# \chapter{Optimize}

## %introduction

## This chapter aims to discuss the optimization methods to improve the Fiber-to-Chip coupling efficiency. In Fiber-to-Chip coupling light propagates through 3 tracks (source fibers, vacuum or air, photonic waveguides). The application of replacing regular fiber with TLF has optimized properties of output light from fibers. In this chapter we investigate optimal methods in other two tracks for improving the 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 it is considered 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 lens structures mounted at the end face of waveguides are discussed.

## %Version 2

## This chapter aims to discuss the optimization methods to improve the Fiber-to-Chip coupling efficiency. In Fiber-to-Chip coupling light propagates through 3 tracks (source fibers, vacuum or air, photonic waveguides). The application of replacing regular fiber with TLF has optimized properties of output light from fibers. In this chapter we investigate optimal methods in other two tracks for improving the coupling efficiency. Six 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. The third proposal is to insert a lens between TLF and waveguides. In the fourth 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}

%\section{Coupling by location shifting}

%coupling\_shifting

In this section we consider shifting the waveguide to affect the light properties in second propagating track. As a 3D model the waveguide can be shifted on transverse and or longitude directions as Fig. \ref{fig:shift\_all\_axis}.

\begin{figure}[!ht]

\centering

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

\caption{Displacing the waveguide along x, y, z-axis.}

\label{fig:shift\_all\_axis}

\end{figure}

\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}

Performe above arrangements and record their simulation results $|S\_{21}|$ in Tab. \ref{tab:shift\_result}:\\

\begin{table}[!ht]

\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}

According results in the table we can draw curves in Fig. \ref{fig:shift\_curve}, which presents coupling efficiencies due to waveguide shifting. For transversal shifting among range $-0.5\mu$m to $0.5\mu$m the coupling efficiency falls very quickly in vertical or horizontal directions from $48.9\%$ to about $32\%$. In another word, the coupling efficiency stands for the highest value of $48.9\%$ when there is not shifting in transversal directions. From this Figure it can also be revealed 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 are not symmetric. This trend can be explained by the geometric characteristic of the waveguide, which is same in X-Dimension and different in Y-Dimension. In longitudinal direction among the shifting range $-0.5\mu$m to $0.5\mu$m the lowest coupling efficiency is $46\%$ at distance $3.5\mu$m from TLF, while the highest coupling efficiency of $49.7\%$ due to shifting along Z-Axis stands not at working distance $4\mu$m but $4.3\mu$m, which agree with the estimation of minimum spot location about $4.26\mu$m at section \ref{sect:model\_model\_model\_TLF}. \\

Through above discussions following can be concluded:

\begin{itemize}

\item Shifting in transversal directions cannot improve the coupling efficiency and obviously affect the coupling ability.

\item Shifting in longitudinal direction can gently affect the coupling ability.

\end{itemize}

Although the minimum spot location lies not on the working distance $4\mu$m, displacement of the waveguide cannot obviously improve the coupling efficiency, difference of $1\%$. Hereby the working distance will be maintained in following simulations.\\

## \section{Simulation in oil environment}

% coupling\_oil

\begin{figure}[!ht]

\centering

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

\caption{Spot size curve of TLF in oil. The z-coordinate indicates the distance from TLF end.}

\label{fig:oil\_spot\_curve}

\end{figure}

In this section we consider affecting the light propagation in the second track by changing the surrounding condition. In default condition the experimental setup is placed in vacuum or air. Here the coupling in a different condition is investigated. For the practical experiment there are not many options for changing the environment. In this section the coupling simulation will be placed in an environment full of oil, $n=1.526$ or $\epsilon=2.33$. \\

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 it can be found from the spot size cure that the minimum spot in oil lies at the position of about $19\mu$m from the TLF, farer than the original minimum spot location in air.\\

Then in the new coupling setup the waveguide is placed at the new working distance of $19\mu$m. Fig. \ref{fig:oil\_coupling\_curve} is the $S\_{21}$ curve of this arrangement from CST MWS. It shows 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}. So using oil environment can not improve the coupling ability.\\

