# \chapter{Optimize}

## %introduction

## This chapter aims to discuss the optimization methods to improve the Fiber-to-Chip coupling efficiency. Five proposals will be obtained in this chapter. One is to relocate the waveguide. Another is to replace the round condition of the simulation setup with oil. In the third proposal we will consider to change the composed material of the waveguide. The application of a taper interface at the beginning of the waveguide is involved in the next consideration. At last we are going to mount a lens at the waveguide end face.

## \section{Coupling by location shifting}

As a 3D model the waveguide can be shifted in transversal (Fig. \ref{fig:shift\_x\_axis} and Fig. \ref{fig:shift\_y\_axis}) or longitudinal (Fig. \ref{fig:shift\_z\_axis}) direction.

\begin{itemize}

\item Shift the waveguide along X-Axis: Relocate the waveguide from $-0.5\mu$m to $0.5\mu$m:

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7\textwidth]{bilder/shift\_x\_axis}

\caption{Displacing the waveguide along x-axis}

\label{fig:shift\_x\_axis}

\end{figure}

\item Shift the waveguide along Y-Axis: Relocate the waveguide from $-0.5\mu$m to $0.5\mu$m:

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7\textwidth]{bilder/shift\_y\_axis}

\caption{Displacing the waveguide along y-axis}

\label{fig:shift\_y\_axis}

\end{figure}

\item Shift the waveguide along Z-Axis: Relocate the waveguide from $-0.5\mu$m to $0.5\mu$m:

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7\textwidth]{bilder/shift\_z\_axis}

\caption{Displacing the waveguide along z-axis}

\label{fig:shift\_z\_axis}

\end{figure}

\end{itemize}

\begin{table}

\caption{Coupling efficiency by shifting the waveguide along X,Y and Z-Axis}

\centering

\begin{tabular}{c|ccc}

\hline

Shift distance & X-Asis & Y-Axis & Z-Axis \\

\hline

$-0.5\mu$m &$32.4\%$ &$32.4\%$&$46.6\%$ \\

$-0.4\mu$m &$37.3\%$ &$36.5\%$&$47\%$ \\

$-0.3\mu$m &$41.9\%$ &$41.3\%$&$48.2\%$ \\

$-0.2\mu$m &$45.5\%$ &$45.2\%$&$49.1\%$ \\

$-0.1\mu$m &$48\%$ &$47.8\%$&$49.1\%$ \\

$0\mu$m &$48.9\%$ &$48.9\%$&$48.9\%$ \\

$0.1\mu$m &$47.8\%$ &$48.4\%$&$48.9\%$ \\

$0.2\mu$m &$45.5\%$ &$46.4\%$&$49.4\%$ \\

$0.3\mu$m &$41.9\%$ &$42.9\%$&$49.7\%$ \\

$0.4\mu$m &$37.5\%$ &$38.5\%$&$49.5\%$ \\

$0.5\mu$m &$32.3\%$ &$33.1\%$&$48.8\%$ \\

\hline

\end{tabular}

\label{tab:shift\_result}

\end{table}

\begin{figure}[!ht]

\centering

\includegraphics[width=0.8\textwidth]{bilder/shift\_curve}

\caption{Coupling efficiency due to the displacement of the wavguide.}

\label{fig:shift\_curve}

\end{figure}

Tab. \ref{tab:shift\_result} contains the results of above simulations. According these results we can draw coupling-efficiency curves due to shifting waveguide in Fig. \ref{fig:shift\_curve}. It is obvious that the coupling efficiency falls very quickly for vertical or horizontal shifting, while it stays relative stable for longitudinal displacement. From this Figure we can also reveal that coupling efficiencies are symmetric due to positive and negative X-Axis shifting. While the coupling efficiencies due to negative and positive Y-Axis shifting is not symmetric. This trend can be explained by the geometric characters of the waveguide, which is same in X-direction and different in Y-direction. The highest coupling efficiency due to shifting along Z-Axis lies not exactly at working distance of $4\mu$m but of $4.3\mu$m, which agree with the estimation of minimum spot location about $4.26\mu$m at section \ref{sect:model\_model\_model\_TLF}. Alought the minimum spot location lies not on the working distance $4\mu$m, displacement of the waveguide cannot greatly improve the coupling efficiency. Thus the waveguide will stay at the working distance of $4\mu$m in following simulations.

