**Chapter Introduction**

**For the research of photonic waveguides it is normally in use to project lights from optical fibers to photonic waveguides (Fiber-to-Chip). In this case the source fiber is generally connected with the laser source because a laser is diffraction limited and highly concentrated. As the signal source optical fibers have usually a lager end face than that of waveguides and the direct coupling from fibers to waveguides cause a very low coupling efficiency. In order to handle this problem tapered lensed fibers (TLF), which are optical fibers with a lens on the end face, are used to replace normal fibers. In Fiber-to-Chip this new end face of fibers will focus rays emitted from fibers, so that more light power can be coupled into waveguides.** The purpose of this work is to analyze the coupling ability from TLF to photonic waveguide through simulations in CST MWS (CST Studio suite 2010) and optimize the Fiber-to-Chip interface to achieve more effective coupling.\\

In this work the related basic knowledge for research and analysis will be firstly introduced to make some terms in this work clear for readers. Then the chapter\ref{chp:model} will address readers information about the technical detail of the experimental objects and the modeling procedure. After then we will simulate the unoptimized coupling arrangement and analyze the coupling behavior. In chapter\ref{chp:optim} we will divide the development about the effective coupling between TLF and the waveguide into four parts. In the first part, we aim at the effect of displacing the waveguide on the coupling efficiency. In the second part we will simulate the unoptimized coupling configuration in oil environment. Then in the third and forth parts we will provide two important techniques of waveguide interface, tapered and lensed interface, for promoting the coupling ability respectively.\\

%optimize the coupling efficiency, which is a electromagnetic simulator basically with the % implementation of the Finite Integration Technique (FIT)\cite{cst\_help\_siulation\_method}.

**Modelling**

# Chapter Modelling

**%Introduction.tex**

In this chapter the configurations of the experimental objects and corresponding technical detail will be at first introduced. Then it will be described the detail how the simulation models are approximated in CST MWS (CST Studio suite 2010) and the some performances of the simulations will also be illustrated in compare with the practical objects, such as working distance, minimum spot size, power distribution, etc .

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

In this chapter the modelling process of the experimental setup will be addressed. Firstly, we will describe the experimental arrangement and the corresponding technical detail. Then through the approximation of these technical details the fiber-to-chip models for the simulation can be constructed with the aid of CST MWS. At the end of this chapter, the original arrangement is simulated for addressing the unoptimized performance.

## %Problem Deskription.tex

**\section{Project description}**

% Problem description

Coupling single-mode fibers to waveguides with the help of microlenses is a very common setup in integrated optics \cite{ integrated\_optics}. Because a lensed fiber has a minimum focal length, by means of this technique simple and reliable optical systems with a small size become possible. In this work the implement of the lensed fiber-to-chip will be discussed and it coupling efficiency will be discussed.\\

\begin{figure}[!ht]

\centering

\includegraphics[width=.7\textwidth]{bilder/experiment\_object}

\caption{Fiber-to-Chip interface}

\label{fig:experiment\_object}

\end{figure}

Fig. \ref{fig:experiment\_object} is a schematic demonstration of fiber-to-chip interface. At the one side there is a lensed tapered fiber as laser source and at another side there is a rib waveguide\cite{integrated\_optics}, located at the working distance of the fiber, as the signal receiver.

\begin{figure}[!ht]

\centering

\subfigure[Picture of a real Single mode lensed fiber\cite{nanoscal\_tapered\_fiber}.]{

\includegraphics[width=0.3\textwidth]{bilder/single\_mode\_lensed\_fibber}

\label{fig:single\_mode\_lensed\_fiber}

}

\hfill

\subfigure[Schema of a tapered lensed fiber\cite{nanoscal\_tapered\_fiber}.]{

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

\label{fig:tapered\_lensed\_fiber}

}

\label{fig:TLFs}

\caption{ Tapered and Lensed Fibers by NANOICS }

\end{figure}

In the experimental setup for this work the tapered lensed fiber from NANONICS\cite{nanoscal\_tapered\_fiber} is used. Fig. \ref{fig:single\_mode\_lensed\_fiber} shows the original image of the tapered fiber by NANONICS and Fig. \ref{fig:tapered\_lensed\_fiber} indicate its schema. In Tab. \ref{tab:technical parameters\_lensed\_fiber} parts of technical parameters are listed. Additional information about the experimental setup is that the working frequency is $\lambda=1064$nm and working distance $4\mu$m.

\begin{table}

\caption{Technical parameters about tapered lensed fiber.\cite{nanoscal\_tapered\_fiber}}

