiency is however small. It was measured that the coupling efficiency varied only 0.23 dB, if the state of polarisation of the wave was varied.
- The far field intensity distribution of the fiber output differs from the perfect Gaussian shape.
- Reflection loss at the single mode fiber endface.
6.3. A packaging method of a single ball lens coupler.

In this section, a packaging method for a single ball lens coupler is discussed. The packaging of the ball lens and the waveguides is the major problem with respect to reliability and stability. It can be seen from section 4.3. that the alignment tolerances of the planar waveguide are very small. This means that the most practical solution of the packaging problem is to start with the fastening of the ball lens to the planar waveguide. The misalignments caused by this fastening can be cancelled by flexible fiber attachment. With the fastening of the ball lens to the planar waveguide a problem arises. When a ball lens is fastened to the planar waveguide, half of the ball lens holder touches the planar waveguide device, the other half doesn't. This means that the package is not very stable and reliable. This problem is depicted in figure 43.

![fig. 43. The problem of packaging a ball lens to a planar waveguide.](image)

A solution of this problem is the use of a small block fixed on top of the planar waveguide [12]. The waveguide endface is a problem: Usually, the endface of the waveguide is polished mechanically or mechano-chemically. Another solution is the use of a cutting machine. This is depicted in figure 44 [13]:

![fig. 44. Waveguide end fabrication using a cutting machine.](image)

Now, the ball lens must be attached to the planar waveguide. A possible solution is schematically depicted in figure 45:
The ball lens must now be aligned with the waveguide. In front of the ball lens at a distance of approximately 7.3 mm (this is the distance between the lens and the fiber) a camera is placed in order to control the alignment. If there is a good alignment between the ball lens and the planar waveguide, the adhesive can be cured by irradiating it with ultra-violet light. The quantity of adhesive required is very small because the gap between the ball lens holder and the planar waveguide is very small. This results in a good thermal stability. Now the fiber has to be attached to the ball lens holder. A solution of this problem is depicted in figure 46.

With use of three plastic screws, the fiber holder can slightly be aligned with respect to the ball lens. The distance between the fiber holder and the package has to be a few micrometers (e.g. 5 μm) in order to allow flexible fiber alignment. Instead of plastic screws, thermosetting epoxy between the fiber holder and the package can be used.
7. THE USE OF OTHER LENSES IN THE COUPLER.

7.1. Introduction.

In this chapter some couplers are discussed, which consists of other types of lenses such as micro-lenses and GRIN-rod lenses. The use of a micro-lens tipped on the end of a tapered single mode fiber is discussed in section 7.2. The two ball lens coupler, discussed in chapter 5, has relatively large alignment tolerances. There are however no ball lenses available with the desired ratio of focal distances \(f_2/f_1 = 6.52\). Instead of a ball lens, a GRIN-rod lens can also be used. In section 7.3. a coupler is discussed which consists of a ball lens and a graded index multi-mode fiber lens fused to the single mode fiber. A coupler consisting of a ball lens and two graded index multi-mode fiber lenses is discussed in section 7.4. In section 7.5. a coupler is discussed which consists of a ball lens and a graded index fiber lens fused to the planar waveguide.

7.2. The use of micro-lenses.

A micro-lens tipped on the end of a tapered single mode fiber can be used to perform the coupling with (see e.g. [14]). This solution is depicted in figure 47.

![fig. 47. The use of a microlens in a coupler.](image)

The lens effectively demagnifies the fiber waist down to the dimensions of the planar waveguide waist (approximately 0.8 \(\mu\)m). This method has a major disadvantage: There are stringent sub-micron alignment tolerances between the tapered fiber and the planar waveguide. This results in difficulties maintaining the alignment during the fiber attachment process, and requires careful package design to achieve fiber stability and package reliability after the fiber attachment process. This means that the use of micro-lenses in the coupler is not a practical solution of the coupler problem.
7.3. The use of a graded index lens and a ball lens in a coupler.