## \section{Simulation in oil environment}

% coupling\_oil

In default condition the simulation models are surrounded by vacuum background in CST MWS.

In this section we will run the coupling simulation in a different background. For the practical experiment there are not many options for changing the environment. Here the coupling configuration will be placed in an environment full of oil, $n=1.526$ or $\emps=2.33$. Changing around conditions of the simulation may greatly affect the working distance of the TLF. Therefore determining the new working distance is necessary before coupling the TLF to the waveguide. Similar as in section \ref{sect:model\_model\_model\_TLF} the spot size curve Fig. \ref{fig:oil\_spot\_curve} can be drawn by loading data of TLF beam propagation in oil from CST MWS. Here we can tell from the spot size cure that the minimum spot in oil lies at the position more remote than the original minimum spot in vacuum.

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7\textwidth]{bilder/spot\_curve\_oil}

\caption{Spot size curve of TLF in oil.}

\label{fig:oil\_spot\_curve}

\end{figure}

Place the waveguide at the new working distance and execute the coupling simulation. The coupling efficiency of Fiber-to-Chip in oil can be found in curve Fig. \ref{fig:oil\_coupling\_curve}. The result shows that the coupling efficiency at working frequency $282$THZ achieves about $34.5\%$, which is lower than that of the original configuration in section \ref{sect:model\_model\_model\_TLF}.

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7\textwidth]{bilder/s21\_oil\_curve}

\caption{Coupling efficiency between TLF and the rib waveguide due to frequency domain in oil background.}

\label{fig:oil\_coupling\_curve}

\end{figure}

## \section{Different refract index}

It is obvious that the refractive index of the waveguide affects the coupling ability. To find the best configuration, we will keep the substrate setup and test guide in refractive indexes form $1.6$ to $2.5$ in this section. Tab. \ref{tab: refractive\_index}.

\begin{tabel}[ht]

\caption{Coupling efficiency due to refractive indexes}

\centering

\begin{tabular}{c|c|c|c|c|c|c}

\hline

$n$ & $1.6$ & $1.8$ & $2.0$ & $2.2$& $2.33$& $2.5$

\hline

& & & & & &

\hline

\end{tabular}

\label{tab:refractive\_index}

\end{tabel}

Simulation results can also be drawn in Fig. \ref{fig:refractive\_index}. It can be told from the figure that the coupling ability rise sharply within $n=1.6$ to $1.8$ then decline softly due to the increasing of refractive indexes. The highest value of the coupling efficiency among the arrangements in this section is about $$ when the guide is composed of material of $n=$.

Surely, it is not possible to find the material of any refractive index. If we want to improve the coupling ability by this means, we can only choose a material with a refractive index close to xxxx.

## \section{Tapered waveguide}

Tapered waveguide is inhomogeneous waveguide on shape, whose dimensions in the tapered section changes slowly along the longitude dirccetion\cite{linear\_tapered\_waveguides}. Tapered structure enables the waveguide to receive more light so that improve the coupling efficiency between beam source and waveguide.

The author of \cite{design\_fabrication\_tapered\_waveguide} has presented two general types of tapered waveguide: conventional taper like Fig. \ref{fig:conventional\_taper} and inverse taper like Fig. \ref{fig:inverse\_taper}. For a conventional taper the entry is wider than the exit while for an inverse taper the entry is narrower than the exit. In this section the conventional taper will be discussed

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7\textwidth]{bilder/convernational\_taper}

\caption{Schema of the conventional taper.}

\label{fig:conventional\_taper}

\end{figure}

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7\textwidth]{bilder/inverse\_taper}

\caption{Schema of the inverse taper.}

\label{fig:inverse\_taper}

\end{figure}

.

