Enabling research: Silicon optics steady state magnetic field sensor

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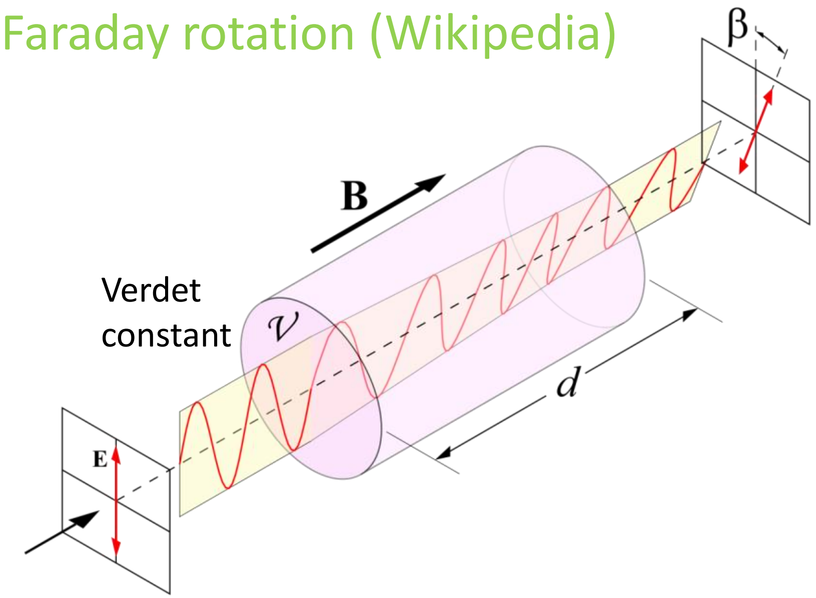
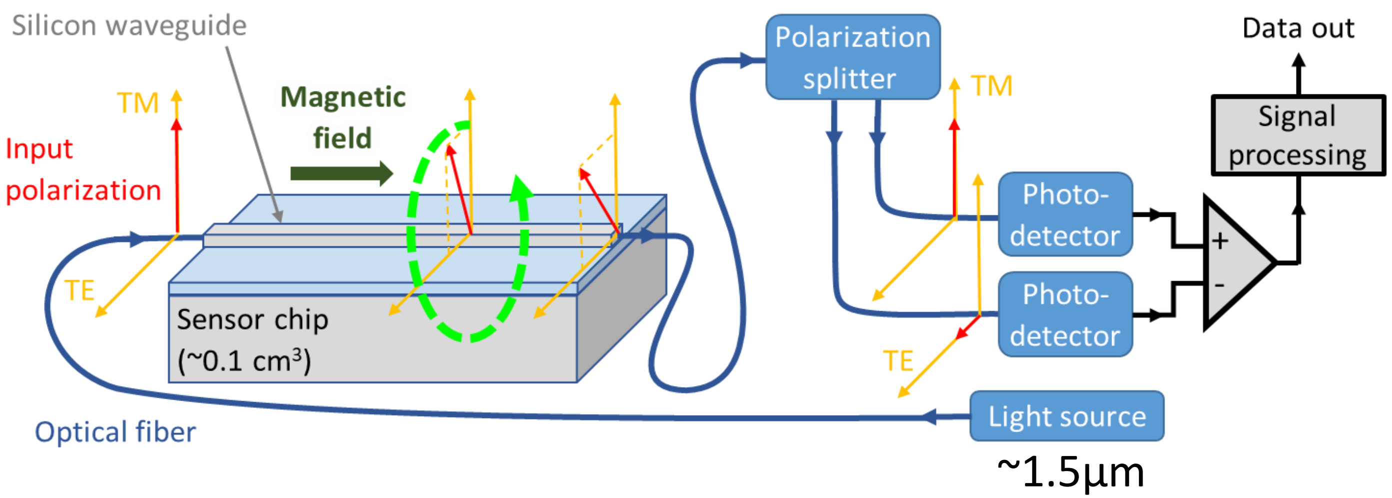
Measurement concept

VTT

Faraday rotation (Wikipedia)