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

\hline

\multicolumn{2}{c|}{\textbf{Parameter}}&\textbf{Specification(Single-Mode)}\\

\hline

\multirow{3}{\*}{\parbox[t]{0.25\textwidth}{Spot Size of Aspheric and Convex Lenses($1/e^2$)}}&\multirow{2}{\*}{Minum}&$1.7\mu$m($\lambda=1.5\mu$m)\\

& &$0.6\mu$m($\lambda=0.6\mu$m)\\

\cline{2-3}

&Maxium &$6.0\mu$m($\lambda=1.5\mu$m)\\

\hline

\multirow{2}{\*}{Spot Size Tolerance}&\parbox[t]{0.25\textwidth}{Without near-field characterization} &$\pm 0.5\mu$m\\

\cline{2-3}

&\parbox[t]{0.25\textwidth}{With near-field characterization} &$\pm 0.25\mu$m\\

\hline

\multirow{2}{\*}{Working Distance} &Minimum &$5\mu$ m($\lambda=1.5\mu$m)\\

\cline{2-3}

& Maximum &$50\mu$ m($\lambda=1.5\mu$m)\\

\hline

\end {tabular}

\label{tab:technical parameters\_lensed\_fiber}

\end{table}

\begin{figure}

\centering

\includegraphics[width=0.4\textwidth]{bilder/orignial\_waveguide}

%\subfigure[Schema of a real waveguide.]{

%\includegraphics[width=0.4\textwidth]{bilder/orignial\_waveguide}

%\label{fig:orignial\_waveguide}

%}

%\hfill

%\subfigure[Schema of a approxmate waveguide.]{

%\includegraphics[width=0.4\textwidth]{bilder/approxmate\_waveguide}

%\label{fig:approxmate\_waveguide}

%}

\caption{Schema of the photonic waveguide}

\label{fig:photonic\_waveguide}

\end{figure}

Actually, the waveguide in experimental setup is a trapezoid guide on a semiconductor like Fig. \ref{fig:orignial\_waveguide}. The angles $\theta$ of this guide approximate to $90^{o}$ and is not easy to measure because of the micro-size of the structure. Thus a simplified guide model Fig.\ref{fig:approxmate\_waveguide} will be used in this work. The detailed technical properties of the photonic waveguide used in the experimental setup are given as following:

\begin{itemize}

\item Working frequency: $\lambda=1064$nm

\item Waveguide: LiNbO$\_{3}$ with $n\_{1}=2.516, w\approx 1\mu$m, $h\approx 0.5 \mu$m

\item Substrate: SiO$\_{2}$ with $n\_{2}=1.544 $

\end{itemize}

## \section{Modelling and Simulation}

In \cite{nanoscal\_tapered\_fiber} the maximum diameter of the TLF in experimental setup is $150\mu$m, which is very larger than the working wavelength $\lambda=1064$nm and the dimensions of the waveguide, $w\approx 1\mu$m, $h\approx 0.5 \mu$m. If a full-size TLF model is used, it takes a great long time for the simulation. For an economic simulation there is no need to create exactly identical models and only parts of the specifics are requested for modelling. In this section the modelling process will be discussed.

### \subsection{Modeling the Lensed Fiber}

%fiber\_modeling.tex

The first agenda is to determine the Tapered and Lensed Fiber (TLF) model. Because of the heave computing cost creating a full size fiber is not economical. Therefore only the end of the fiber, which provides approximately the equal technical properties, will be modeled in this work. In \cite{TLF\_analysis,TLF\_mode\_transforming} two types of TLF configurations are discribed.

\begin{figure}[!ht]

\centering

\subfigure[Tapered cladding TLF.]{

\includegraphics[width=0.4\textwidth]{bilder/lense\_fiber\_01}

\label{fig:lense\_fiber\_01}

}

\hfill

\subfigure[Tapered core TLF.]{

\includegraphics[width=0.4\textwidth]{bilder/lense\_fiber\_02}

\label{fig:lense\_fiber\_02}

}

\label{fig:two\_TLF}

\caption{Two types of Tapered and Lensed Fibers}

\end{figure}

The tapered cladding TLF Fig. \ref{fig:lense\_fiber\_01} shows that its cladding diameter decreases along the propagation direction (O-O'Axis) and the core diameter stays a constant. For the tapered core TLF Fig. \ref{fig:lense\_fiber\_02} its cladding diameter and core diameter both decrease along the propagation direction. In \cite{TLF\_mode\_transforming} the Author tried to develop methods to estimate the performance of both type of TLF. Results in \cite{TLF\_mode\_transforming} show that the performance of the Tapered cladding TLF agrees well with the estimation and that of the Tapered core TLF is unpredictable. In this section two simulation models of each type are created to compare the efficiency of spot size and working distance.\\

