Design and Simulation of Optical Interfaces for Photonic Integrated System-in-Package

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Contents

- Motivation
- Photonics Interconnection Layer for Converged Microsystems using System-in-Package (PICSiP)
- Optical interfaces
    - Optical nanowaveguide
    - Coupling to fiber
- Summary

Motivation

Biometrics

FTTx

USB 4.0

Phased array receiver systems for astronomy

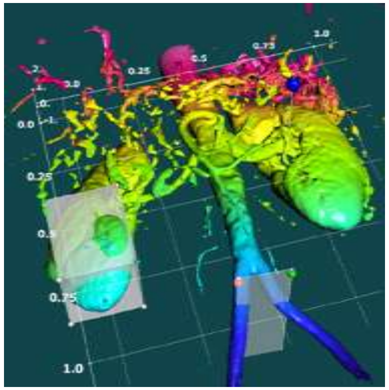
3D imaging

Microwave systems

Supercomputer

Multi-core processor

4D medical diagnostic



Real-time medical visualization

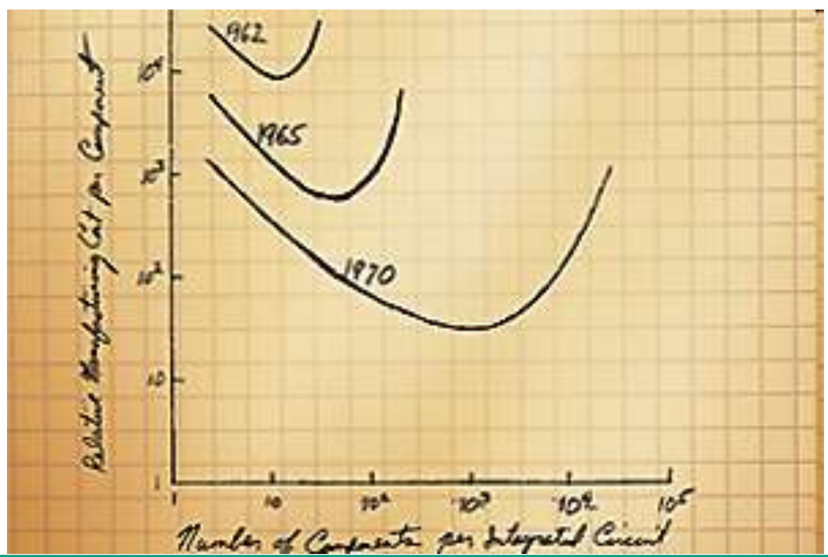
RF-over-fiber

Micro projector

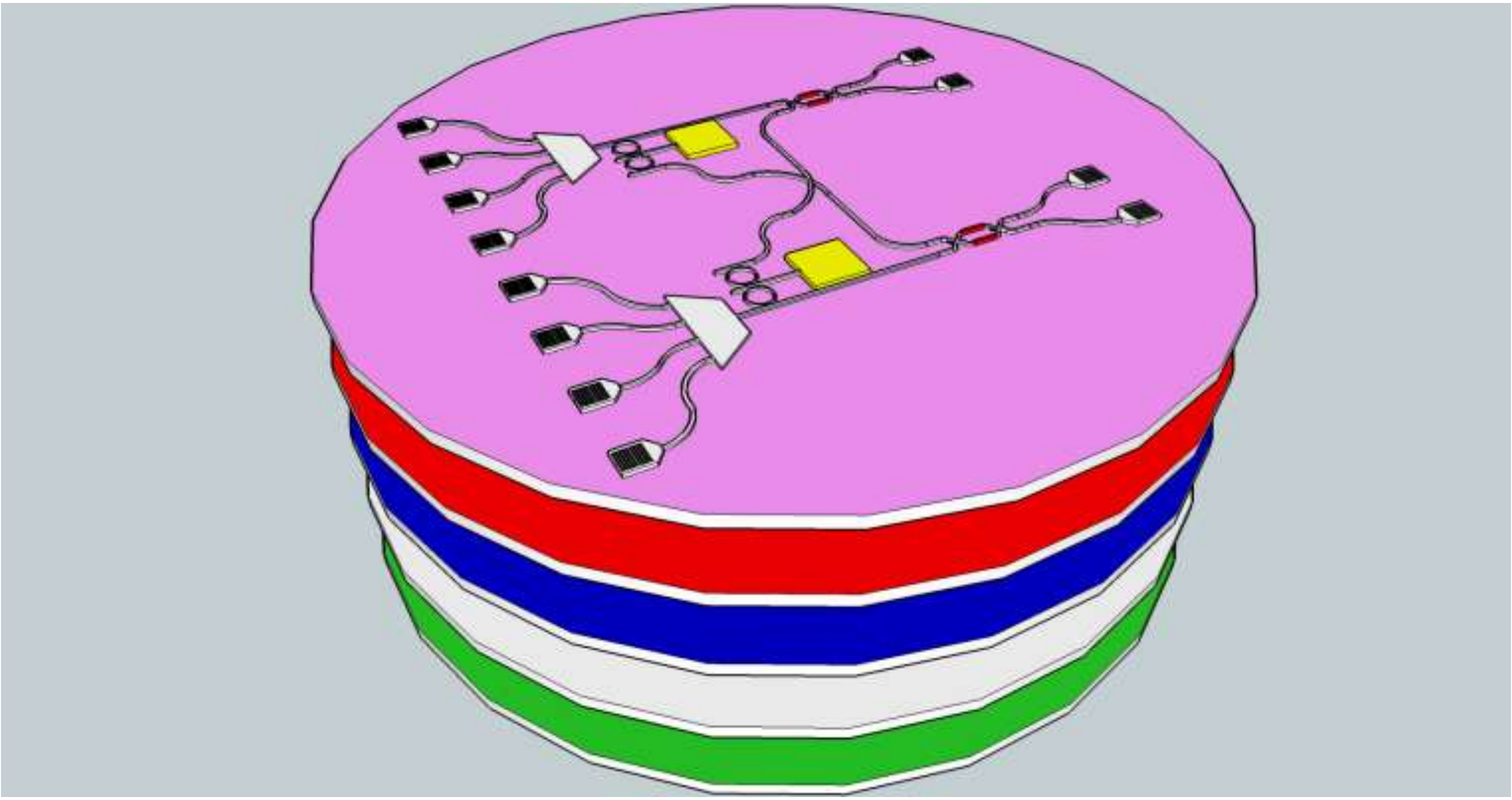
Motivation

- Integrated chips are required to provide better performance, less power consumption, smaller footprint and reduced cost.
- CMOS scaling is not enough to achieve these requirements, since the semiconductor technology is approaching its physical limitations.
- “More than Moore” will be required.

Gordon Moore



3D Integration



System-in-Package

- The main goal of System-in-Package (SiP) is to integrate many different components (e.g. passives, MEMS or optical components) into a single package.
- Key bottleneck to realization of high performance microsystems, including SiP is the lack of off-chip interconnects with:
  - Low latency
  - High bandwidth
  - High density

Silicon Photonics

Photonics to overcome the limitations of electrical interconnects and leverage optical communication

The objective is to develop a CMOS compatible underlying technology to enable next generation photonic layer within the 3D SiP towards converged microsystems

Photonics Interconnection Layer for Converged Microsystems using System-in-Package Technology (PICSiP)

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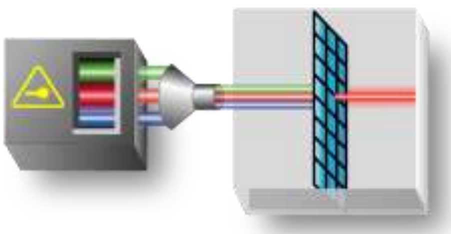
Merging of Silicon Electronics and Photonics

BUILDING BLOCKS OF SILICON PHOTONICS by Intel

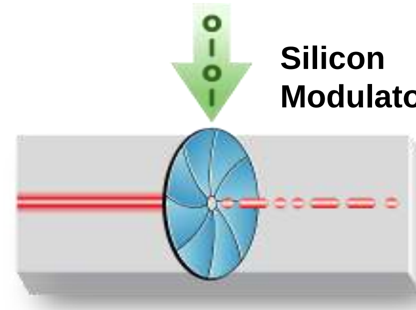
1) Light Source

External Cavity Laser
Light Source



2) Guide Light

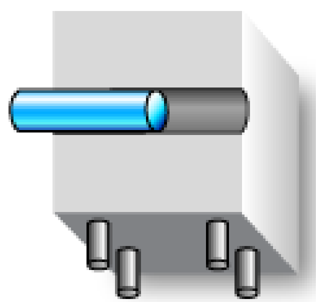
3) Fast Modulation



4) Detect Light

Photo-Detector

5) Low Cost Assembly



6) Intelligence

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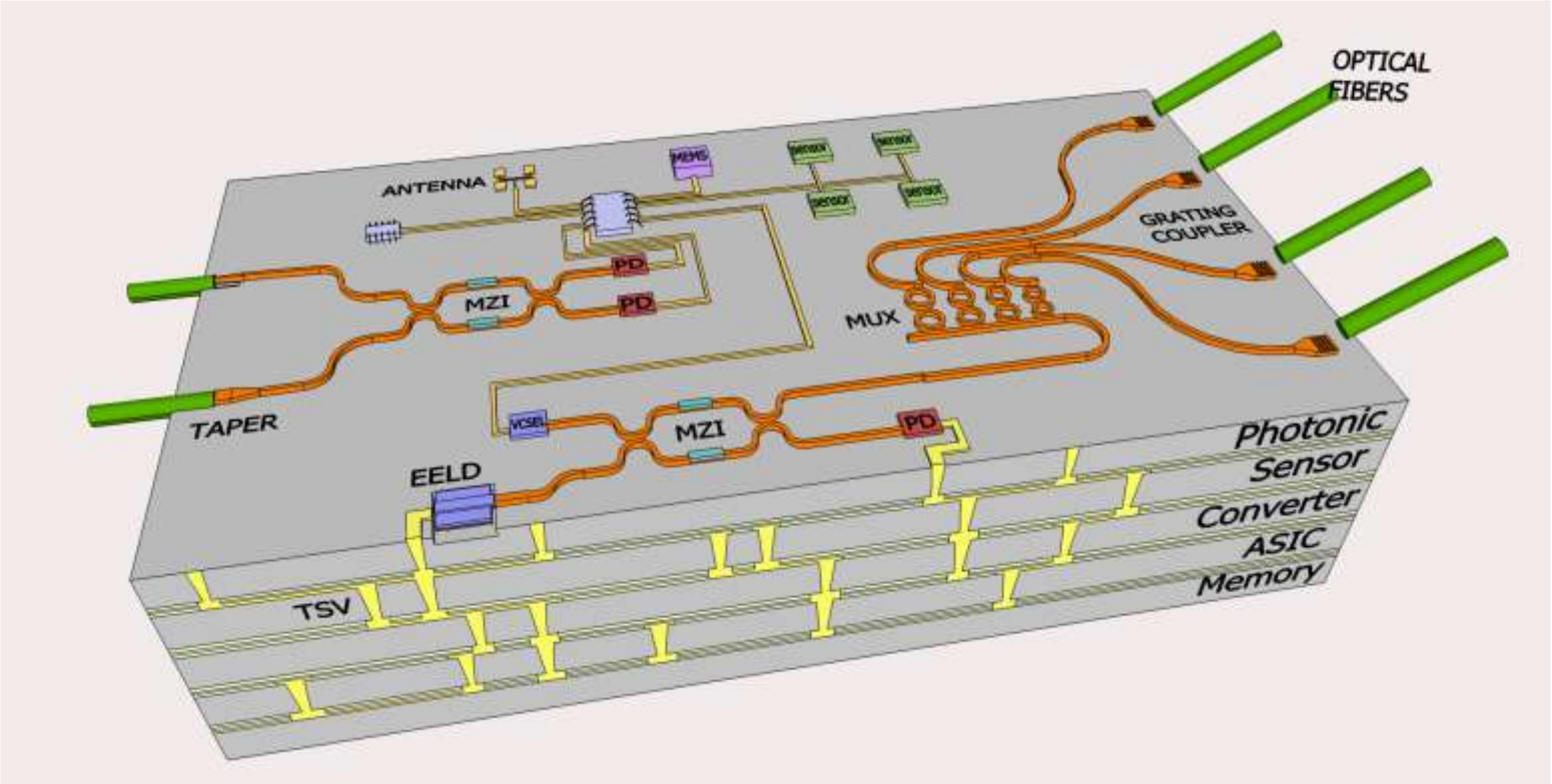
Photonics Interconnection Layer for Converged Microsystems using System-in-Package (PICSiP)