\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 indexes}

%\section{Different refract index}

%\section{Different refract index}

From this section we begin to investigate optimal methods in the third propagating track: waveguide. The refractive index of the waveguide can also affect the coupling ability. In this section the effect of varying refractive index for coupling will be discussed. The experimental setup of the waveguide is substrate with index $n=1.544$ and guide with index $n=2.516$. For simplifying the simulation the substrate setup is kept and only the refractive indexes of the guide is varied from $1.6$ to $2.5$ in this section.\\

\begin{figure}[!ht]

\centering

\includegraphics[width=0.6\textwidth]{bilder/s21\_refractive\_index}

\caption{Coupling efficiency between TLF and the rib waveguide at $f=282$THz due to refractive indices.}

\label{fig:refractive\_index}

\end{figure}

Fig. \ref{fig:refractive\_index} exhibits simulation results of this arrangement at working frequency of $282$ THz. It can be told from the figure that the coupling ability rises sharply from $n=1.6$ to $1.8$ and decline gently to $n=2.5$. It can also be derived that coupling efficiency will be decreased with the increasing of refractive indexes if $n>2.5$. Thus there is no need to do more simulations for other indexes of $n>2.5$. The highest value of the coupling efficiency among this index range is about $62.6\%$ when the guide is composed of material of $n=1.8$.\\

The reason for this behavior in the figure is complicated. One of them is the numerical aperture (NA) of the waveguide. Through lens theory it can be calculated that light form given TLF is confined in a divergence angle of about $106^°$. In order to match the incident light, the minimal NA should be larger than $0.798$. Using equation (\ref{eq:NA}) the NA for index $1.6$ is obtained by

\begin{equation\*}

\sqrt{n\_{1}^2-n\_{2}^2}=\sqrt{1.6^2-1.544^2}=0.42.

\end{equation\*}

This value is smaller than above request. Thus heavy power loss occurs at the end face of the waveguide. The value of NA is raised with the index increasing, $0.711$ for $n=1.7$ and $0.925$ for $n=1.8$. When the index is still expanding other aspects become dominated. One aspect is the reflection at the end face. Fig. \ref{fig:s11\_index} collects the relation between reflection and indices. After index of $1.7$ reflection is proportional to the value of the index. Combing other aspects of power loss the coupling efficiency falls after index of $1.9$.\\

\begin{figure}[!ht]

\centering

\includegraphics[width=0.6\textwidth]{bilder/s11\_index}

\caption{Reflection due to refractive indices.}

\label{fig:s11\_index}

\end{figure}

As the conclusion the most efficient material of guide here is the one with index $n=1.8$. Surely, it is not possible to find the material of any refractive index. If we want to improve the coupling ability by this means, the material with a refractive index close to $n=1.8$ can be optional.

## \section{Tapered waveguide}

## %tapered\_waveguide

## Tapered waveguide is composed of a regular waveguide and a taper interface, whose dimensions in the tapered section changes slightly along the longitudinal direction\cite{linear\_tapered\_waveguides}. Tapered structure enables the waveguide to receive more light so that this structure can improve the coupling efficiency between beam source and waveguide.\\

## Nathaniel in \cite{design\_fabrication\_tapered\_waveguide} has presented two general types of tapered waveguide: conventional taper like Fig. \ref{fig:conventional\_taper} and 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. Because the entry of the inverse taper has smaller dimensions than that of beam spots in this work, only the conventional taper will be discussed in this section.\\

## \begin{figure}[!ht]

## \centering

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

## \caption{Schema of a conventional taper.}

## \label{fig:conventional\_taper}

## \end{figure}

## %\begin{figure}[!ht]

## %\centering

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

## %\caption{Schema of a inverse taper.}

## %\label{fig:inverse\_taper}

## %\end{figure}

## In this section only the simple taper structure is involved for considering the fabrication process of a rib waveguide. Therefore only two taper properties, the width $d\_{1}$ of a taper interface and the divergence angle $\theta$ of the taper, are discussed. For convenient calculations simulations in this section will be arranged respectively due to variations of taper width and taper length $L\_{taper}$.