First of all, determination the lens of both types is the primary work. In order to simplifying the lens structure, a hemispherical lens is assumed at the end of the fiber. Refer to the working distance for the experimental TLF, the lens configuration can be estimated through lens theory. Combining calculations in matlab and simulations in CST MWS one configuration of the parameters of the lens can be carefully selected. Tab. \ref{tab:model\_fiber\_configuration}) summarizes the closest parameters for the TLF designs in this work.

\begin{table}[!ht]

\caption{Configurations of the TLF Models}

\centering

\begin{tabular}{ccc}

\hline

&Tapered Cladding&Tapered Core\\

\hline

R($\mu$m) & $6$ &$6$ \\

n$\_{core}$&$1.68$&$1.68$\\

n$\_{cladding}$&$1.66$&$1.66$\\

D$\_{clad}$($\mu$m) & $17$ & $17$\\

D$\_{core}$($\mu$m) & $10$ & $17$\\

D$\_{tip}$ ($\mu$m) & -- & $6$\\

\hline

\end{tabular}

\label{tab:model\_fiber\_configuration}

\end{table}

With the parameters in Tab. \ref{tab:model\_fiber\_configuration} the minimum spot location can be estimated. Fig. \ref{fig:lens\_spot} demonstrates the beam propagation from the lens based on lens theory. As in previous section \ref{ sect:background\_optics} described, the minimum spot not exactly locates at coordinate calculated through the focal length. From measurements of the location of Paraxial focal plane (PP) and that of meridional plane (MP) the location of the minimum spot (MS) can be estimated. In the above configuration the theoretical distance from lens end to PP is $8.82 \mu$m and the distance from lens end to MP is about $2.74 \mu$m. Backward $3/4$ longitudinal spherical aberration (LAm) form PP, the MS is found at the place about $4.26 \mu$m away from lens end. \\

\begin{figure}[!ht]

\centering

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

\label{fig:lens\_spot}

\caption{Beam Propogation from lens.}

\end{figure}

\begin{figure}[!ht]

\centering

\includegraphics[width=0.8 \textwidth]{bilder/cst\_lensed\_fiber\_equ\_efield}

\caption{E-Field demonstration in [logarithm](dict://key.0895DFE8DB67F9409DB285590D870EDD/logarithm) value of Tapered cladding TLF}

\label{fig:Tapered\_cladding\_efield}

\end{figure}

\begin{figure}[!ht]

\centering

\includegraphics[width=0.8 \textwidth]{bilder/cst\_lensed\_fiber\_efield}

\caption{E-Field demonstration in logarithm value of Tapered core TLF}

\label{fig:Tapered\_core\_efield}

\end{figure}

Above we only estimated the theoretical working distance of the lens. To determine the actual working distance and actual spot size we have to analyze the simulation results from CST MVS. Fig. \ref{fig:Tapered\_cladding\_efield} and Fig. \ref{fig:Tapered\_core\_efield} show E-Field demonstrations in logarithm value in the xz-plane of both types of TLFs. We load the power flow data into matlab workspace and draw Fig.\ref{fig:Tapered\_cladding\_spot\_curve} and Fig.\ref{fig:Tapered\_core\_spot\_curve}, which show the beam spot diameters through their absolute beam power flow density or its z-compents (propagation direction) of the beam power flow density along the propagation distance. From these two figures, curves of the absolute value of their power flow density show the location of the minimum spot matching the previous theoretical location of the minimum spot of lenses. This guess will also be verified in section \ref{sect:optim\_shift}. In Fig.\ref{fig:Tapered\_cladding\_spot\_curve} that the minimum spot size locate at about $4.1 \mu$m from lense end and spot size equal about $1.5 \mu$m. While in Fig.\ref{fig:Tapered\_core\_spot\_curve} that the minimum spot size is found at $4.3 \mu m$ from lense end and spot size equal about $1.5 \mu$m. Thus it is concluded that two configuration has only a small difference. Comparing with the properties given by experimental setup: minimum spot diameter $0.6<d<1.7 \mu$m and working distance $4\mu$m, both TLF model can be acceptable for the following development. In this works the tapered core TLF will be used for further simulations.\\

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7 \textwidth]{bilder/Tapered\_cladding\_spot\_curve}