- The PICSiP aims to provide a generic platform for further development independent from the application rather than addressing product related applications



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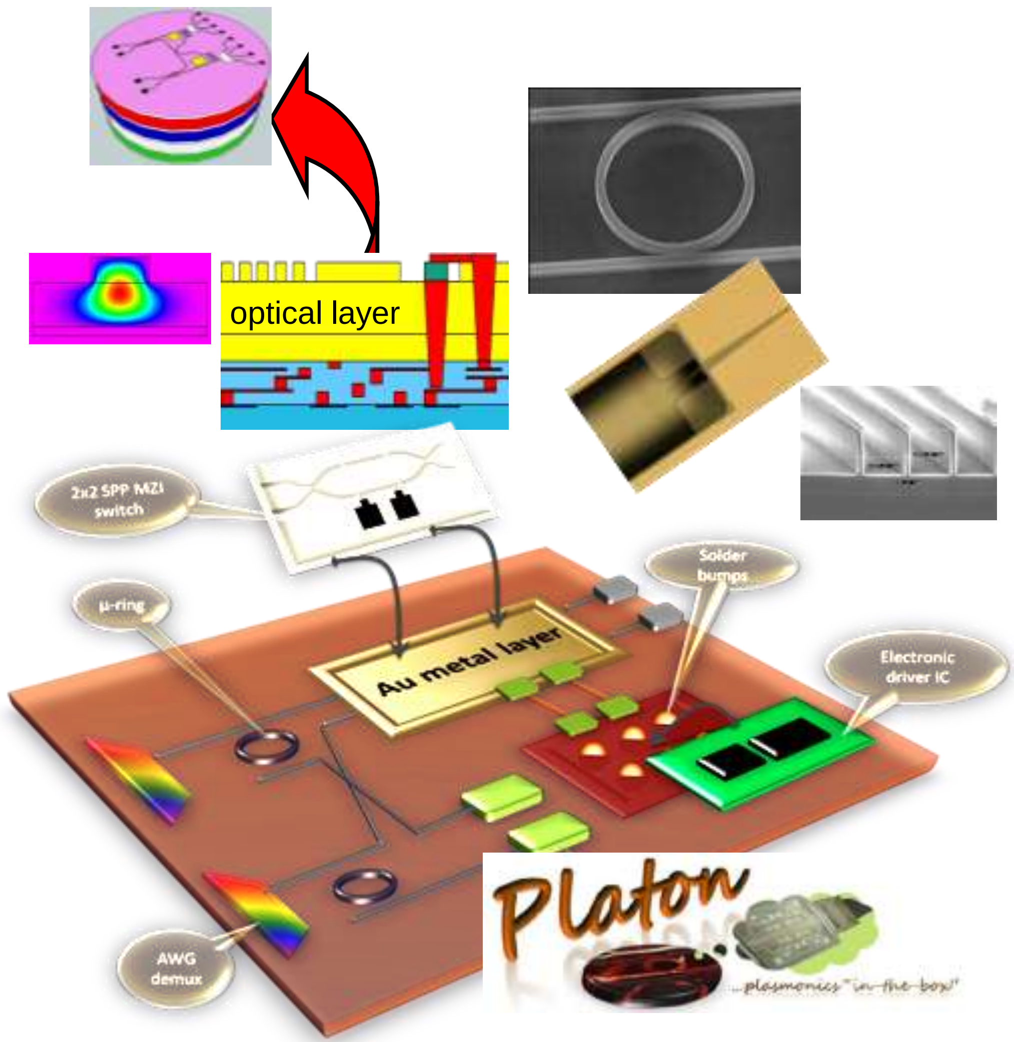
3D Silicon Photonics Heterogeneous Integration



- Redefine the system and application requirements.
- Materials and process models for on-chip/off-chip optoelectronic elements, coupling between electrical and optical systems, optical interconnect models, semiconductor laser modeling.
- Simultaneously consider digital, analog, RF and micro-electro-mechanical systems (MEMS) and optical components
- CMOS compatible design.

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Toolbox for PICSiP

Optical

Optical waveguides

Coupling to fiber

3dB splitter

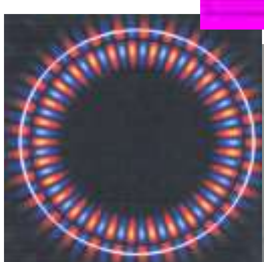
Ring Resonators

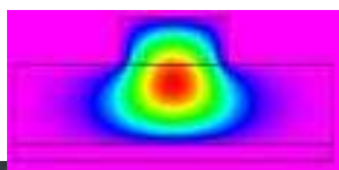
MUX/DEMUX

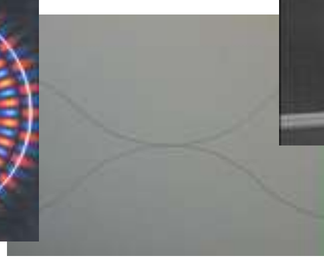
Switches

MZI

…

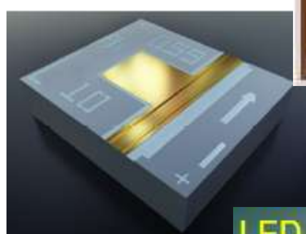


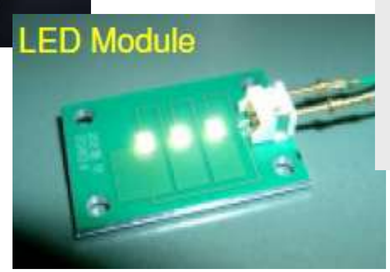




Electro-optical

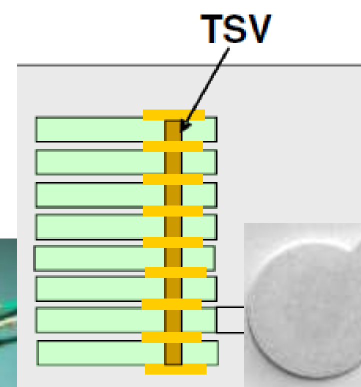
Photodetectors
Light sources: LED, VCSEL…
…

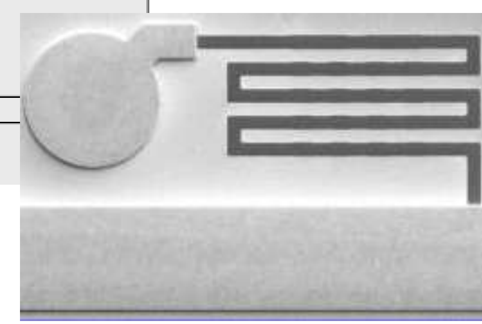




Electrical

Through-Silicon Vias (TSV)
Transmission line: CPW, slotline…
Antenna
Heater
…





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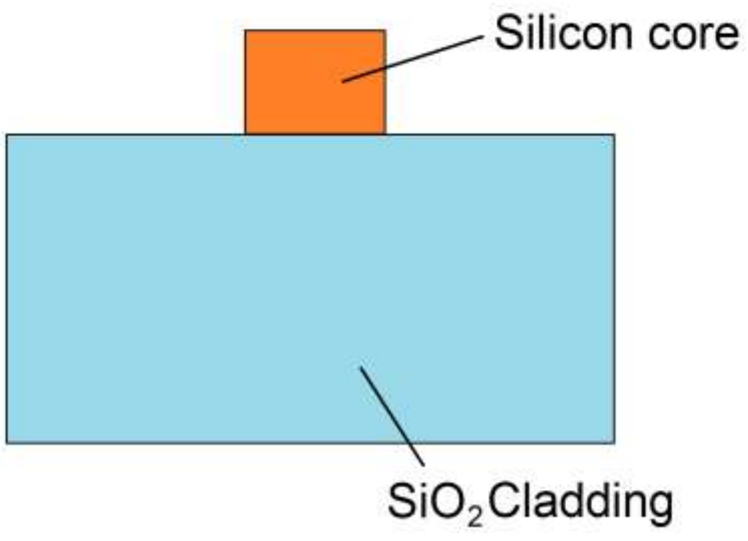
Silicon nano waveguide

- The optical interconnects are implemented by silicon nano waveguides consisting of a silicon core on top of a SiO_2 cladding.