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

%\subsection{Tapered waveguide due to interface width}

%tapered\_width

The taper width of the waveguide affects the acceptable scale of light power. It is given in Fig. \ref {fig:Tapered\_core\_spot\_curve} that the beam spot diameter at the working distance is about $1.5\mu$m, while the regular waveguide has smaller dimensions (w=$1\mu$m and h=$0.5\mu$m). That means the original waveguide dimension is not adaptable for more incident power. In this section the tapered waveguide is placed at the working distance of $4\mu$m from TLF and the taper width starting with $1.2\mu$m to $3\mu$m with step $0.2\mu$m, taper length is a constant of $5.5\mu$m. \\

Fig. \ref{fig:tapered\_waveguide\_wxx} exhibits 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 from $51.5\5$ for $d\_{1}=1.2\mu$m and achieves the peak value of about $54.2\%$ for the taper width $d\_{1}=2\mu$m and $2.2\mu$m. Then the efficiency falls as the taper width increasing. This tendency can be explained that a wider interface can confine more incident rays into the propagation tunnel but if the interface expands continually, other aspects, such as the divergence angle, may cause the decline of the coupling ability over the effect of the interface width. That means, an efficient taper structure depends not only on taper width. In next subsection we will discuss another property of the taper structure.\\

\begin{figure}[!ht]

\centering

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

\caption{Coupling efficiency between TLF and tapered waveguide with constant taper length $= 5.5\mu$m due to the variations of the interface width, working frequency $282$THz.}

\label{fig:tapered\_waveguide\_wxx}

\end{figure}

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

%\subsection{Tapered waveguide due to taper length}

%tapered\_length

The value of the divergence angle is also a important property of the tapered waveguide to determine the coupling ability. In order to simplify the modeling process the variation of taper length, instead of divergence angle, will be performed in the following coupling simulations. \\

As previous simulations the waveguide is placed at the distance of $4\mu$m from the TLF. We will keep the taper width as a constant of $d\_{1}=2\mu$m and change the taper length from $L\_{taper}=2\mu$m to $ L\_{taper}=5.5\mu$m in following simulations.\\

\begin{figure}[!ht]

\centering

\includegraphics[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}

Fig. \ref{fig:tapered\_waveguide\_dxx} it exhibits the coupling behavior of these arrangements.

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 coupling efficiency starts with the value of $51.5\%$ and is rising monotonously with the taper length increasing. After taper length $4.5\mu$m of the coupling efficiency rise more and more gently, close to a constant $54.2\%$.

Therefore, for an efficient coupling the optimal divergence angle of the taper in this arrangement is less than:

\begin{equation}

\theta=\arctan\frac{d\_{1}-d\_{0}}{L\_{taper}}=\arctan\frac{2-1}{5.5}=10.3^{o}

\label{eq:divergence\_angle}

\end{equation}

The reason of this trend is explained by mode conversion for light propagating in tapers. In \cite{integrated\_optics,mode\_conversion\_optical\_waveguide} mode conversion in taper is analyzed through the local normal mode theory. The taper is divided into small steps as Fig. \ref{fig: discontinue\_taper}. Each step is regarded approximately as an unvaried guide. Supposing the incident mode $i$ propagates from $m$th step to $m+1$th step, part of the power is converted to that of the high-order mode $j$ in step $m+1$. At the end of the taper more modes appear and more power of incident mode is converted. But the mode conversion in a linear taper can be minimize by controlling the aspect ratio $L\_{taper}/d\_{1}$ . A high aspect ratio makes the transition more gradual in the taper, thus leading to limited mode conversion. Yip’s result in \cite{mode\_conversion\_optical\_waveguide} showed that power converted from incident mode to high-order modes can be controlled under $5%$ for an aspect ratio over $100$.\\

\begin{figure}[!ht]

\centering

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

\caption{Taper is divided into discontinued steps.}

\label{fig: discontinue\_taper}

\end{figure}

From previous discussions about taper structure following advices can be given for design of the efficient tapered waveguide:

\begin{itemize}

\item The taper width should expand enough wide to adapt the spot size of incident light.