\caption{Spot Size Curve of Tapered cladding TLF}

\label{fig:Tapered\_cladding\_spot\_curve}

\end{figure}

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7 \textwidth]{bilder/Tapered\_core\_spot\_curve}

\caption{Spot Size Curve of Tapered core TLF}

\label{fig:Tapered\_core\_spot\_curve}

\end{figure}

For a more impression of the relation between beam power density and beam propagation distance of the tapered core TLF, 3D Fig.\quad\ref{fig:3d\_spot\_sub1}-\ref{fig:3d\_spot\_sub8} are drawn as demonstrations. It is obvious that the power density of the beam center rise firstly along the distance and at $4\mu$m reach the highest value. Then it falls slowly. This tendency agrees with the spot size curve inversely.

\begin{figure}[!ht]

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\flushleft

\subfigure[3D Beam Power at distance $1\mu m$]{

\includegraphics[width=0.4 \textwidth]{bilder/surf\_spot\_1um}

\label{fig:3d\_spot\_sub1}%

}

\subfigure[3D Beam Power at distance $2\mu m$]{

\includegraphics[width=0.4 \textwidth]{bilder/surf\_spot\_2um}

\label{fig:3d\_spot\_sub2}

}

\end{figure}

\begin{figure}[!ht]

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\subfigure[3D Beam Power at distance $3\mu m$]{

\includegraphics[width=0.4 \textwidth]{bilder/surf\_spot\_3um}

\label{fig:3d\_spot\_sub3}

}

\subfigure[3D Beam Power at distance $4\mu m$]{

\includegraphics[width=0.4 \textwidth]{bilder/surf\_spot\_4um}

\label{fig:3d\_spot\_sub4}

}

\end{figure}

\begin{figure}[!ht]

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\subfigure[3D Beam Power at distance $5\mu m$]{

\includegraphics[width=0.4 \textwidth]{bilder/surf\_spot\_5um}

\label{fig:3d\_spot\_sub5}

}

\subfigure[3D Beam Power at distance $6\mu m$]{

\includegraphics[width=0.4 \textwidth]{bilder/surf\_spot\_6um}

\label{fig:3d\_spot\_sub6}

}

\end{figure}

\begin{figure}[!htp]

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\subfigure[3D Beam Power at distance $7\mu m$]{

\includegraphics[width=0.4 \textwidth]{bilder/surf\_spot\_7um}

\label{fig:3d\_spot\_sub7}

}

\subfigure[3D Beam Power at distance $8\mu m$]{

\includegraphics[width=0.4 \textwidth]{bilder/surf\_spot\_8um}

\label{fig:3d\_spot\_sub8}

}

\caption{3D Beam Power }

\end{figure}

### \subsection{Modeling the Fiber-to-Chip-Interface}

%fiber2chip\_modelings

At the beginning of this chapter the waveguide will be approximate with a rectangular waveguide. We place the waveguide at the distance of $4\mu$m in front of the TLF. Fig. \ref{fig:coupling\_e\_field} from the simulation of this configuration shows that the E-Field spreads more widely at the interface of the waveguide than that in the case without the waveguide. Apparently, a great part of E-Field penetrates into the waveguide rather than accepted by guide. Thus by checking the S-parameter of this simulation Fig.\ref{fig:orignial\_coupling\_efficiency}, which present the |$S\_{21}$| in frequency domain, the coupling efficiency (|$S\_{21}$|) is about $48.8\%$ at the working frequency $282$Hz ($\lambda=1064$nm). This result will act as the reference sample for thefollowing simulations.\\

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7 \textwidth]{bilder/cst\_basic\_waveguide\_efield}

\label{fig:coupling\_e\_field}

\caption{E-Field distribution in logarithm value for the Fiber-to-Chip-Interface.}

\end{figure}

Furthermore we can analyze the power distribution in this arrangement by executing the integral operation of power flow density over the cross-section of the waveguide (see Appendix. \ref{app:powwer\_distribution}). In the Fig. \ref{fig:power\_distribution} it can be found that about $40\%$ of the power propagates in the guide while another $40\%$ in the substrate and the rest is losing in the air or reflecting.

\begin{figure}

\centering

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

\caption{Coupling efficiency in Frequency domain.}

\label{fig:orignial\_coupling\_efficiency}

\end{figure}

\begin{figure}[!ht]

\centering

\includegraphics[width=0.7\textwidth]{bilder/power\_distribution1}

\caption{power distribution along the waveguide.}

\label{fig:power\_distribution}

\end{figure}