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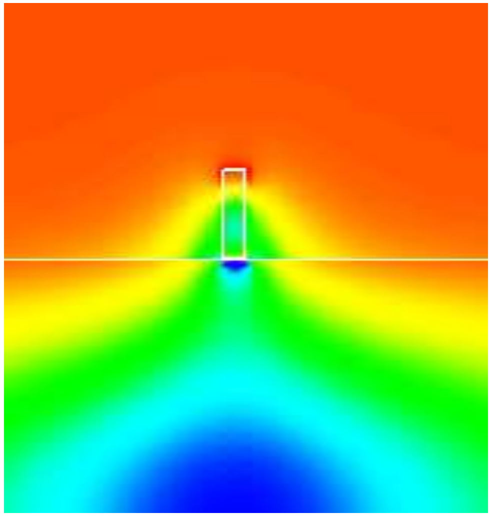
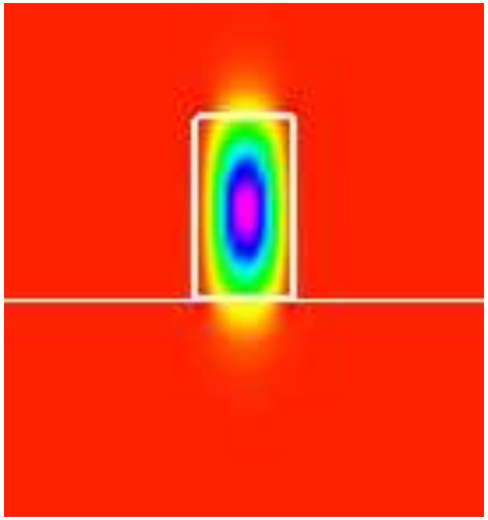
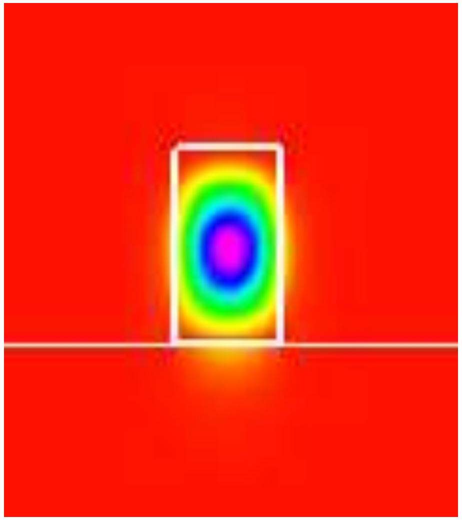
Propagation profile

- This structure provides high light confinement.
- A single mode behaviour can be achieved for core widths around 400 nm.

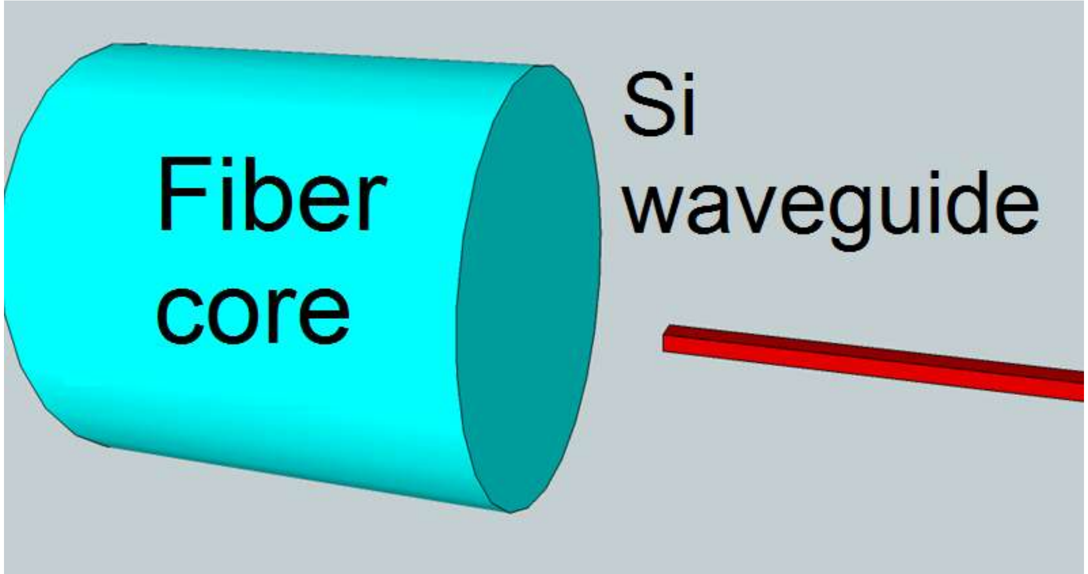




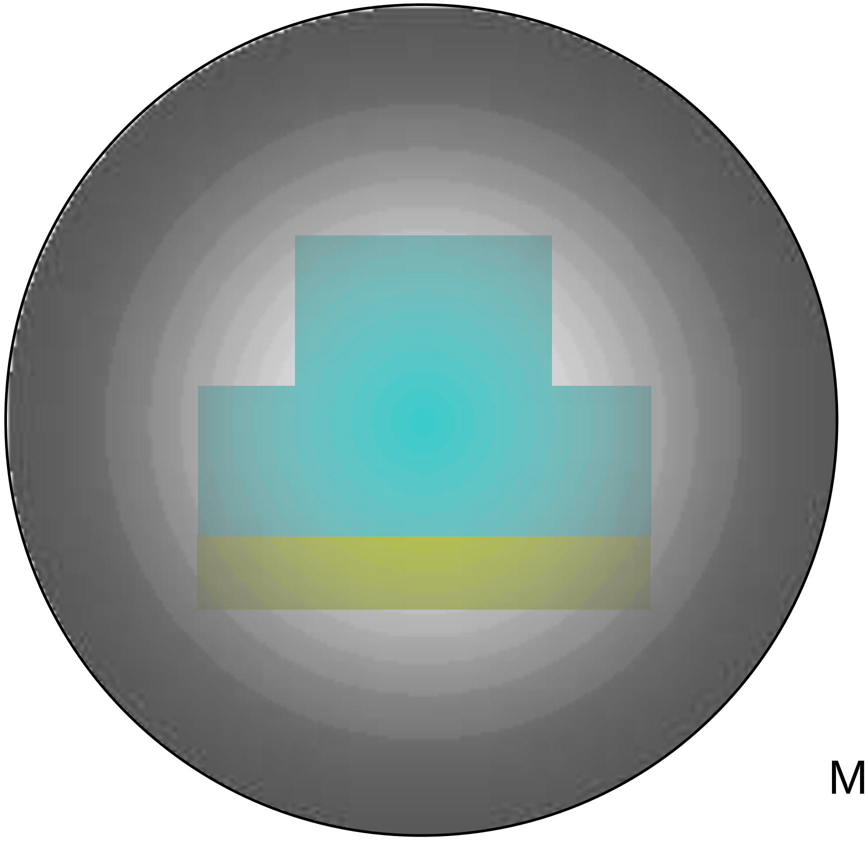


Coupling to fiber

- Dimension mismatch between silicon waveguides and single mode optical fibers



Endfire coupling to 4 µm rib waveguide



Best case:
~3 dB loss

SMF28
Modedistribution

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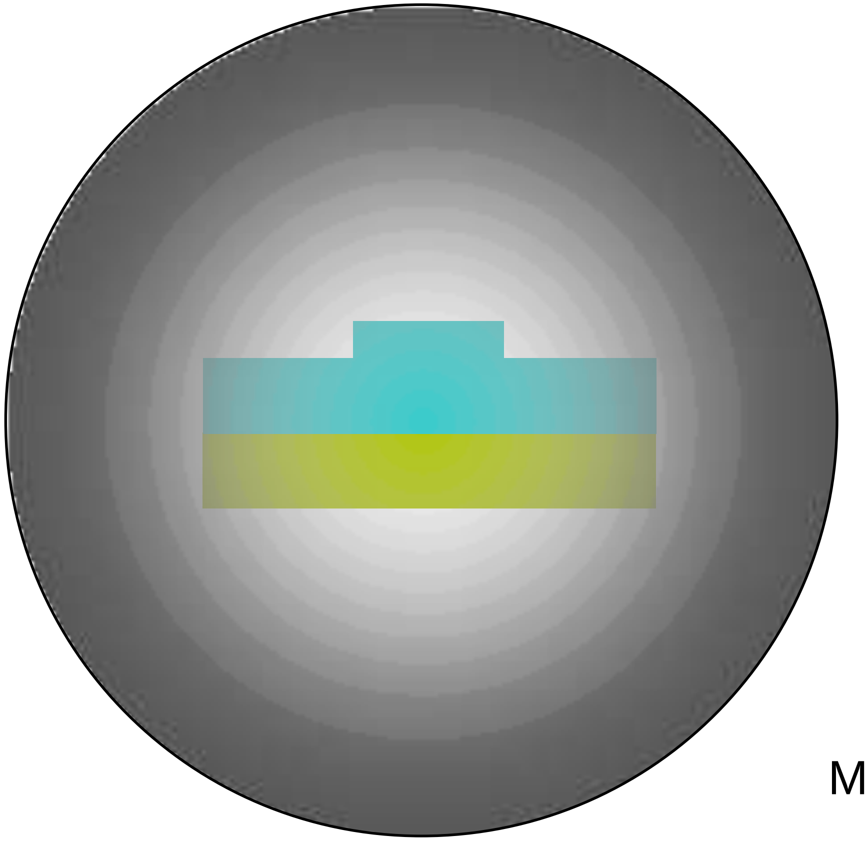
Endfire coupling to 1.5 µm rib waveguide



Best case:
~12 dB loss

SMF28
Modedistribution

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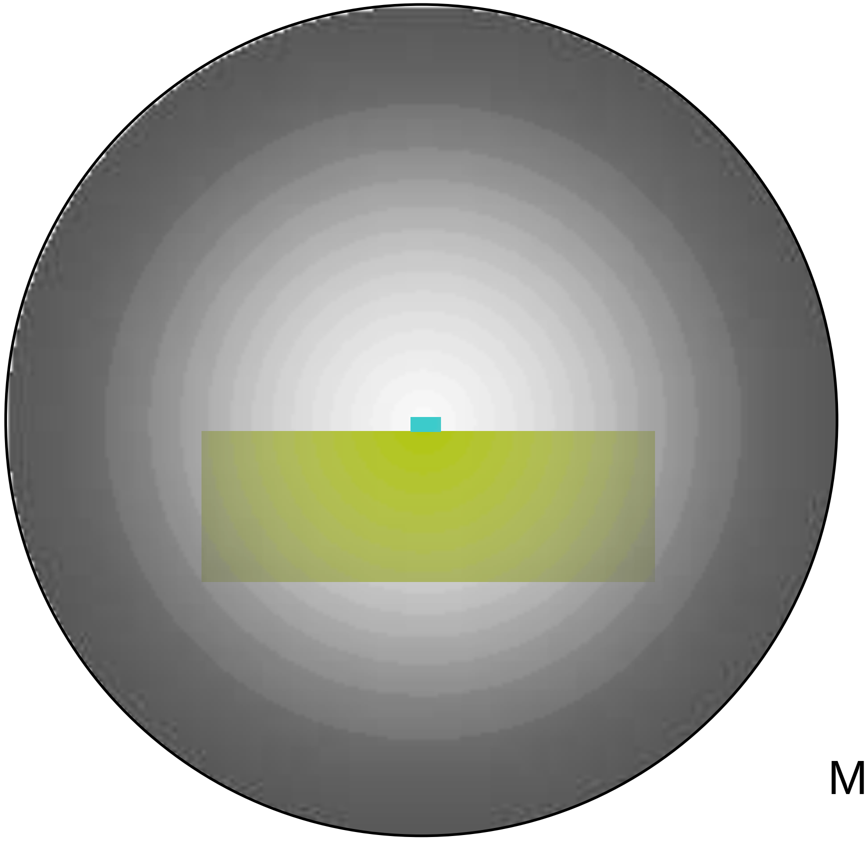
Endfire coupling to 0.2 µm nano waveguide