Although high coupling efficiency can be obtained with the single ball lens coupler, tight misalignment tolerances limit the fabrication ease, stability and reproducibility. The use of a ball lens in combination with a graded index lens (fiber lens or selfoc lens) could be a solution of this problem. There are a few options for the coupler configuration. These options will be discussed in this section and the sections 7.4. and 7.5. In this section a coupler will be discussed in which a piece of a multi-mode graded index fiber is used as a lens and is fused to the single mode fiber [15]. The coupler configuration is depicted in figure 48.

After the multi-mode fiber is fused to the single mode fiber, it is cleaved to the appropriate length. The multi-mode fiber acts as a graded index lens with a refractive index given by:

\[ n(r) = n_0 \sqrt{1 - g^2 r^2} \]  

(82)

where:

- \( n_0 \) = the refractive index on the optical axis.
- \( r \) = the radial position from the axis.
- \( g \) represents the strength of the refractive index gradient. \( g \) can be expressed as:

\[ g = \frac{\sqrt{2\Delta}}{a} \]  

(83)

with:

- \( \Delta \) = the relative refractive index difference between the center of the core and the cladding.
- \( a \) = the radius of the core.

\( g \) is approximately 5.6 mm\(^{-1}\), if a standard graded index multi-mode 50/125 \( \mu m \) fiber is used. The ray transfer matrix of a piece with length \( L \) of a graded index multi-mode fiber is given by [16]:

![Fig. 48. Diagram of the coupler configuration.](image-url)
The pitch of the graded index lens is given by:

\[ p = \frac{Lg}{2\pi} \]  

(85)

If a 0.25 pitch lens is used, the output light-beam of the graded index lens is parallel. The imaging characteristics of a 0.25 pitch lens are shown in figure 49.

The ray transfer matrix of the coupler is given by \( M \). It can be written as (light transmission is chosen from left to right in figure 48):

\[ M = M_{45} M_{34} M_{23} M_{12} \]  

(86)

The following relations can be used for \( M_{12} \), \( M_{23} \), \( M_{34} \) and \( M_{45} \) (0.25 pitch graded index lens):

\[
M_{12} = \begin{pmatrix} 0 & \frac{1}{g} \\ -g & 0 \end{pmatrix}, \quad M_{23} = \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix}
\]

\[
M_{34} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}, \quad M_{45} = \begin{pmatrix} 1 & d_2 \\ 0 & 1 \end{pmatrix}
\]

If the following relations are chosen for the distances \( d_1 \) and \( d_2 \), the ray transfer matrix \( M \) reduces to a simple matrix (\( m \) is the magnification factor, see also section 4.2.):

\[
d_1 = \left[ 1 + m + \frac{1}{fg} \right] f
\]

(87)

\[
d_2 = \left[ 1 + \frac{1}{m} \right] f
\]

(88)

This means for \( M \):
\[
M = \begin{pmatrix}
\frac{1}{m} & -\frac{1}{mg} \\
g \left( m + \frac{1}{fg} \right) & -\frac{1}{fg}
\end{pmatrix}
\]

(89)

\[m = 6.52 \text{ (see also section 4.2.)}\]

If a ball lens is chosen with a focal distance of \( f = 1.11 \text{ mm} \) (diameter 2 mm), the following distances can be calculated:

\[d_1 \approx 15.25 \text{ mm}.\]
\[d_2 \approx 1.28 \text{ mm}.\]
\[L \approx 280 \mu \text{m}. \text{ (0.25 pitch lens, } g = 5.6 \text{ mm}^{-1})\]

This configuration is not a practical solution of the coupling problem. The distance between the lensed fiber and the ball lens is very large and the position of the ray at the planar waveguide \((x_z)\) is dependent on the angle (with respect to the optical axis) of the ray at the single mode fiber endface \((x'_1)\) (see also equation (18)).

7.4. The use of two graded index lenses and a ball lens in a coupler.

In this configuration, the coupler consists of three lenses: a ball lens and a graded-index lens, which consists of two lenses (lens 11 and lens 12) \([17]\). The coupler configuration is depicted in figure 50.