Two properties, the width of a taper interface and the taper angle, of the taper may strongly affect the coupling efficiency. For convenient calculations simulations are running due to variations of taper width and taper length respectively.

## \subsection{Tapered waveguide due to interface width}

Considering the beam spot diameter of about $1.5\mu$m at the working location, the taper width in this case can be designed greater than $1.5\mu$m. Here we discuss the tapered waveguide starting with $1.6\mu$m to match the beam spot. Fig. ref{ fig:tapered\_waveguide\_wxx} presents the coupling behavior of the tapered waveguide along the variation of the interface width. From the figure it can be told that the coupling efficiency of this arrangement rise firstly with the width increasing and achieve its peak value at the width$=2$ and $2.2\mu$m. Then the efficiency falls along the interface width. This phenomenon can be explained that a wider interface can confine more incident wave into propagation tunnel but if the interface expands too wide, other aspects may cause the decline of the coupling ability over the effect of the interface width.

\begin{figure}[!ht]

\centering

\includegraphis[width=0.7\textwidth]{bilder/tapered\_waveguide\_wxx}

\caption{Coupling efficiency between TLF and tapered waveguide due to interface width and taper length = $5.5\mu$m }

\label{fig:tapered\_waveguide\_wxx}

\end{figure}

## \subsection{Tapered waveguide due to taper length}

The value of the divergence angle is also a important character of the tapered waveguide to determine the coupling ability. The author of \cite{study\_linear\_tapered\_waveguides} has presented that the smaller the divergence angle is, the more power of fundamental mode propagates in the taper. In order to simplify the modeling process the variation of taper length will be performed in the fowling coupling simulations to discuss the effect of the divergence angle.

Keep the taper interface width of the waveguide as a constant $2\mu$m and change the taper length from $2\mu$m to $5.5\mu$m in our coupling arrangement.

\begin{figure}[!ht]

\centering

\includegraphis[width=0.7\textwidth]{bilder/tapered\_waveguide\_dxx}

\caption{Coupling efficiency between TLF and tapered waveguide due to taper length and taper width = $2\mu$m}

\label{fig:tapered\_waveguide\_dxx}

\end{figure}

The coupling behavior of the arrangement, the taper length vary from $2\mu$m to $5.5\mu$m, is shown in Fig. \ref{fig:tapered\_waveguide\_dxx }. The figure illustrate that the coupling efficiency increase monotonously with the taper length expanding. After taper length $xx\mu$m of the coupling efficiency rise more and more gently, close to a constant $xx%$.

Therefore for an efficient coupling the optimal divergence angle of the taper is less than:

\begin{equation}

\theta=atan\frac{d\_{1}-d\_{0}}{L}

\label{eq:divergence\_angle}

\end{equation}

## \subsection{Extension}

Moreover, there are other optional designs for tapered waveguide can be involved to improve the Fiber-to-Chip coupling.

In the other simulations of coupling between TLF and tapered waveguide there is another interesting result. If the taper is made from a proper material different from both guide and substrate, a more efficient coupling can be achieved in compare with our previous designs. For example, for a taper chosen for $n=2.0$, $w=2\mu$m and $h=5\mu$m the coupling efficiency reaches $%$. Because this design is not easy for fabrication, in this section no more attention will be paid on it.