\item The aspect ratio $L\_{taper}/d\_{1}$ should be big enough to minimize mode conversion.

\end{itemize}

## \subsection{Extension}

%tapered\_extension

Moreover, there are other optional designs of tapered waveguide can be involved to improve the Fiber-to-Chip coupling ability. In this section other possibilities of tapered structures are only delivered for reference and most of them will not be verified in this work. \\

\subsubsection\*{Hybrid tapered waveguides}%\\

\begin{figure}[!ht]

\centering

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

\caption{Schema of a tapered waveguide combined with two different materials.}

\label{fig:tapered\_waveguide\_others}

\end{figure}

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.\\

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7\textwidth]{bilder/s21\_tapered\_waveguide\_others}

\caption{Coupling efficiency between TLF and the tapered waveguide combined with two different materials.}

\label{fig:tapered\_waveguide\_others\_coupling}

\end{figure}

For example, for a taper chosen for $n=2.0$, $d\_{1}=2\mu$m, $L\_{taper}=5.5\mu$m and other configurations maintain as that of the original simulation models. In this case the coupling efficiency reaches $|S\_{21}|=63\%$ according the simulation result Fig. \ref{fig:tapered\_waveguide\_others\_coupling}. Because this design is not easy for fabrication, no more attention will be paid on it in this section.\\

\subsubsection\*{Other tapered waveguides}

%\subsubsection\*{Tapered plasmonic waveguides}%\\

Verhagen mentions in \cite{tapered\_plasmonic\_waveguides} a tapered plasmonic waveguide, which is composed of a thin tapered metal film, on the surface of which lies many small holes like Fig. \ref{fig:tapered\_waveguide\_plasmonic}. For transmission input beams excite the surface plasmon polariton (SPP) wave, which is explained by quantum emission, provided by the metal/dielectric interfaces of the plasmonic waveguides. By means of this arrangement the coupling efficiency can even achieve a value greater than $100\%$.\\

\begin{figure}[!ht]

\centering

\subfigure[Schema of a taperd plasmonic waveguide.]{

\includegraphics[width=0.48 \textwidth]{bilder/tapered\_waveguide\_plasmonic}

\label{fig:tapered\_waveguide\_plasmonic}

}

\subfigure[Schema of a taperd waveguide with grating.]{

\includegraphics[width=0.48 \textwidth]{bilder/tapered\_waveguide\_grating}

\label{fig:tapered\_waveguide\_grating}

}

\caption{Other tapered waveguide technigues.}

%\includegraphics[width=0.65\textwidth]{bilder/tapered\_waveguide\_plasmonic}

%\caption{Schema of a taperd plasmonic waveguide.}

%\label{fig:tapered\_waveguide\_plasmonic}

%\end{figure}

%\subsubsection\*{Grating tapered waveguides}%\\

%\begin{figure}[!ht]

%\centering

%\includegraphics[width=0.65\textwidth]{bilder/tapered\_waveguide\_grating}

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

%\label{fig:tapered\_waveguide\_grating}

\end{figure}

Alonso-Ramos has provided in \cite{fiber\_to\_chip\_grating\_waveguides} an inversely tapered waveguide with gratings like Fig. \ref{fig:tapered\_waveguide\_grating}. The gratings of this waveguide are delicately designed to match the work mode: bloch mode. In \cite{fiber\_to\_chip\_grating\_waveguides} the author presented his achievement of $65.6\%$ coupling efficiency. \\