![Diagram of the coupler configuration.](image)

The graded index lens from section 7.3. is now divided into two lenses. Lens 11 is fused to the single mode fiber in order to create a virtual fiber. It can be seen from reference \([17]\) that the largest alignment tolerances for the virtual fiber are found by a lens dividing pitch
ratio of $P_1/P_{12} = 3$. The total pitch length ($P_{11} + P_{12}$) of the lenses 11 and 12 was maintained at 0.24 pitch. This means that lens 11 is a 0.18 pitch lens and lens 12 is a 0.06 pitch lens. The 0.18 pitch lens is thus fused to the single mode fiber in order to enhance the fiber spotsize. This increases the tolerable offsets for the single mode fiber (there exists naturally a trade-off between the lateral and angular alignment tolerances). Lenses 11 and 12 are made from a standard graded index multi-mode fiber. This means that $g \approx 5.6$ mm$^{-1}$. The ray transfer matrix of the coupler will now be calculated. Light transmission is chosen from left to right in figure 50. $M$ can be written as:

$$ M = M_{67}M_{56}M_{45}M_{34}M_{23}M_{12} $$

with:

$$ M_{12} = \begin{bmatrix} \cos(L_1g) & 1/g \sin(L_1g) \\ -g \sin(L_1g) & \cos(L_1g) \end{bmatrix} \approx \begin{bmatrix} 0.43 & 1.62E-6 \\ 5067 & 0.43 \end{bmatrix} $$

$$ M_{34} = \begin{bmatrix} \cos(L_2g) & 1/g \sin(L_2g) \\ -g \sin(L_2g) & \cos(L_2g) \end{bmatrix} \approx \begin{bmatrix} 0.93 & 6.47E-5 \\ -2061.5 & 0.93 \end{bmatrix} $$

$$ M_{23} = \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix}, \quad M_{45} = \begin{bmatrix} 1 & d_2 \\ 0 & 1 \end{bmatrix} $$

$$ M_{56} = \begin{bmatrix} 1 & 0 \\ -1/f_{12} & 1 \end{bmatrix}, \quad M_{67} = \begin{bmatrix} 1 & d_3 \\ 0 & 1 \end{bmatrix} $$

Lens 12 and lens 2 (the ball lens) are positioned under nearly confocal conditions. This means for the distances $d_1$, $d_2$ and $d_3$:

$$ d_1 = f_{12} + \alpha $$

$$ d_2 = f_{12} + f_2 + \beta $$

$$ d_3 = f_2 + \gamma $$

The parameters $\alpha$, $\beta$ and $\gamma$ represent the deviations from the confocal positions of the lenses. $f_{12}$ is the focal length of lens 12. $f_{12}$ can be calculated using the following equation:

$$ f_{12} = \frac{1}{n_g \sin(L_2 g)} $$

This means that $f_{12} \approx 0.33$ mm. The graded index lens lengths are very small:

$L_1 \approx 200$ $\mu$m.

$L_2 \approx 67$ $\mu$m.
A ball lens with a diameter of 2 mm can be used in the coupler. This ball lens has a focal length of: \( f \approx 1.11 \text{ mm} \). The matrix \( M \) reduces to the desired matrix, if the following values are chosen for \( \alpha \), \( \beta \) and \( \gamma \):

\[
\alpha = 85.4 \mu \text{m}.
\beta = 1.2 \mu \text{m}.
\gamma = 182 \mu \text{m}.
\]

This means for \( M \):

\[
M \approx \begin{bmatrix}
0.152 & 0 \\
2900 & 0.75
\end{bmatrix}
\]  \( \text{(92)} \)

Now, the fiber waist \( W_f \) is reduced to \( W_f/m \) \( (m = 6.52, \text{ see also section 4.2.}) \). This values agrees with the planar waveguide waist \( W_p \). \( (W_p = \sqrt{(W_x W_y)}) \). The distances \( d_1 \), \( d_2 \) and \( d_3 \) can now be calculated:

\[
d_1 \approx 0.415 \text{ mm}.
\]

\[
d_2 \approx 1.441 \text{ mm}.
\]

\[
d_3 \approx 1.292 \text{ mm}.
\]

It can be calculated that the lateral and axial misalignments of the virtual fiber are large [17]. A disadvantage of this method is the use of three lenses. One lens has to be attached to the single mode fiber. The other two lenses must be aligned with respect to the planar waveguide and the virtual fiber.