\cite{tapered\_plasmonic\_waveguides} mentions a tapered plasmonic waveguide, which is composed of a taper shape metal film on the dielectric substrate. Under surface Plasmon polariton (SPP) wave

\cite{fiber\_to\_chip\_grating\_waveguides} provide a inversely tapered waveguide with gratings.

\begin{figure}[!ht]

\centering

\includegraphis[width=0.7\textwidth]{bilder/tapered\_waveguide\_grating}

\caption{Schema of a taperd waveguide with grating.}

\label{fig:tapered\_waveguide\_dxx}

\end{figure}

## \section{Lensed waveguide}

In many articles it has been well discussed about the coupling between laser source and lensed fiber\ref{microlensese\_to\_fiber\_coupling}\ref{integrated\_coupling \_between\_LD\_SMF}. Authors of \ref{microlensese\_to\_fiber\_coupling} proved that the coupling efficiency of their design reached maximum about $56\%$. \ref{integrated\_coupling \_between\_LD\_SMF} has also shown a minimum coupling loss less than $2$dB with application of a microlens. In compare with our previous works, our design could gain higher performance by the use of a microlens at the interface of the waveguide. For the fabrication it may be not easy to mount a microlens on a stript rib waveguide. But in \ref{lens\_end\_manufacture} the process sequence for fabricating the lens on the fiber end brings us the possibility to create a lens on a buried waveguide. In this section the coupling efficiency between TLF and the buried and lensed waveguide (or lensed waveguide) will be discussed. In this section the coupling efficiency between TLF and basic buried waveguide will at first be calculated as the reference for further discussing. Then we will engage the lensed waveguide and the effect of changing the lens geometric parameters of the waveguide.

### \subsection{Coupling between TLF and basic buried waveguide}

In agreement with the waveguide in the experiment, the buried waveguide model likes Fig. \ref{fig:buried\_waveguide} is created with the same corresponding parameters. The waveguide in this section contains the identical dimensions ($w$ and $h$) and refractive indexes (n$\_{1}$ and n$\_{2}$) with the original waveguide.

\begin{figure}[!ht]

\centering

\includegraphics[width=0.6\textwidth]{bilder/buried\_waveguide}

\caption{Schema of a basic buried waveguide}

\label{fig:buried\_waveguide}

\end{figure}

Fig. \ref{} shows the coupling efficiency between TLF and the basic buried waveguide due to the frequencies. The coupling efficiency at the working frequency $282$THZ reaches about $51.3\%$, which is relative better than stripped rib waveguide. We will refer this value for further discussion about coupling between TLF and the lensed waveguide.

\begin{figure}[!ht]

\centering

\includegraphics[width=0.6\textwidth]{bilder/curve\_coupling\_basic\_buried\_waveguide}

\caption{Coupling efficiency curve between TLF and the basic buried waveguide due to frequency. }

\label{fig:curve\_coupling\_basic\_buried\_waveguide}

\end{figure}

### \subsection{Effect of lens height}

Form this section we aim to find out the geometric effect of lensed waveguide and the lens is made from the same material with the substrate. Here we are going to change the lens property height with a constant lens radium. In Tab. \ref{tab:coupling\_lensed\_waveguide\_height} the coupling efficiency for these arrangements are collected. The results can also be presented as Fig. \ref{}, from which the coupling behaviors between TLF and lensed waveguide

\begin{table}

\caption{Cupling efficiency between TLF and lensed waveguide due to changing the lens height}