Best case:
~20 dB loss

SMF28
Modedistribution

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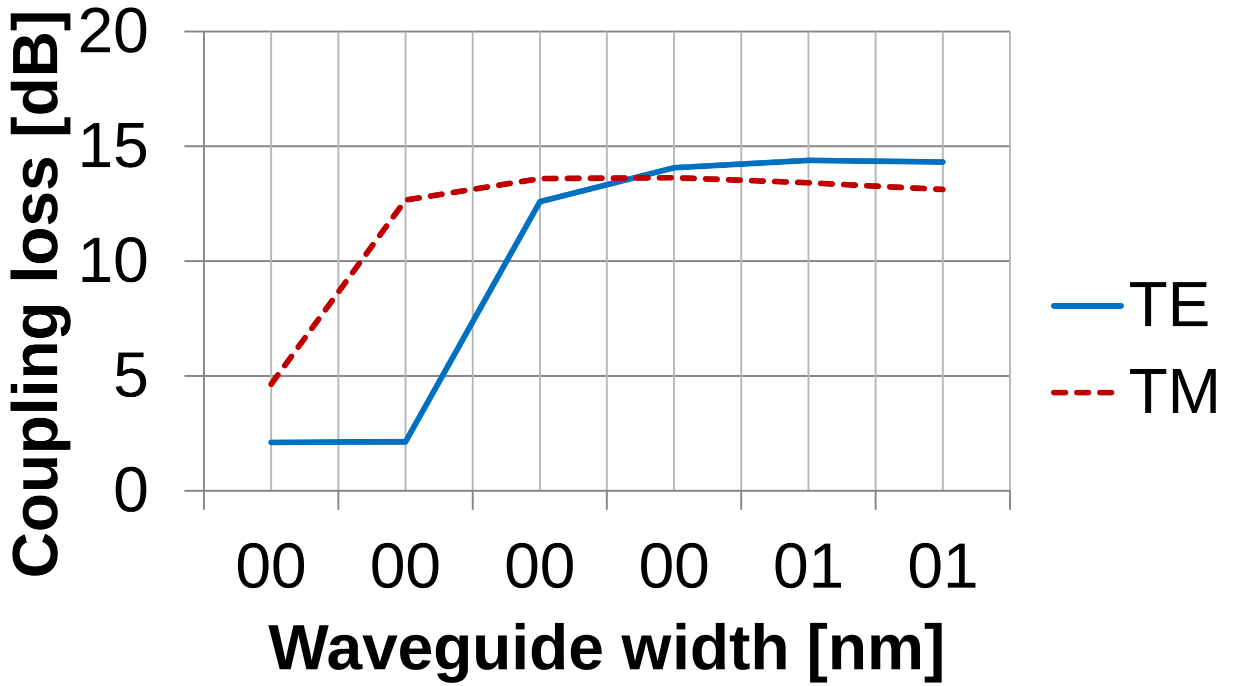
Butt coupling losses

- Direct butt coupling between the waveguides and optical fibers provide high losses, around 14 dB.
- These losses have been calculated with an overlap integral.



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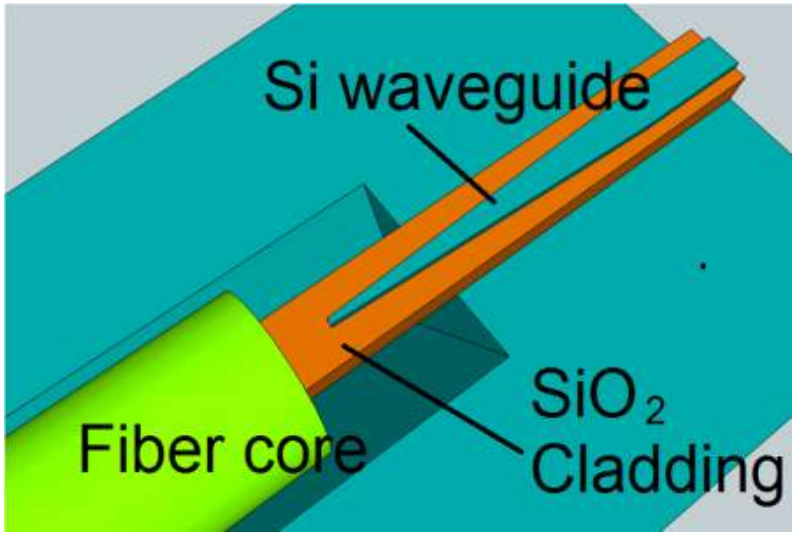
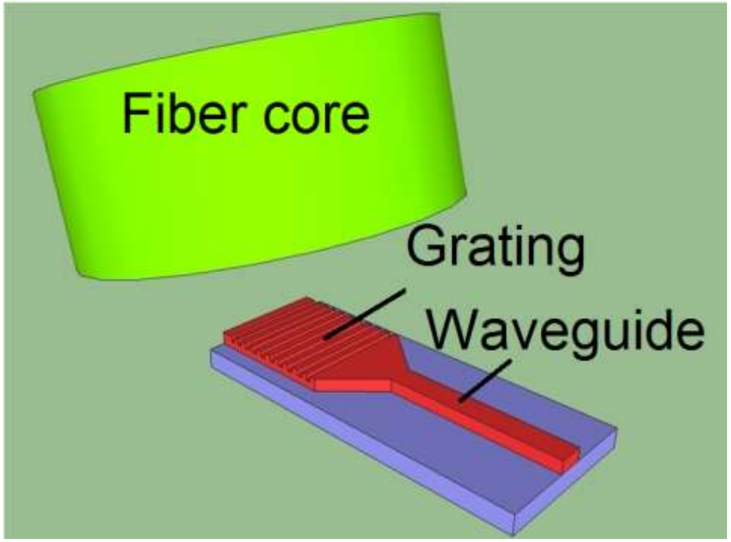
Solutions to the coupling problem

- Two solutions are used:
  - In-plane coupling by means of an inverted taper.
  - Out-of-plane coupling by means of a grating coupler.





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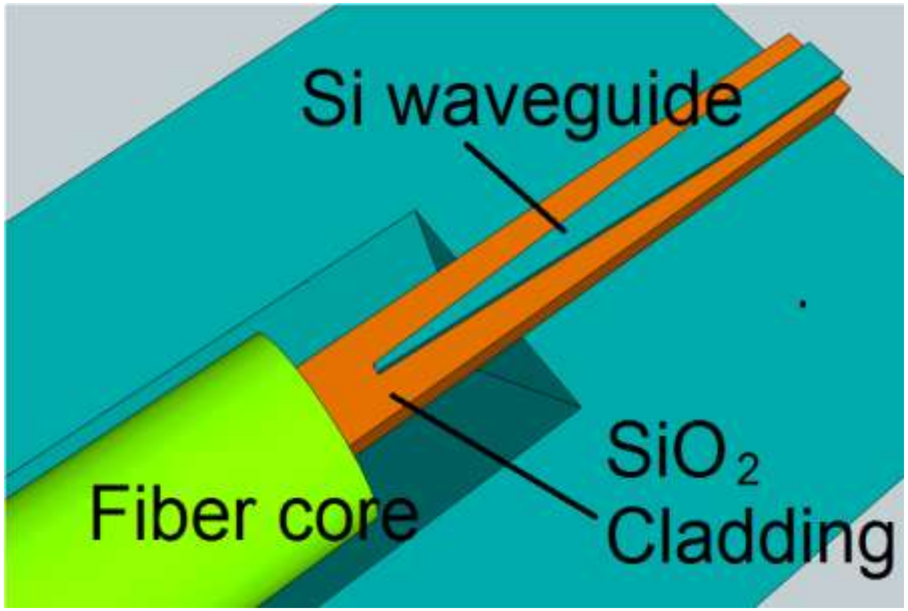
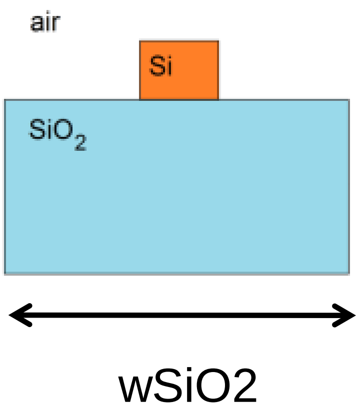
In-plane coupling to fiber

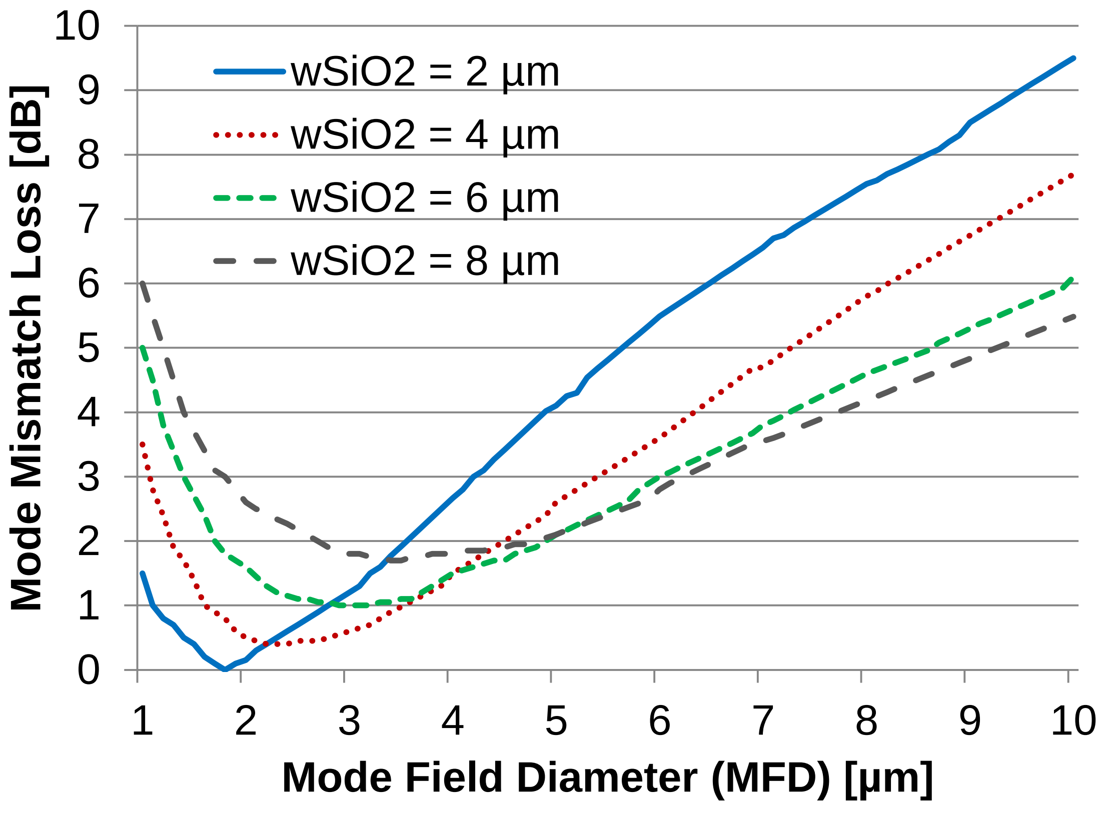
- The silicon core is tapered and the fiber is coupled to the silicon dioxide cladding to perform the coupling.
- The following parameters have been optimised:
  - Width of SiO_2 waveguide (w_{SiO2}),
  - Inverted taper tip width (w_{tip}),
  - Inverted taper length (L_{taper}).