7.5. A coupler consisting of a ball lens and a graded index lens attached to the planar waveguide.

In this section a coupler is discussed which consists of a ball lens and a 0.25 pitch graded index multi-mode fiber lens attached to the planar waveguide. In this configuration, the alignment tolerances for the virtual waveguide are large. The coupler configuration is depicted in figure 51.
Firstly the ray transfer matrix $M$ of the coupler is calculated. Light transmission is chosen from left to right in figure 51. $M$ can be written as:

$$M = M_{56}M_{45}M_{34}M_{23}M_{12}$$

(93)

with:

$$M_{12} = \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix}, \quad M_{23} = \begin{bmatrix} 1 & 0 \\ -1/f_i & 1 \end{bmatrix}$$

$$M_{45} = \begin{bmatrix} \cos(L_i g) & 1/g \sin(L_i g) \\ -g \sin(L_i g) & \cos(L_i g) \end{bmatrix} = \begin{bmatrix} 0 & 1/g \\ -g & 0 \end{bmatrix}$$

$$M_{34} = \begin{bmatrix} 1 & d_2 \\ 0 & 1 \end{bmatrix}, \quad M_{56} = \begin{bmatrix} 1 & 0 \\ 0 & \frac{n_p}{n_{MMF}} \end{bmatrix}$$

$n_p$ = the refractive index of the planar waveguide.
$n_{MMF}$ = the on axis refractive index of the multi-mode fiber lens.

$M$ reduces to a simple matrix if the following relations are chosen for $d_1$ and $d_2$:

$$d_1 = f_i$$

(94)

$$d_2 = \frac{f_i}{1 - f_i}$$

(95)

This means for $M$:

$$M = \begin{bmatrix} -\frac{1}{f_i g} & 0 \\ \frac{n_p f_i g}{n_{MMF} (1 - f_i)} & -\frac{n_p f_i g}{n_{MMF}} \end{bmatrix}$$

(96)

The fiber waist has to be demagnified with a factor $m$ ($m = 6.52$, see also section 4.2.). This means that $f_i g = 6.52$. For a standard graded index multi mode fiber ($g = 5.6 \text{ mm}^{-1}$), $f_i$ must be: $f_i \approx 1.16 \text{ mm}$. This value agrees well with the focal distance of a 2 mm diameter ball lens ($f_i = 1.11 \text{ mm}$). The length $L_i$ of the multi mode fiber lens is calculated to be: $L_i = \pi/(2g) = 280 \mu\text{m}$ (0.25 pitch lens).

The distances $d_1$ and $d_2$ can now calculated to be:

$$d_1 = 1.11 \text{ mm}.$$  
$$d_2 \approx 1.11 \text{ mm}.$$
The ball lens and the multi-mode fiber lens must be antireflection coated. There is one problem with this coupling configuration: The reduction of back-reflection from the fiber lens - planar waveguide interface is important. A solution to this problem is the use of an angled waveguide endface and a tapered hemispherical end of the fiber lens [12]. This solution reduces the back-reflection, while maintaining low excess loss. This is depicted in figure 52.

fig. 52. A solution to reduce the back-reflections between the fiber lens and the planar waveguide.

With this coupler configuration, the alignment tolerances of the planar waveguide are enhanced, by attaching a graded index multi mode fiber lens to it.

7.6. Conclusions.

The use of a microlens tipped on the end of a tapered fiber is no solution of the coupling problem. There are stringent sub-micron alignment tolerances between the tapered fiber and the planar waveguide. A coupler consisting of a graded index lens fused to the single mode fiber and a ball lens is no solution of the coupling problem either. The distance between the lensed fiber and the ball lens is very large. A possible solution of the coupling problem is the use of two graded index lenses and a ball lens. The alignment and antireflection coating of three lenses is a disadvantage of this configuration. Another practical solution is a coupler which consists of a ball lens and a graded index lens attached to the planar waveguide. This solution is practical if the backreflection from the graded index fiber lens - planar waveguide interface can be reduced to a low level. Selfoc lenses can also be used in the coupler, instead of graded index fiber lenses. The alignment tolerances of all the coupling configurations, discussed in this chapter, are not calculated.
8. GENERAL CONCLUSIONS AND RECOMMENDATIONS.