\begin{tabular}{|c|c|c|c|}

\hline

Height($\mu$m)|Radium($\mu$m)& 2& 2.5& 3\\

\hline

$0.4$&$54\%$&$53.4\%$&$52.9\%$\\

$0.6$&$58.35\%$&$57.4\%$&$56.9\%$\\

$0.8$&$57.3\%$&$56.7\%$&$56.3\%$\\

$1.0$&$60\%$&$58.8\%$&$57.8\%$\\

$1.2$&$60.7\%$&$59.1\%$&$57.9\%$\\

$1.4$&$61.7\%$&$59.9\%$&$58.8\%$\\

$1.6$&$65.1\%$&$62.7\%$&$60.7\%$\\

$1.8$&$62.9\%$&$60.9\%$&$59.9\%$\\

$2.0$&$69\%$ & $66\%$&$63\%$\\

$2.2$&--------&$62.5\%$&$61.6\%$\\

$2.4$&--------&$68.8\%$&$64.4\%$\\

$2.6$&--------&--------&$66.7\%$\\

$2.8$&--------&--------&$64.8\%$\\

$3.0$&--------&--------&$68.9\%$\\\hline

\end{tabular}

\label{tab:coupling\_lensed\_waveguide\_height}

\end{table}

Compare these values with that of the coupling between TLF and basic buried waveguide, a proper designed micro lens on the waveguide can greatly improve the coupling efficiency. And it can also be found from Fig. \ref{} that for a fix radium the most efficient lens configuration exist at the highest lens height or a hemisphere lens. But an exact hemisphere structure (height$=2\mu$m,Radium$=2\mu$m) may be not so easy for fabrication. Therefore the second efficient configuration (height$=1.6\mu$m,Radium$=2\mu$m) can be an optimal option.

\begin{figure}[!ht]

\includegraphics[width=0.6\textwidth]{bilder/ }

\caption{Coupling efficiency }

\label{fig: coupling\_lenses\_curve\_rxx}

\end{figure}

The reason of the efficiency change can be explained by Fig. \ref{}-\ref{}. From the former cure Fig. \ref{fig:Tapered\_core\_spot\_curve} we can tell that beam spot size at the working distance is bigger than the dimensions of the waveguide interface and from Fig. \ref{} we understand the reason because rays near margin are penetrating mostly into substrate. In Fig. \ref{} rays near margin are refracted and focused to axis, so that the beam spot size decreased and more rays concentrate into waveguide so that the coupling become more adaptable.

\begin{figure}[!ht]

\includegraphics[width=0.7\textwidth]{bilder/ }

\caption{The marginal rays are concentrated by lens of the waveguide.}

\label{fig:matlab\_coupling\_lenses\_rxx}

\end{figure}

For more information we can draw the Fig. \ref{fig: lensed\_guide\_spot\_size\_ curve}. And the spot sizes changing agree well with the corresponding coupling efficiency.

\begin{figure}[!ht]

\includegraphics[width=0.7\textwidth]{bilder/lensed\_guide\_spot\_size\_ curve}

\caption{The spot size curve at lensed waveguide interface due to changing lens height}

\label{fig: lensed\_guide\_spot\_size\_ curve }

\end{figure}

### \subsection{Effect of lens radium}

In this part we are going to fixed height of the lens on the waveguide and change the lens radium.

In Tab. \ref{tab:coupling\_lensed\_waveguide\_radium} the lens height is choosed for $1\mu$m, $1.5\mu$m and $2\mu$m respectively. Change the lens radium from $2\mu$m to $3.6\mu$m and observe $|S21|$ as coupling efficiency.

\begin{table}

\caption{Cupling efficiency between TLF and lensed waveguide due to changing the lens radium}

\centering

\begin{tabular}{|c|c|c|c|}

\hline

Radium($\mu$m)|Height($\mu$m)& 1& 1.5&2\\

\hline

$2.0$& $59.5\%$ &$61.3\%$ &$69\%$\\

$2.2$& $59\%$ &$60.8\%$ &$68.3\%$\\

$2.4$&$59\%$ &$60.3\%$ &$66.8\%$\\

$2.6$&$58.6\%$ &$59.9\%$ &$65.3\%$\\

$2.8$&$58.2\%$ &$59.3\%$ &$64\%$\\

$3.0$&$57.8\%$ &$58.7\%$ &$63\%$\\

\hline

\end{tabular}

\label{tab:coupling\_lensed\_waveguide\_radium}

\end{table}

According above data the coupling behavior curve can be mapped in Fig. \ref{fig:coupling\_lenses\_curve\_rxx}. Apparently it can be told that the coupling efficiencies under different lens heights are monotonously declining due to the variation of the lens radium.

\begin{figure}[!ht]

\includegraphics[width=0.8\textwidth]{bilder/s21\_fix\_lens\_height\_rxx}

\caption{Coupling efficiency due to changing the lens radium}

\label{fig:coupling\_lenses\_curve\_rxx}

\end{figure}

And the spot size curve in Fig. \ref{fig: lensed\_guide\_spot\_size\_ curve} along the variation of the lens radium behave inversely in compare with the trends of coupling efficiency.