SiO_2 Waveguide design

- The fiber is coupled directly to the BOX layer. There is a width of these layer for which the coupling losses are minimal.





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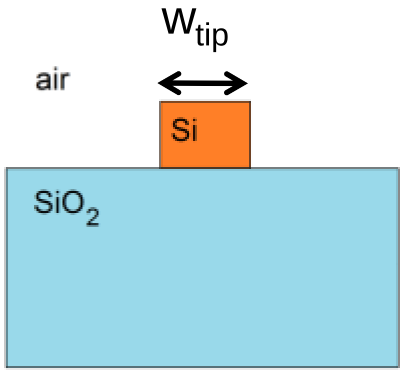
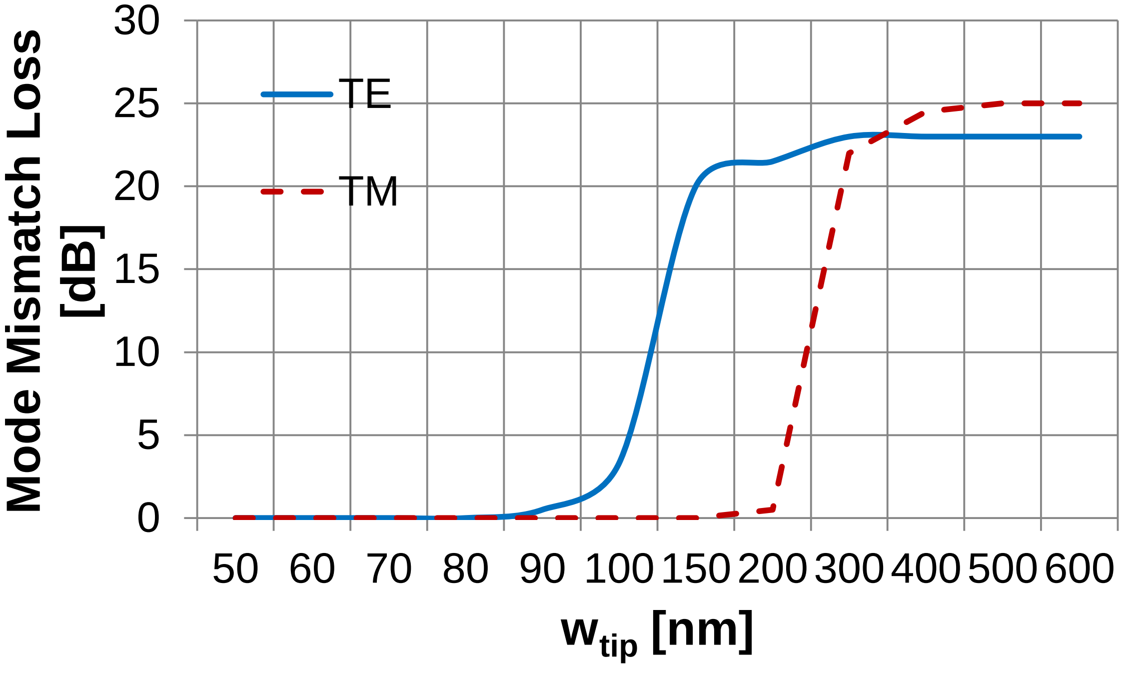
Tip width design

- The mode mismatch loss is calculated between the modes in the SiO_2 waveguide with and without the Si waveguide on top, for different core widths.





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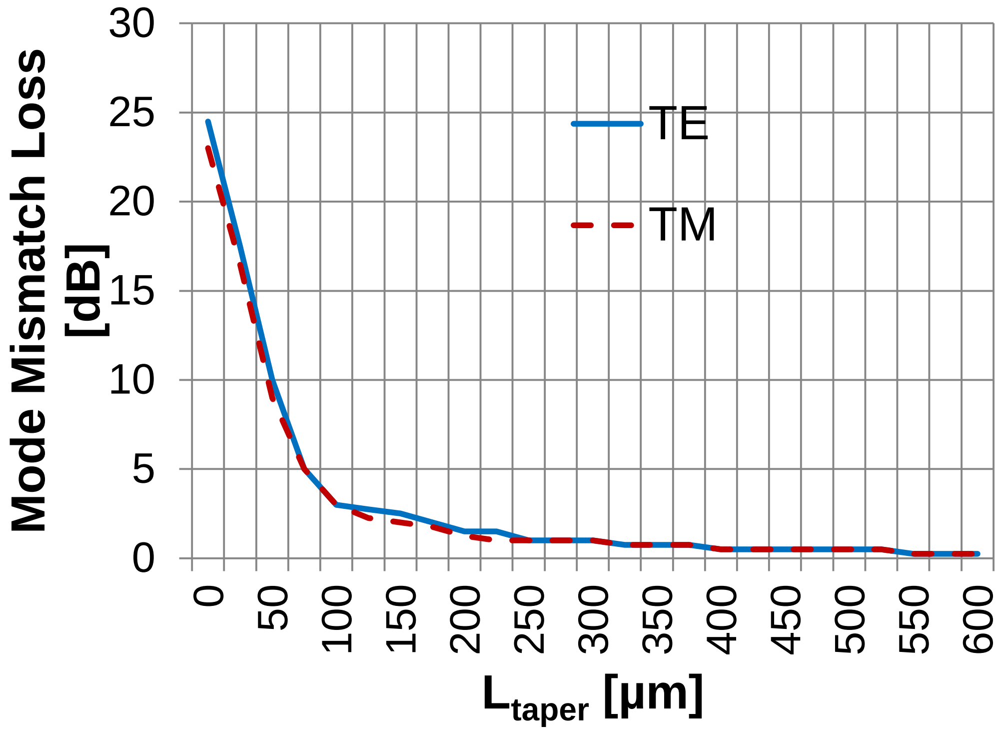
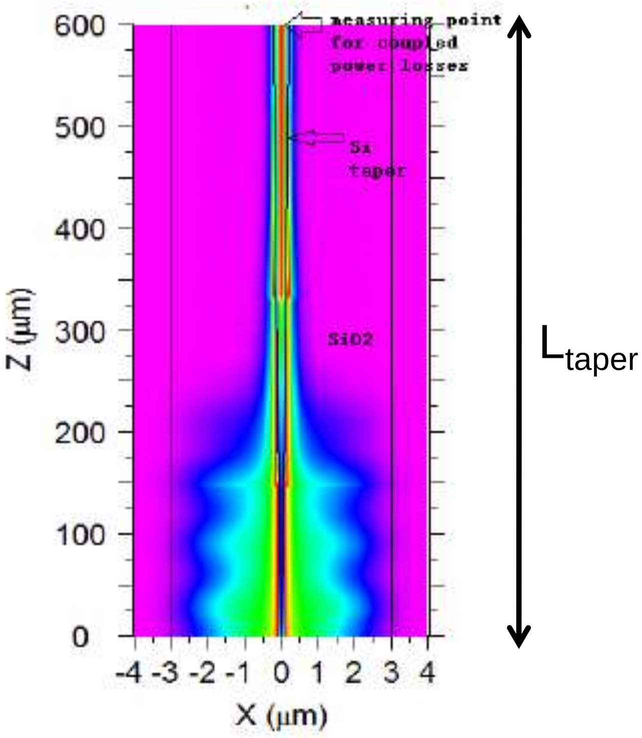
Inverted taper length design

- The coupling losses decrease as the inverted taper gets longer.





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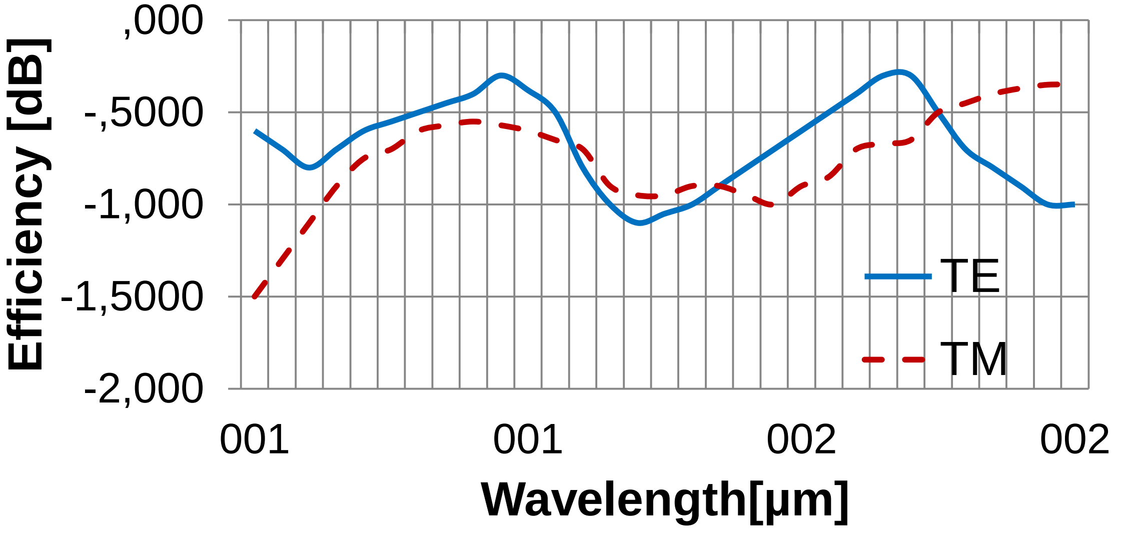
Spectral analysis

- The spectral response is obtained once the design parameters are optimized.
- The structure is polarisation insensitive at the wavelength of interest

(λ = 1550 nm).



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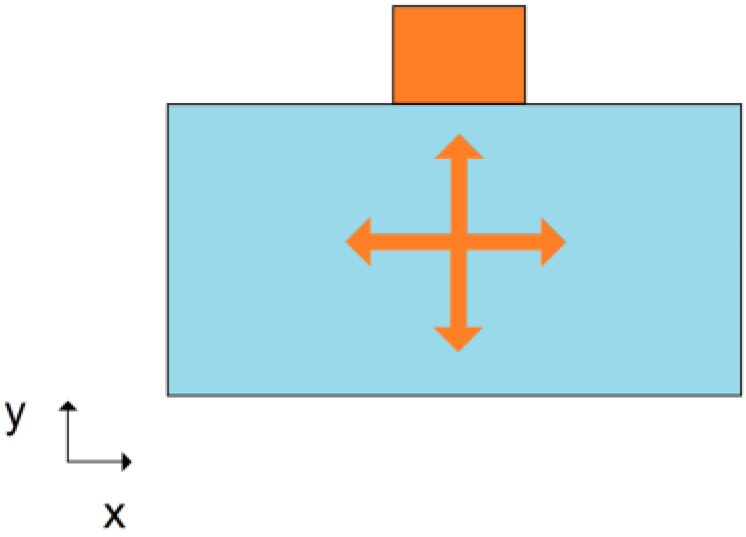
Alignment tolerances analysis

- For misalignments smaller than 0.5 µm in both x and y directions, the effect of misalignment is negligible.