General conclusions.

The spotsize parameters of the single mode fiber (W_F) and the planar waveguide (W_x and W_y) are determined. It was measured that the fiber had a half beam width of W_F = 5.05 μm (wavelength 1550 nm). W_x and W_y are both measured and calculated and their values agree well. The calculated values are used in the calculations, which are made in order to design the coupler. These values are: W_x = 1.2 μm and W_y = 0.5 μm.

A coupler consisting of a single ball lens is used to perform the coupling. The ball lens has a diameter of 2 mm and a focal distance of 1.11 mm. The distance between the single mode fiber and the center of the ball lens is approximately 8.31 mm. The distance between the planar waveguide and the center of the ball lens is approximately 1.24 mm. This coupler has small alignment tolerances which cause packaging problems with respect to reliability and stability. The theoretical coupling loss is 1.8 dB. This loss is caused by different geometrical cross-sections of the fiber spotsize and the planar waveguide spotsize and by the spherical aberration of the ball lens. The power coupling efficiency is measured using an experimental setup. The measured coupling loss is 4.1 dB, which is larger than the theoretical coupling loss. This extra loss is mainly caused by misalignments and scattering of the light, which is caused by rough and irregular endfaces of the planar waveguide.

A coupler consisting of two ball lenses has relatively large alignment tolerances. The influence of spherical aberrations of the ball lenses on the coupling efficiency is small. This coupler can not be realised because there are no ball lenses available with the desired ratio of focal distances (f_2/f_1 = 6.52).

Recommendations.

A possible solution of the coupling problem is a coupling configuration which consists of multi-mode graded index fiber lenses (or selfoc lenses) and a ball lens. There are two practical configurations: The first configuration consists of a ball lens and two graded index lenses (a 0.18 pitch lens and a 0.06 pitch lens). The 0.18 pitch lens is fused to the single mode fiber. A disadvantage of this configuration is the need of three lenses which have to be aligned and anti-reflection coated. The second configuration consists of a ball lens and a 0.25 pitch graded index lens attached to the planar waveguide. This configuration can only be used if the back-reflection between the lens – planar waveguide interface can be reduced to a low level. The alignment tolerances of both coupler configurations are not calculated. These calculations might give a definite answer to the question of which coupler configuration has the best performance.

Furthermore, research must be done in the field of coupler packaging. The packaging of the lens (lenses) and the waveguides is the major problem with respect to fabrication ease, reliability and stability. The planar waveguide must also be anti-reflection coated, because the air InGaAsP interfaces cause a large amount of reflection losses.
9. REFERENCES.

[1] Etten van W. and Plaats van der J.
Fundamentals of optical fiber communications.

Spot size measurements for single mode fibers - a comparison of four techniques.
J. of Lightwave Technology vol.1 1983 no.1 pp. 20-26

Glasvezelkoppelingen met een radiale fout.
Report of project-work Eindhoven University of Technology 1991

[4] Smit M.
Integrated optics in Silicon based Aluminum oxide.
Thesis Delft University of Technology 1991

[5] Nicia A.
Micro-optical devices for fiber communication.
Thesis Eindhoven University of Technology 1983

Optics.
Mill Valley (CA): University Science Books 1988

[7] Hecht E. and Zajac A.
Optics.
London: Addison-Wesley second edition 1987

Lens aberration effect on a laser diode to single mode fiber coupler.
Electronics Letters vol.18 1982 no.14 pp. 586-587

Lens coupling of laserdiodes to single-mode fibers.
J. of Lightwave Technology vol.7 1989 no.2 pp. 305-311
High efficiency two lens laserdiode to single mode fiber coupler with a silicon planconvex lens.
J. of Lightwave Technology vol.7 1989 no.2 pp. 244-249

Lens coupling in fiber-optic devices: efficiency limits.
Applied Optics vol.20 1981 no.18 pp. 3136-3145

[12] Verdeyen J.
Laser electronics.