\begin{figure}[!ht]

\includegraphics[width=0.8\textwidth]{bilder/spot\_fix\_lens\_height\_rxx}

\caption{The spot size curve at lensed waveguide interface due to changing lens height}

\label{fig: lensed\_guide\_spot\_size\_ curve}

\end{figure}

### Subsection{Extension}

From \cite{integrated\_coupling\_between\_LD\_SMF} we can find more ideas to promote the coupling efficiency between TLF and lensed waveguide. The author at the end has presented a tapered core fiber, with which the core is capable to confine more beam rays. And we also get to know there is a small distance between the lens end and core interface because the lens end may not be the minimum spot location for a lensed waveguide. Thus is it possible to gain higher coupling efficiency by expanding properly the distance between the lens and the core within the lensed waveguide.

Conclusion

%description of the project and theory.

Coupling the light from optical fiber to photonic waveguide (fiber-to-chip) is a common topic for research and application in optical communication. As the light source the normal fiber has a generally an interface bigger than the dimension of the photonic waveguide. In order to promote the coupling efficiency the tapered lensed fibers (TLF) are usually applied as the light source. Thus the coupling between TLF and photonic waveguide become an attractive agenda of the optic research. \\

%purpose of this work

This work aims for the optimal solution for the effective coupling between TLF and photonic waveguide. In order to achieve this goal the coupling models have been constructed and simulated with the aid of CST MWS. In this work the modeling procedure and the analyses of the result are recounted.\\

%the content and the result of this work

%summary of each chapter,

In chapter\ref{chp:background} the basic knowledge about the geometric optic, fiber optic, Gaussian beam, finite integral method and S-Parameter is listed. The above knowledge could be helpful to understand some terms of this work. The chapter\ref{chp:model} gives readers of this work at first an impression about the technical detail of the experimental objects. Then the modeling procedure, how the model is simplified and how the properties of models look like, is introduced. Especially, two types of TLF models are compared and one is finally chosen for the further discussion. In chapter\ref{chp:optim} simulations about the effective coupling between TLF and the waveguide is divided into four parts. In the first part, the simulation aim at the effect of displacing the waveguide on the coupling efficiency. In the second part we try the same coupling configuration in oil environment instead of in air. After that, the third and forth parts provide two important techniques of waveguide interface, tapered and lensed interface, for promoting the coupling ability.\\

%compare and conclude the results, advice for experiment

According the results from all simulations in this work, a good designed waveguide interface can greatly affect the coupling ability of Fiber-to-Chip. The original coupling arrangement in this work achieve an efficiency $48.9\5$. The simply constructed tapered interface in this work gains maximally a value about $54\%$. In comparison to the tapered interface, lensed interface of the waveguide can catch the efficiency about $69\%$ in this work. From this view, the lensed interface is the most optimal option for Fiber-to-Chip coupling in this work. But coupling ability is not the exclusive aspect for the practical application. The fabrication cost must be considered. The simple tapered interface is easier for the fabrication than the lensed interface. Thus the simple tapered interface is an more economical solution. \\

% the extensions of this work.

Techniques advance every day. There are more interesting designs for the effective Fiber-to-Chip coupling. The tapered plasmonic waveguide in \cite{tapered\_plasmonic\_waveguides} is the application of SPP mode wave provided by metal/dielectric interface. This design may achieves coupling efficiency over $100\%$. Alonso-Ramos involve grating as coupler in \cite{fiber\_to\_chip\_grating\_waveguides} to extract beams into another planner waveguide. In his developments he reaches the coupling efficiency of $65.6\%$. Beside above two designs section \ref{chp:optim\_tapered\_ext} and section \ref{chp:optim\_lensed\_ext} of this work also mension two extension for further development. The hybrid tapered interface and lensed interface with a neck are properly uneasy for fabrication, but as a simulation project they can still engage our attentions.