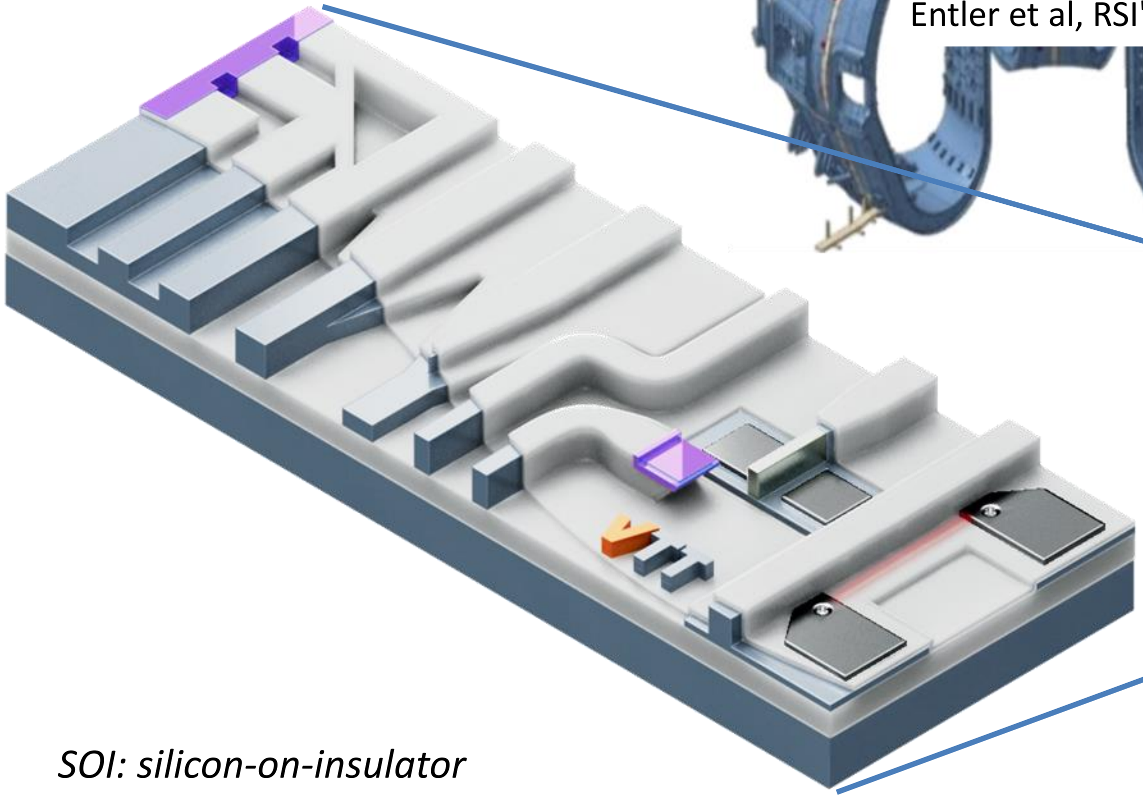
Sensor on silicon (simplified schematic)



- **Aim**: develop a prototype steady state magnetic field sensor
- **Physics principle**: Faraday rotation of light under magnetic field influencing the output of an integrated polarization splitter
- **Technology**: Photonic integrated circuit (PIC) based on 3 µm thick silicon-on-insulator (SOI) waveguides
- **Speciality**: Folded waveguides and mirror-based U-bends to accumulate Faraday rotation, novel mirror-based polarization splitters, and a method to avoid the impact of unwanted Faraday rotation in input/output fibers

Big picture

3 µm SOI PIC platform with passive and active functions (schematic)