## \section{Lensed waveguide}

%\section{Lensed waveguide}

%lensed\_waveguide

In this section we will discuss another important waveguide structure for efficient coupling. In many articles it has been well discussed about the coupling between laser source and lensed fiber\cite{microlensese\_to\_fiber\_coupling} and \cite{integrated\_coupling \_between\_LD\_SMF}. Edward in \cite{microlensese\_to\_fiber\_coupling} provided a microlens design for coupling lasers to fibers. The coupling efficiency in his work reaches maximum about $56\%$. SHIRAISHI has also presented in \cite{integrated\_coupling \_between\_LD\_SMF} some lensed fiber designs and has gained a minimum coupling loss less than $2$dB with those microlens designs. It brings us a idea, by means of mounting a microlens on the waveguide interface higher performance can be achieved 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 \cite{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 from TLF to the lensed buried waveguide (or lensed waveguide Fig. \ref{fig:lensed\_waveguide}) will be discussed.\\

\begin{figure}[!ht]

\centering

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

\caption{Schema of a lensed buried waveguide.}

\label{fig:lensed\_waveguide}

\end{figure}

In the first subsection the coupling efficiency between TLF and regular buried waveguide is calculated as the reference for further discussing. Then we can continue to talk about the lensed waveguide and the effect of varying the lens geometric ($h'$ and $R$) parameters of the lensed waveguide. \\

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

%basic\_buried\_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}

In agreement with the waveguide in the experiment, the buried waveguide model like Fig. \ref{fig:buried\_waveguide} in this section obtains the identical dimensions ($w01\mu$m and $h00.5\mu$m) and refractive indexes (n$\_{1}$ and n$\_{2}$) with the original waveguide.\\

Fig. \ref{fig:curve\_coupling\_basic\_buried\_waveguide} shows the coupling efficiency between TLF and the regular buried waveguide due to the frequencies. The coupling efficiency at the working frequency $282$THz reaches about $51.3\%$, which is relative higher than that of the stripped rib waveguide. This value will be referred for further discussion about coupling from TLF to the lensed waveguide.

\begin{figure}[!ht]

\centering

\includegraphics[width=0.8\textwidth]{bilder/s21\_sym\_waveguide}

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

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

\end{figure}

### \subsection{Effect of lens height}

In this section we aim to find out the effect of the lens height $h’$ to the coupling, while the lensed interface is made from the same material with the substrate. Here the guide end face is maintained at the distance of $4\mu$m from the TLF and lens radius as a constant. Meanwhile the lens height $h’$ is varying from $0.4\mu$m to $3\mu$m. \\

Tab. \ref{tab:coupling\_lensed\_waveguide\_height} obtains three group of simulation results for lens radius of $R=2\mu$m, $2.5\mu$m and $3\mu$m and Fig. \ref{fig:coupling\_lenses\_curve\_hxx} presents these results as curves.

It can be told that coupling efficiencies of each group are rising with the lens height increasing. The coupling efficiency for the lens radius of $R=2.0\mu$m rises from $54\%$ at $h’=0.4\mu$m to $69\%$ at $h’=2.0\mu$m; the coupling efficiency for the lens radius of $R=2.5\mu$m rises from $53.4\%$ at $h’=0.4\mu$m to $68.8\%$ at $h’=2.4\mu$m; the coupling efficiency for the lens radius of $R=3.0\mu$m rises from $52.9\%$ at $h’=0.4\mu$m to $68.9\%$ at $h’=3.0\mu$m. Therefore, the most efficient lens configuration exists at the highest lens height when the radius of the lens is a constant. In another word a hemisphere lens is the best coupling configuration. \\

\begin{table}

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

\centering

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

\hline

\multirow{2}{\*}{Height($\mu$m)}&\multicolumn{3}{c|}{Radius($\mu$m)}\\

\cline{2-4}

& 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}

\begin{figure}[!ht]

\centering

\includegraphics[width=0.8\textwidth]{bilder/s21\_fix\_lens\_radium\_hxx}

\caption{Coupling efficiency due to the variation of the lens height.}

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

\end{figure}

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7\textwidth]{bilder/beam\_ray\_without\_refract}

\caption{Light propagates from TLF to waveguides without refraction in lens structure.}

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

\end{figure}

\begin{figure}[!ht]

\centering

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

\caption{ Light propagates from TLF to waveguides with refraction in lens structure.}