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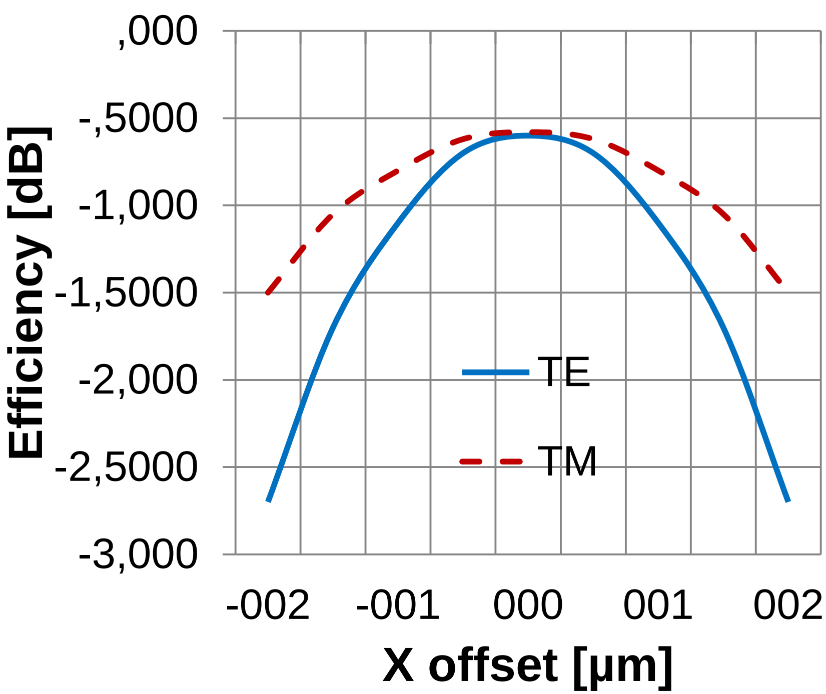
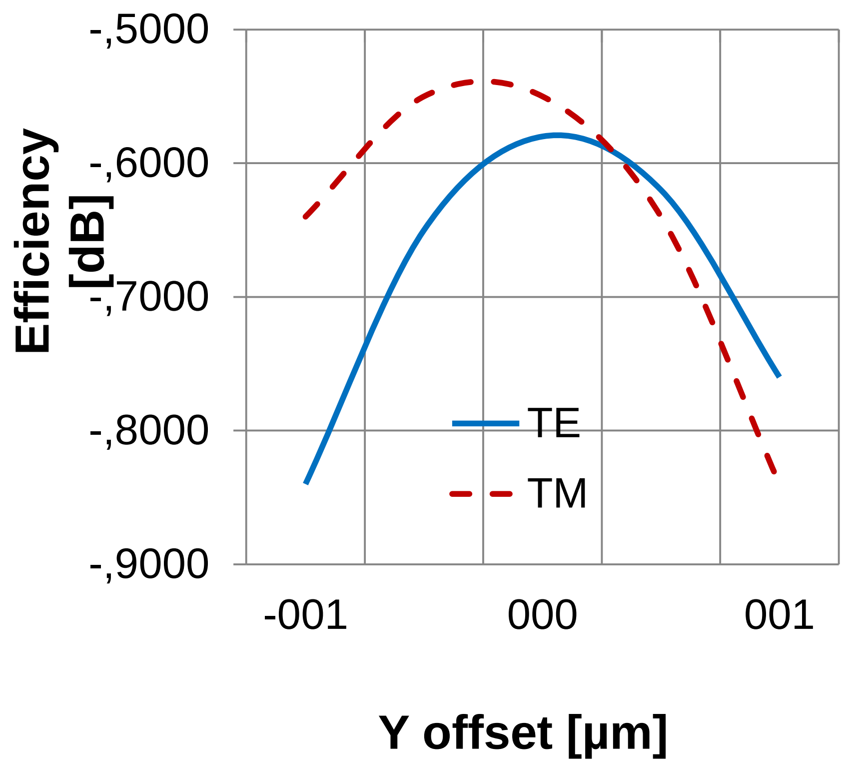
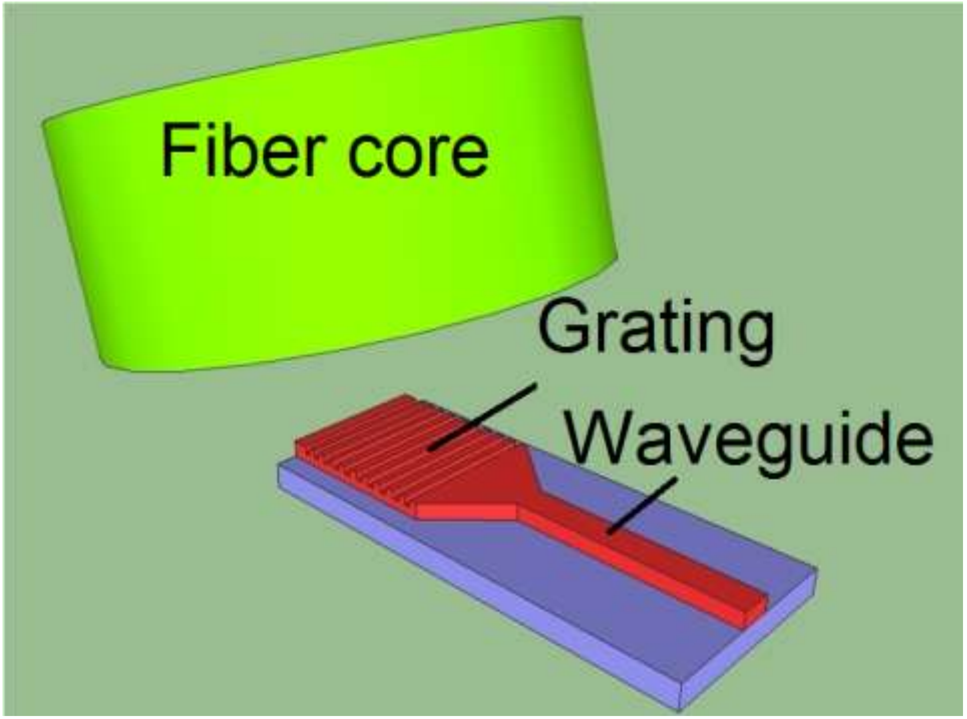
Alignment tolerances analysis



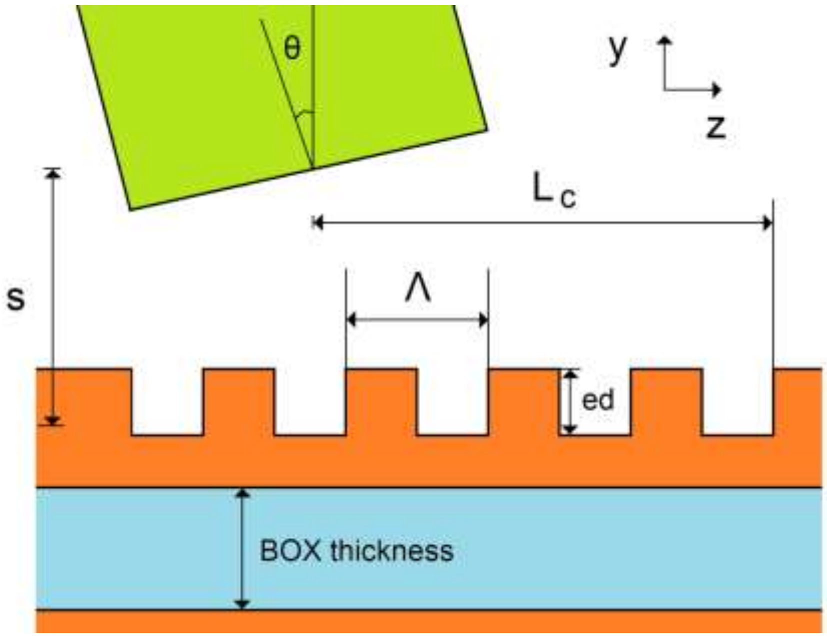


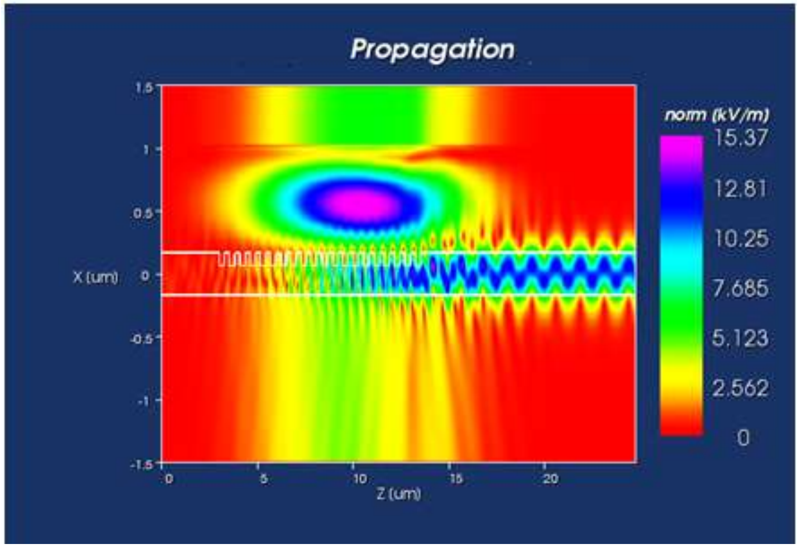
Out-of-plane coupling

- The coupling is performed on a corrugated surface on top of the waveguide.
- The performance of the structure will be studied for a variation in the following parameters:
  - Etching depth (ed),
  - Grating period (Λ).



