# \chapter{Optimize}

## %introduction

This chapter aims to discuss the optimize methods so that the Fiber-to-Chip coupling efficiency improved. Four ideals are engaged in this chapter. One thought is to relocate the waveguide; another is to change the round condition of the coupling. The application of a taper interface at the beginning of the waveguide is involved in the next consideration. The last thought is to mount a lens at the waveguide interface.

## \section{Coupling by location shifting}

As a 3D model the waveguide can be shifted on transverse (Fig. \ref{fig:shift\_x\_axis} and Fig. \ref{fig:shift\_y\_axis}) or longitude (Fig. \ref{ fig:shift\_z\_axis }) directions.

\begin{figure}[!ht]

\centering

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

\caption{Displacing the waveguide along x-axis}

\label{fig:shift\_x\_axis}

\end{figure}

\begin{figure}[!ht]

\centering

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

\caption{Displacing the waveguide along y-axis}

\label{fig:shift\_y\_axis}

\end{figure}

\begin{figure}[!ht]

\centering

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

\caption{Displacing the waveguide along z-axis}

\label{fig:shift\_z\_axis}

\end{figure}

Shift the waveguide along X-Axis: Relocate the waveguide from $-0.4\mu$m to $0.4\mu$m and record their forward gain $S21$:

\begin{figure}[!ht]

\centering

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

\caption{Coupling efficiency due to the displacement the waveguide along x-axis}

\label{fig:efficiency\_shift\_x\_axis}

\end{figure}

Shift the waveguide along Y-Axis: Relocate the waveguide from $-0.4\mu$m to $0.4\mu$m and record their forward gain $S21$:

\begin{figure}[!ht]

\centering

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

\caption{Coupling efficiency due to the displacement the waveguide along y-axis}

\label{fig:efficiency\_shift\_y\_axis}

\end{figure}

Shift the waveguide along Z-Axis: Relocate the waveguide from $-0.4\mu$m to $0.4\mu$m and record their forward gain $S21$:

\begin{figure}[!ht]

\centering

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

\caption{Coupling efficiency due to the displacement the waveguide along z-axis}

\label{fig:efficiency\_shift\_z\_axis}

\end{figure}

And all detail are listed in Tab.\quad\ref{tab:shift\_result}.

\begin{Table}

\caption{shifting the waveguide along X-Axis}

\begin{Tabular}{cccc}

\hline

Shift|direction& X-Asis & Y-Axis & Z-Axis \\

\hline

$-0.4\mu$m &\\

$-0.3\mu$m &\\

$-0.2\mu$m&\\

$-0.1\mu$m&\\

$0\mu$m&\\

$0.1\mu$m&\\

$0.2\mu$m&\\

$0.3\mu$m&\\

$0.4\mu$m\\

\hline

\end{tabular}

\label{tab:shift\_result}

\end{table}

Load all shifting data and draw their curves in Fig. \ref{fig:shift\_curve}, which presents us their coupling efficiency behavior. It is obvious that the coupling efficiency falls very quickly for vertical or horizontal shifting, while it stays relative stable for longitude 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 are not symmetric. This trend can be explained by the geometric characters of the waveguide, which is same in X-Dimension and different in Y-Dimension. And the highest coupling efficiency 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 sectionXXXXX.

\begin{figure}[!ht]

\centering

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

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

\label{fig: shift\_curve}

\end{figure}

## \section{oil Environment}

## \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}

.

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.

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 rib waveguide with gratings.

## \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}

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

\hline

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

\hline

$2.0$& $0.595$ &$0.613$ &$0.69$\\

$2.2$& $0.59$ &$0.608$ &$0.683$\\

$2.4$&$0.59$ &$0.603$ &$0.668$\\

$2.6$&$0.586$ &$0.599$ &$0.653$\\

$2.8$&$0.582$ &$0.593$ &$0.64$\\

$3.0$&$0.578$ &$0.587$ &$0.63$\\

\hline

\end{tabular}

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

\end{table}

Map the the data into a Fig. \ref{fig: coupling\_lenses\_curve\_hxx}

\begin{figure}[!ht]

\includegraphics[width=0.6\textwidth]{bilder/coupling\_lenses\_curve\_hxx }

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

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

\end{figure}

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

\end{figure}