\label{fig:matlab\_coupling\_lenses\_rxx2}

\end{figure}

From simulation results it can told that the highest coupling efficiency in this case has significantly be improved in compare with the coupling efficiency of $51.3\%$ for regular buried waveguide in section \ref{sect:optim\_lensed\_regular}. The reason of the efficiency change can be explained by lens theory with Fig. \ref{fig:matlab\_coupling\_lenses\_rxx}-\ref{fig:matlab\_coupling\_lenses\_rxx2}, which exhibits light propagating from TLF to the lens structure of the lensed waveguide. The left-hand arc presents the end of TLF and the right-hand half circle presents the lens structure of the lensed waveguide. $d\_[spot]$ is the spot diameter at the waveguide end face. In Fig. \ref{fig:matlab\_coupling\_lenses\_rxx} rays are not refracted by right-hand lens structure and $d\_{spot}$ is about $2.4\mu$m. Fig. \ref{fig:matlab\_coupling\_lenses\_rxx2} demonstrate that rays are refracted by right-hand lens, which has refractive index of $n=2.516$. In this case $d\_{spot}$ decreased, become less than $2.0\mu$m . That means, light power is confined in a smaller area and the coupling become more efficient. To verify this derivation we can check the spot size at the waveguide end face from CST MWS.\\

\begin{figure}[!ht]

\centering

\includegraphics[width=0.8\textwidth]{bilder/spot\_fix\_lens\_radium\_hxx}

\caption{The spot size curve at lensed waveguide interface due to changing lens height, working frequency $f=282$THz.}

\label{fig:lensed\_guide\_spot\_size\_curve}

\end{figure}

Fig. \ref{fig:lensed\_guide\_spot\_size\_curve} demonstrates spot size curves of three lens-radii due to lens height at the end face of lensed waveguides. At the smallest lens height $h’=0.4\mu$m the spot size has highest values, about $1.05\mu$m for $R=2\mu$m, $1.07\mu$m for $R=2.5\mu$m and $1.08\mu$m for $R=3\mu$m. At the maximal lens height the spot size has minimum values, about $0.89\mu$m for $h’=2\mu$m and $R=2\mu$m, $0.91\mu$m for $h’=2.4\mu$m and $R=2.5\mu$m, $0.89\mu$m for $h’=3\mu$m and $R=3\mu$m. Curves in Fig. \ref{fig:lensed\_guide\_spot\_size\_curve} reveal that spot sizes changing agree well with the corresponding coupling efficiency inversely.

### \subsection{Effect of lens radius}

%\subsection{Effect of lens radius}

%lensed\_waveguide\_radium

In this part the effect of the radius of the lens interface of the lensed waveguide will be discussed. Coupling simulations of 3 groups are arranged and the lens height is kept as a constant of $1\mu$m, $1.5\mu$m and $2\mu$m, respectively. The distance of the waveguide end face from TLF maintains $4\mu$m and the lens radius of the lensed waveguide is varied from $2\mu$m to $3\mu$m with step of $02\mu$m.\\

\begin{table}

\caption{Coupling efficiency between TLF and lensed waveguide due to changing the lens radius.}

\centering

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

\hline

\multirow{2}\*{Radius($\mu$m)}&\multicolumn{3}{c|}{Height($\mu$m)}\\

\cline{2-4}

& 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}

Tab. \ref{tab:coupling\_lensed\_waveguide\_radium} demonstrates coupling results of these arrangements and Fig. \ref{fig:coupling\_lenses\_curve\_rxx} exhibits their coupling behaviors with the lens radius increasing. Apparently, it can be told that the coupling efficiency of each group is monotonously declining due to the variation of the lens radius. For the smallest radius value of $2\mu$m the coupling efficiency has the maximal values, $59.5\%$ for $h’=1\mu$m, $61.3\%$ for $h’=1.5\mu$m, $69\%$ for $h’=2\mu$m. For the maximal radius value of $3\mu$m the coupling efficiency has the minimum values, $57.8\%$ for $h’=1\mu$m, $58.7\%$ for $h’=1.5\mu$m, $63\%$ for $h’=2\mu$m.\\

\begin{figure}[!ht]

\centering

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

\caption{Coupling efficiency due to changing the lens radius.}

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

\end{figure}

\begin{figure}[!ht]

\centering

\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\_rxx}

\end{figure}

As previous Section \ref{sect:optim\_lensed\_height} the tendency in Fig. \ref{fig:coupling\_lenses\_curve\_rxx} can be verified by their spot size curve in Fig. \ref{fig:lensed\_guide\_spot\_size\_curve\_rxx}. The spot size curve of each group behaves along the variation of the lens radius inversely in compare with the trends of coupling efficiency.