Grating coupler cross section

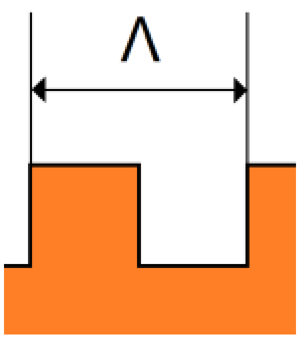


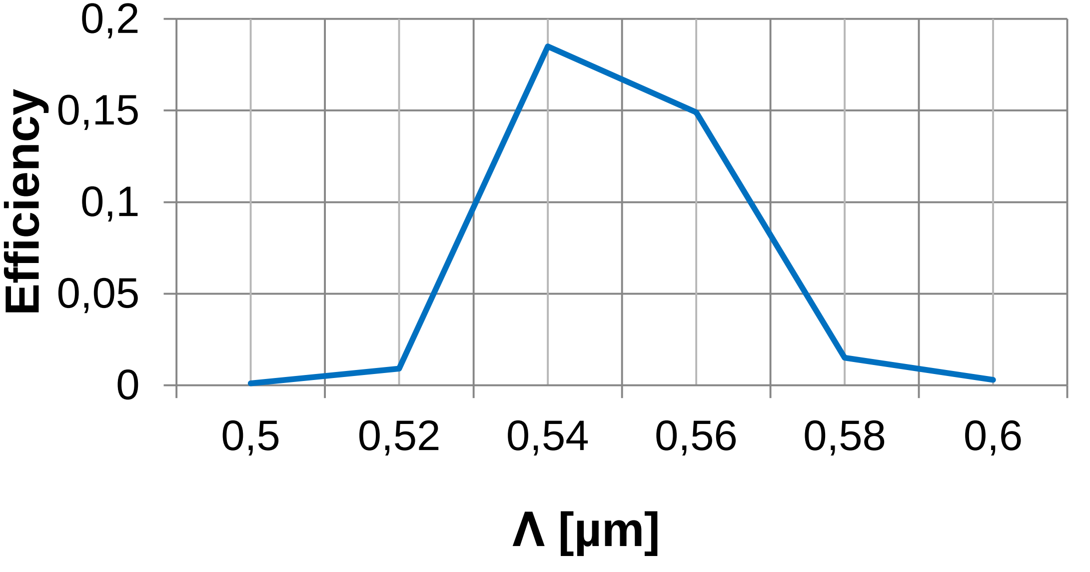


Grating period design

- The theoretical optimal grating period is: $$\Lambda_{theor} = \frac{\lambda_0}{n_{eff} - n_{top}\sin(\theta)}$$

- Values around this optimal are simulated to find the optimal period according to the simulation.





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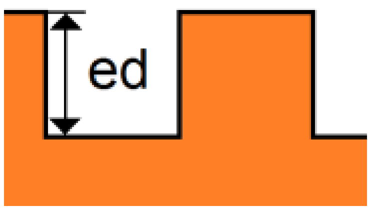
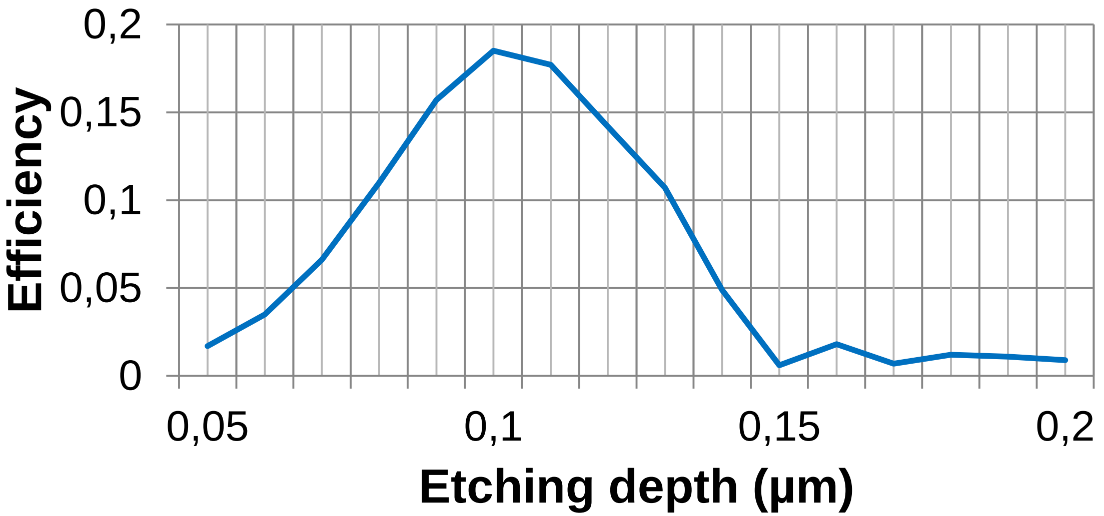
Etching depth design

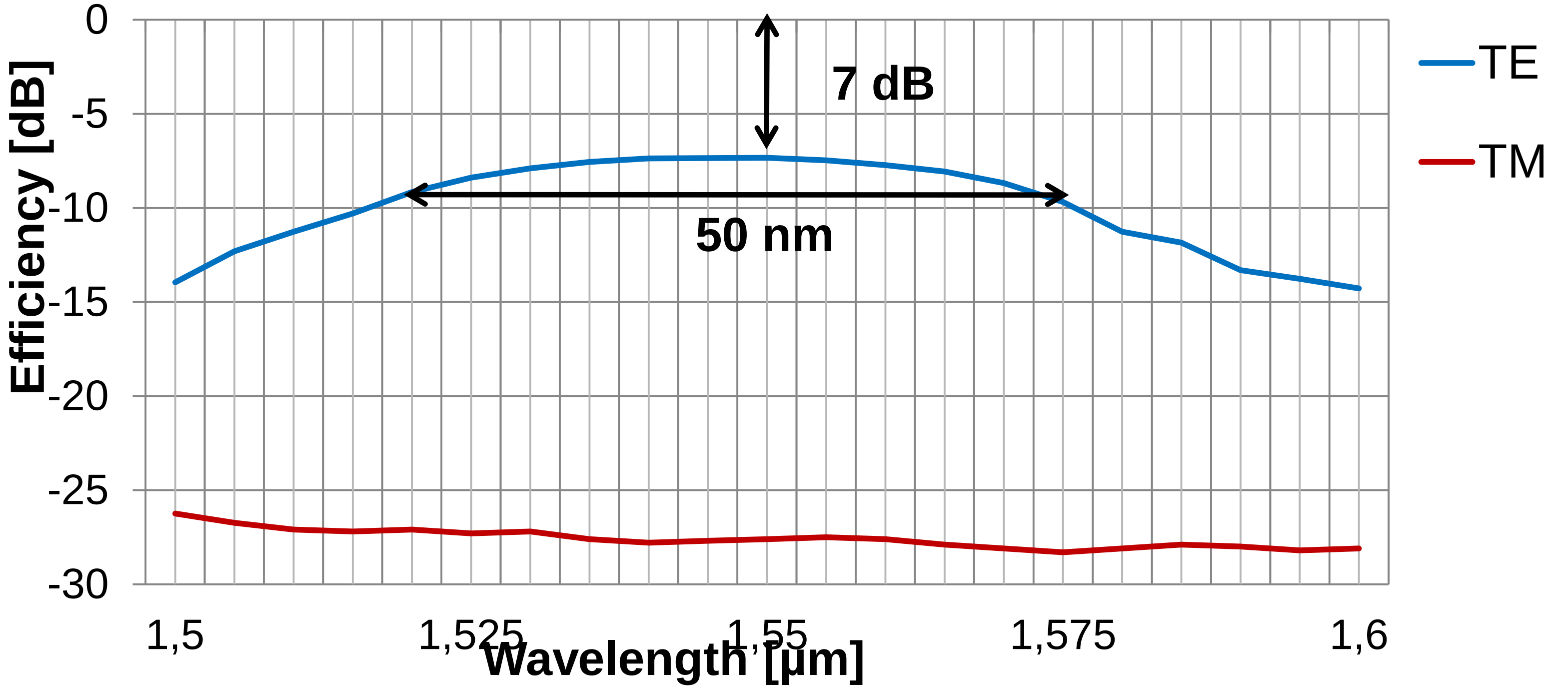
- Once the optimal period is found, the depth with which the grooves of the grating are etched is simulated to improve the coupling.





Spectral analysis

- The spectral response is found.
  - Losses at central frequency = 7 dB.
  - 3 dB bandwidth = 50 nm.
  - TE–TM extinction ratio = 20 dB.



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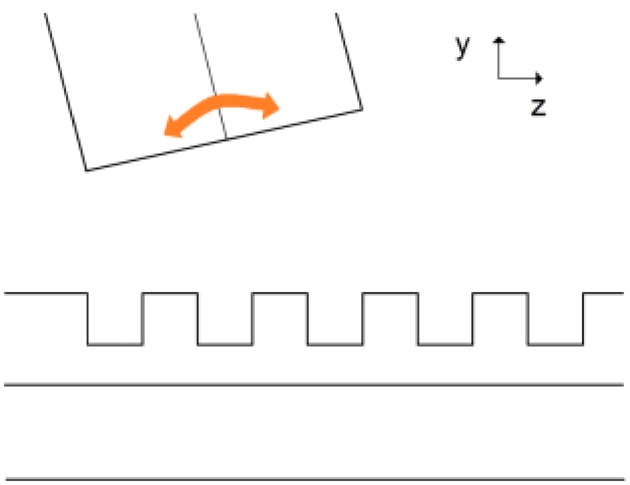
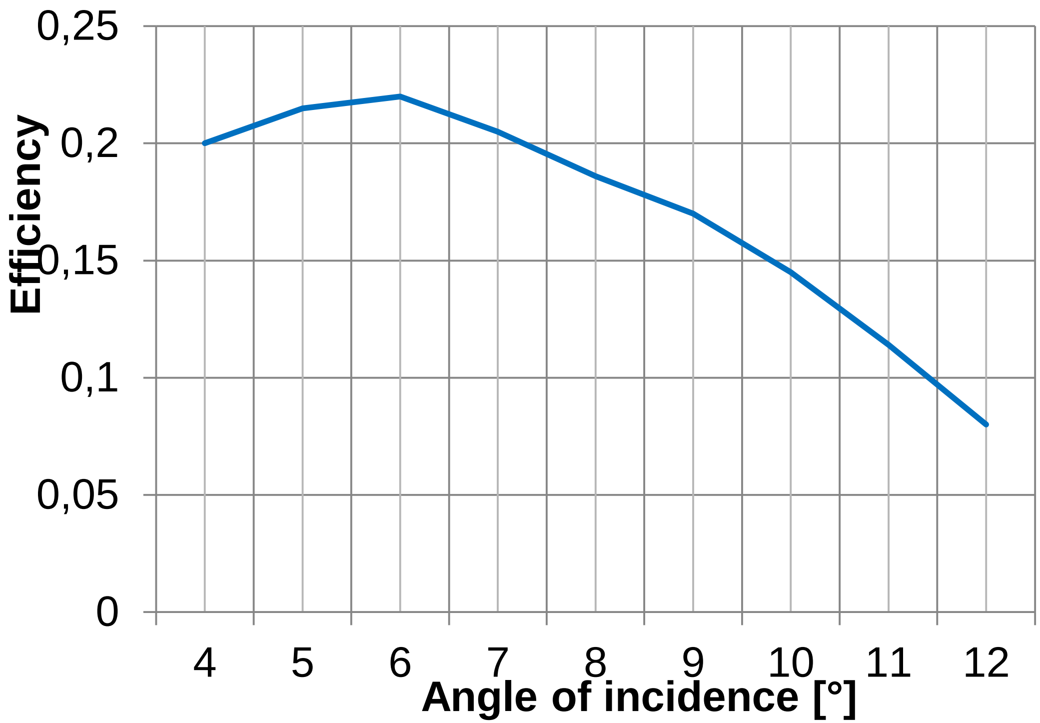
Alignment tolerances

- The variation of the angle that produces losses of 3 dB is ±3°.