Practical method of waveguide-to-fiber connection: direct preparation of waveguide endface by cutting machine and reinforcement using ruby beads.
Applied Optics vol.29 1990 no.34 pp. 5096-5102

Efficient coupling of laser diodes to tapered monomode fibers with high-index ends.
Electronics Letters vol.19 1983 no.6 pp. 205-207

Relaxed-tolerance optoelectronic device packaging.
J. of Lightwave Technology vol. 9 1991 no.4 pp. 477-483

[16] Emkey W. and Jack C.
Analysis and evaluation of graded-index fiber-lenses.
J. of Lightwave Technology vol.5 1987 no.9 pp. 1156-1164

A new confocal combination lens method for a laser-diode module using a single mode fiber.
J. of Lightwave Technology vol.3 1985 no.4 pp. 739-745
Appendix A:

CALCULATION OF THE POWER COUPLING EFFICIENCY OF A MISALIGNED FIBER PLANAR WAVEGUIDE SPlice.

In this appendix, the power coupling efficiency of a misaligned fiber planar waveguide splice is calculated. It is assumed that no angular misalignment and end-separation occurs. Only transverse offsets of the fiber in the two orthogonal directions (x-direction and y-direction) are considered. The transverse offset in the x-direction is called $x_0$. The transverse offset in the y-direction is called $y_0$. The fiber field $E_F$ is power normalised. This means that:

$$\int \int E_F E_F^* \, dx \, dy = 1$$  \hspace{1cm} (A1)

The fiber field can be written as (see also section 4.3.) [1]:

$$E_F = \frac{4^{\frac{1}{2}}}{\sqrt{\pi W_F}} \exp \left[ -\frac{(x-x_0)^2}{W_F^2} \right] \frac{4^{\frac{1}{2}}}{\sqrt{\pi W_F}} \exp \left[ -\frac{(y-y_0)^2}{W_F^2} \right]$$  \hspace{1cm} (A2)

The planar waveguide field $E_p$ is also power normalised. This means that:

$$\int \int E_p E_p^* \, dx \, dy = 1$$  \hspace{1cm} (A3)

The planar waveguide field can now be written as (see also section 4.3.) [1]:

$$E_p = \frac{4^{\frac{1}{2}}}{\sqrt{\pi W_x}} \exp \left[ -\frac{x^2}{W_x^2} \right] \frac{4^{\frac{1}{2}}}{\sqrt{\pi W_y}} \exp \left[ -\frac{y^2}{W_y^2} \right]$$  \hspace{1cm} (A4)

Since both the fiber field and the planar waveguide field are explicitly given as a product of two functions, the power coupling efficiency can be written as:

$$\eta = |C_x C_y|^2 = |C_x|^2 |C_y|^2$$  \hspace{1cm} (A5)

with:

$$C_x = \int_{-\infty}^{\infty} E_p(x) E_p^*(x) \, dx$$  \hspace{1cm} (A6)

$$C_y = \int_{-\infty}^{\infty} E_p(y) E_p^*(y) \, dy$$  \hspace{1cm} (A7)

This means for $C_x$ and $C_y$:
\[ C_x = \frac{\sqrt{2}}{\sqrt{\pi} \sqrt{W_F W_X}} \int_{-\infty}^{\infty} \exp \left[ -\frac{(x-x_0)^2}{W_F^2} \right] \exp \left[ -\frac{x^2}{W_X^2} \right] \, dx \]  
(A8)

\[ C_y = \frac{\sqrt{2}}{\sqrt{\pi} \sqrt{W_F W_Y}} \int_{-\infty}^{\infty} \exp \left[ -\frac{(y-y_0)^2}{W_F^2} \right] \exp \left[ -\frac{y^2}{W_Y^2} \right] \, dy \]  
(A9)

This means for \( \eta \):

\[ \eta = \frac{4 W_F^2 W_X W_Y}{(W_F^2 + W_X^2)(W_F^2 + W_Y^2)} \exp \left[ -\frac{2x_0^2}{W_F^2 + W_X^2} \right] \exp \left[ -\frac{2y_0^2}{W_F^2 + W_Y^2} \right] \]  
(A10)
Appendix B:

DETERMINATION OF THE SPHERICAL ABERRATION OF A BALL LENS.