%\Subsection{Conclusions of lensed waveguide}

According previous discussions about lensed waveguides following conclusions can be given:

\begin{itemize}

\item The coupling efficiency of Fiber-to-Chip can be significantly improved by applying lensed waveguides.

\item The coupling efficiency of lensed waveguide is rising with the lens height increasing and the lens radius decreasing.

\item The optimal design of lensed waveguides is a hemisphere lens structure.

\end{itemize}

### Subsection{Extension}

%lensed\_waveguide\_extension

Besides the previous discussion about the lensed waveguide, there are more operations we can resort to. From \cite{integrated\_coupling\_between\_LD\_SMF} more ideas can be found to promote the coupling efficiency between TLF and lensed waveguide. The author has presented a tapered core fiber like Fig.\ref{fig:tapered\_core\_fiber}, which is capable to confine more beam rays. In this configuration there is a small distance $h\_{1}$ between the lens end $H\_{1}$ and core interface $H\_{2}$, because the lens end is not the exact minimum spot location for a lensed waveguide. Thus it is possible to gain a higher coupling efficiency, if the distance between the lens and the core is expanded properly and this part of waveguides can be named as 'neck' (see Fig. \ref{fig:lensed\_waveguide\_neck}).\\

\begin{figure}[!ht]

\centering

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

\caption {Schema of tapered core fiber\cite{integrated\_coupling\_between\_LD\_SMF}.}

\label{fig:tapered\_core\_fiber}

\end{figure}

\begin{figure}[!ht]

\centering

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

\caption {Schema of a lensed buried waveguide with a 'neck'.}

\label{fig:lensed\_waveguide\_neck}

\end{figure}

With a proper length $h\_{1}$ of the 'neck' higher coupling efficiency should be achieved. Through brief simulations the coupling efficiency of this structure is exhibited in Fig. \ref{fig:s21\_neck}. it can be seen that neck length does affect the coupling efficiency. Because this setup has 3 variables (lense hight, lens radius and neck length), more simulations can be done for further investigation.\\

\begin{figure}[!ht]

\centering

\includegraphics[width=0.9\textwidth]{bilder/s21\_neck}

\caption {Schema of coupling efficiency due to 'neck' length. Curve 'Lens h2r2' presents the configuration of lens height $h=2\mu$m, radius $R=2\mu$m. Curve 'Lens h1.5r3' presents the configuration of lens height $h=1.5\mu$m, radius $R=3\mu$m.}

\label{fig:s21\_neck}

\end{figure}

## Conclusion

%conclusion

%conclusion

%description of the project and theory.

%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 integration technigue 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 five parts. In the first part, the simulation aim at the effect of displacing the waveguide on the coupling efficiency. In the second part the same coupling configuration is tried in oil environment instead of in air. In the third parts the effect of the refractive index is discussed. After that, the fourth and fifth 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 $48.9\%$. The waveguide with $n=1.8$ in coupling leads to an attractive result $62.5\%$. The simply constructed tapered interface in this work gains maximally a value about $54\%$ for a small taper angle less than $10.3^{o}$. In comparison to the tapered interface, lensed interface of the waveguide can catch the efficiency about $69\%$ for a hemisphere lens 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 method of using simple tapered interface or using another guide material is easier for the fabrication than the lensed interface. Thus the simple tapered interface is a 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{sect:optim\_tapered\_ext} and section \ref{sect:optim\_lensed\_ext} of this work also mention 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.