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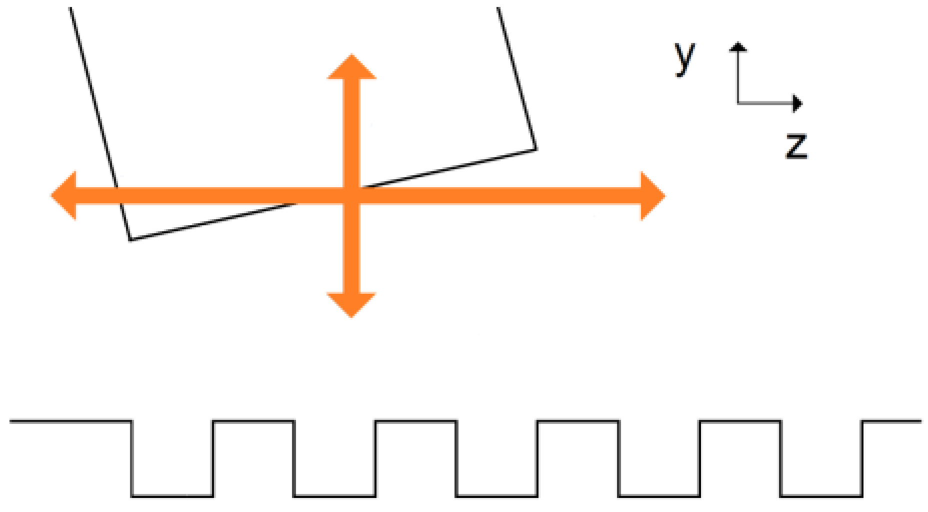
Alignment tolerances

- The structure is quite robust to misalignments in the position of the fiber in the vertical and horizontal direction.



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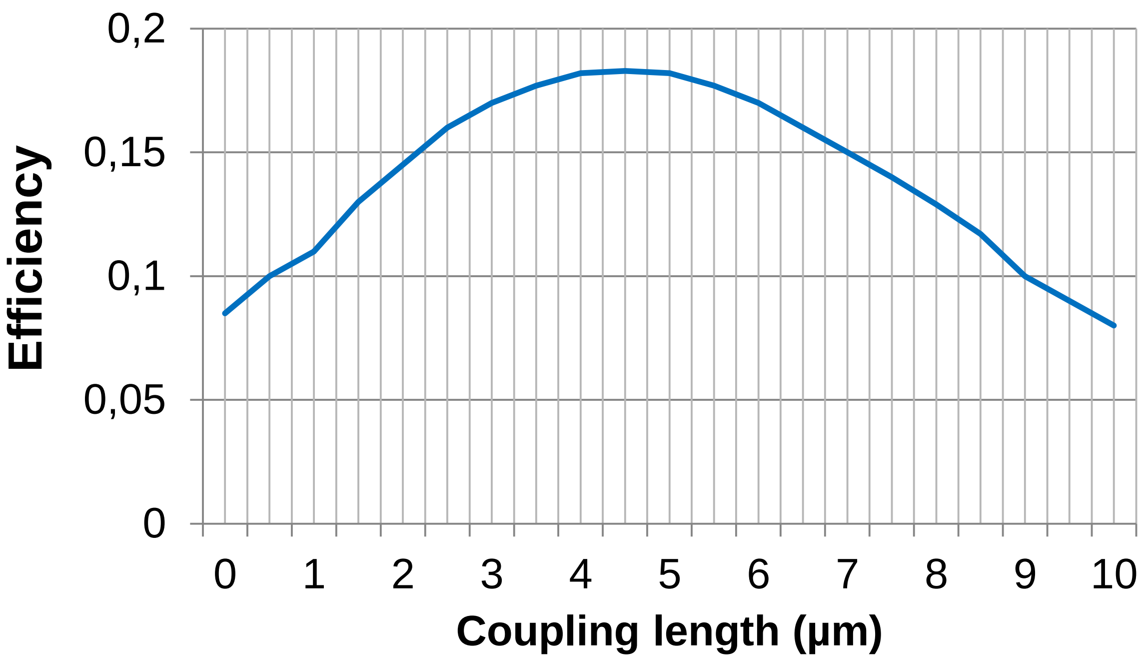
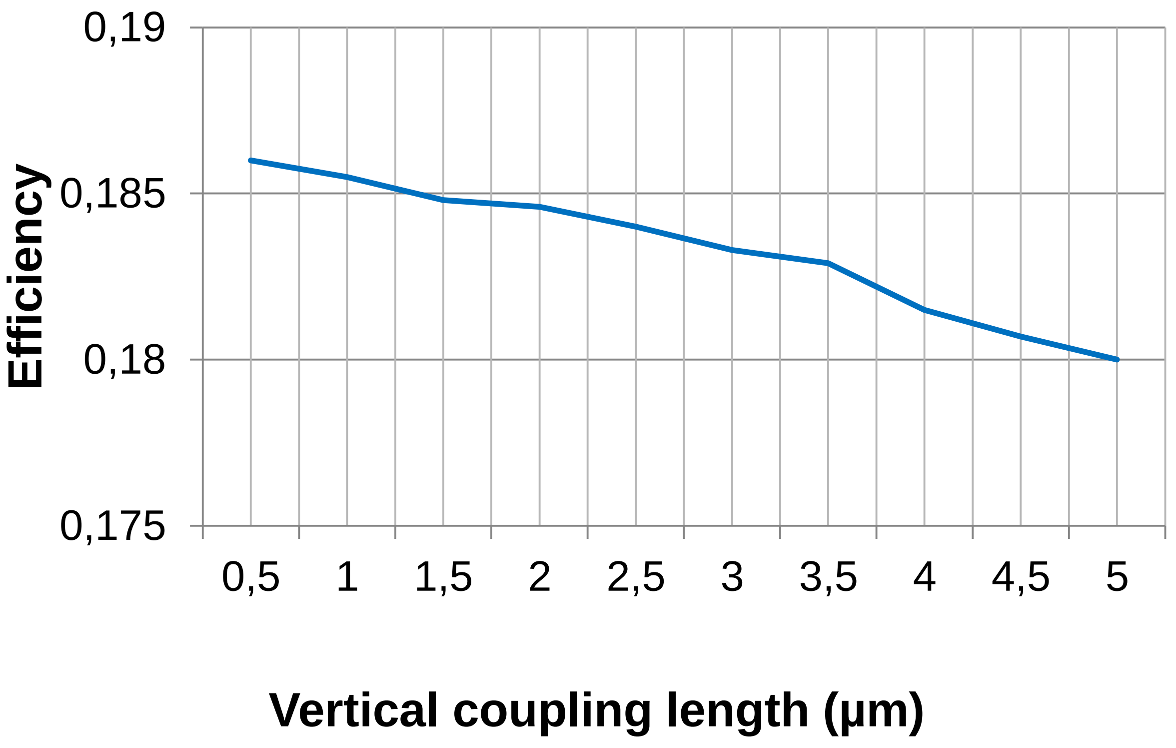
Alignment tolerances

- The optimal coupling length in the horizontal direction is: $$L_{c,opt} = \frac{w_0}{1.37\cos(\theta)}$$



Alignment tolerances



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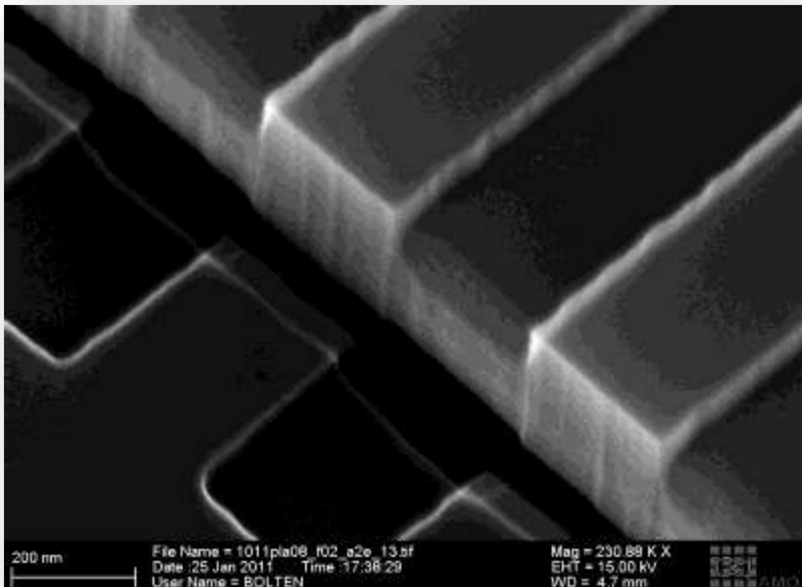
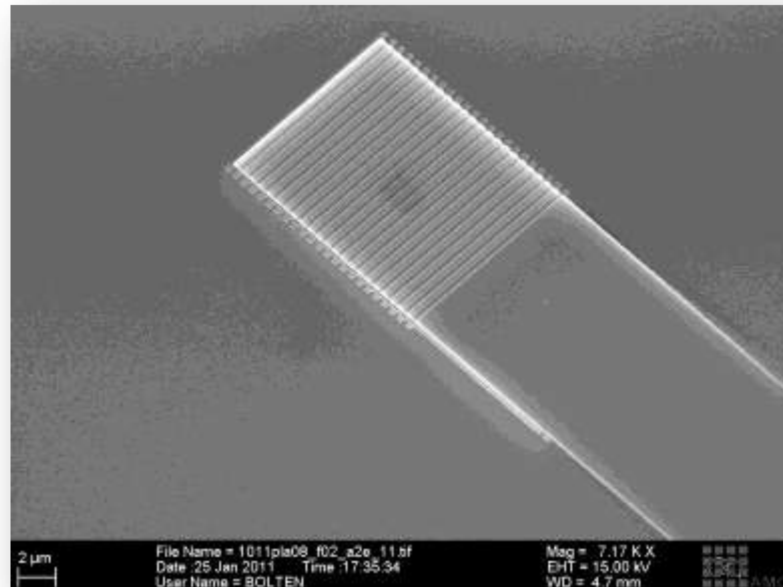
Fabricated structures





Design: IZM (Tekin, Gili, Suna)
Fabrication: AMO

Comparison Grating - Taper

Parameter	Inverted taper	Grating coupler
Coupling losses	Low (0.4 dB)	High (7 dB, can be improved)
Polarisation	Insensitive	Sensitive (can be solved)
Bandwidth	Broadband (300 nm)	Narrower (50 nm)
Sensitivity to fabrication errors	Low	High
Sensitivity to misalignments	High	Low
Facet reflections	High	Low
Coupling position	At the end of the chip	Anywhere on the chip
Fabrication	Complex	Easy

Summary

- Optical interconnects that overcome the main limitations of electrical interconnects have been presented.
- Optical nano waveguides present good theoretical performance in terms of light confinement and single mode propagation.
- Their coupling to fiber is solved by means of an inverted taper and a grating coupler.
- These optical interfaces offer encouraging perspectives for their integration in the PICSiP technology.

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