In this appendix, the spherical aberration of a ball lens is investigated [9,11]. Firstly, the place B is calculated where a ray, emitted at point E with angle $\theta$, crosses the optical axis. Hereafter, the influence of a ball lens on an optical lightbeam is calculated. A sketch of the ray path is given in figure B1.

![Ray path in the lens system.](image)

The distance between point E and the reference plane in the ball lens is expressed with $\mu f$, with $\mu = 1 + m$ (compare to section 4.2.).

The sine rule applied in triangle $EAO$ gives:

$$\sin \theta_1 = \frac{\mu f}{r} \sin \theta \quad (B1)$$

Applying Snell's law gives the following relation between $\theta_1$ and $\theta_2$:

$$n \sin \theta_2 = \sin \theta_1 \quad (B2)$$

After some manipulation, the following relation can be derived for the deviation angle $\delta$ with the optical axis:

$$\delta = 2(\theta_1 - \theta_2) - \theta \quad (B3)$$

This means that:
\[ \delta = 2 \arcsin \left( \frac{\mu f}{r} \sin \theta \right) - 2 \arcsin \left( \frac{\mu f}{nr} \sin \theta \right) - \theta \] (B4)

Third order aberration means that only terms up to the third order in \( \theta \) are taken into account. \( \delta \) can be calculated using the following relation for a ball lens:

\[ \frac{f}{r} = \frac{n}{2(n-1)} \] (B5)

\[ \delta = \theta \left[ \frac{2n\mu f - 2\mu f - nr}{nr} \right] + \theta^3 \left[ \frac{-2n\mu f + 2\mu f}{6nr} + \frac{1}{3} \left( \frac{\mu f}{r} \right)^3 - \frac{1}{3} \left( \frac{\mu f}{nr} \right)^3 \right] \] (B6)

If \( \mu \) is taken 1 and the distance EO reduces to the focal distance \( f \), the following well known relation can be found for \( \delta \):

\[ \delta = \frac{1}{8} \left[ \frac{n}{(n-1)^2} - 1 \right] \theta^3 \] (B7)

Now, distance \( L_2 \) will be calculated. The sine rule applied in triangle \( \triangle A_2OB \) gives:

\[ \sin \theta_1 = \frac{L_2}{r} \sin \delta \quad \text{this means that} \quad L_2 = \frac{\mu f}{\sin \theta} \frac{\sin \delta}{\sin \theta_1} \] (B8)

After some manipulation, the following relation can be derived for \( L_2 \):

\[ \frac{1}{L_2} = \frac{\mu - 1}{\mu f} + \theta^2 \left[ \left( \frac{n}{(n-1)^2} - 1 \right) (\mu^2 + 4 \mu - 4) \right] \] (B9)

Now, there is assumed that a fiber is located at point E. And the assumption is made that the lens is located within the Fraunhofer diffraction region of the fiber. The fiber behaves now as a point source with respect to the lens. It can be assumed that the input field \( \psi_i \) is a spherical wave in front of the lens. Its phase term can be written as:

\[ \exp \left( \frac{jkr^2}{2\mu f} \right) \] (B10)

Denoting the output field immediately behind the lens \( \psi_o \), the action of the lens can be described by the equation:

\[ \psi_o = \exp(j\gamma(r)) \psi_i \] (B11)

where \( \gamma(r) \) is defined as the phase shift factor. Keeping in mind that the rays are orthogonal trajectories of the wavefronts and using formula B9, the phase distribution of the wave immediately behind the lens is given by:
From B10, B11 and B12, the action of the lens can be described as:

\[
\exp \left\{ jk \left[ \left( \frac{\mu - 1}{2\mu f} \right) r^2 + \frac{r^4}{32\mu^2 f^3} \left( \frac{n}{(n-1)^2} - 1 \right) (\mu^2 + 4\mu - 4) \right] \right\} \quad (B12)
\]

Under paraxial approximation, the phase shift factor \( \gamma(r) \) includes only the first term of B13. The second term expresses the degree of the aberration effect.