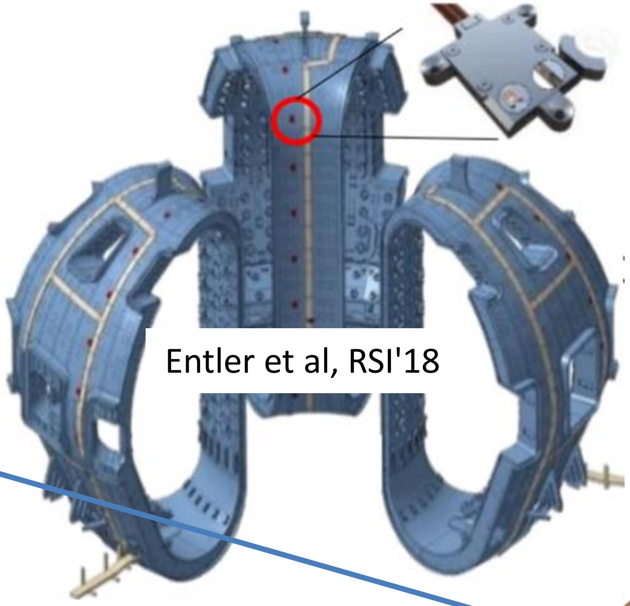
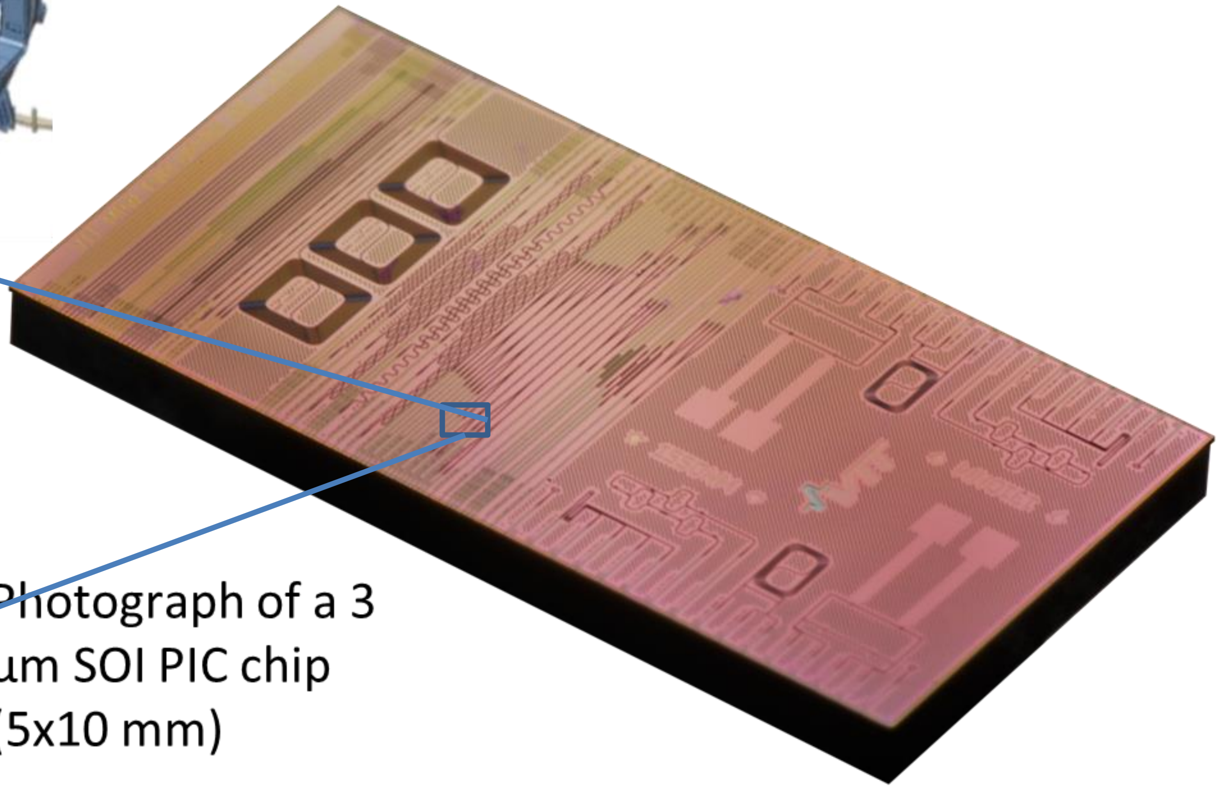


Illustration of a tokamak reactor with a (conventional) magnetic field sensor in one potential place for magnetic field measurement



Photograph of a 3 µm SOI PIC chip (5x10 mm)

SOI: silicon-on-insulator
PIC: photonic integrated circuit

Micronova research centre

- The biggest in the Nordic countries, R&D cleanroom facilities in Otaniemi, Espoo, cover 2,600 m2.
- Provides micro- and nanofabrication facilities for the development of microelectronic, **photonic**, microsystems and nanoelectronic components and devices.
- The facility also has other laboratories for processing, testing and characterization.
- The cleanrooms contain semiconductor processing equipment for lithography, etching and deposition as well as test and measuring equipment such as SEMs.
- In total there are some 200+ pieces of equipment that are used across a range of technology platforms.
- Used by researchers from VTT, Aalto University and other universities as well as several companies.

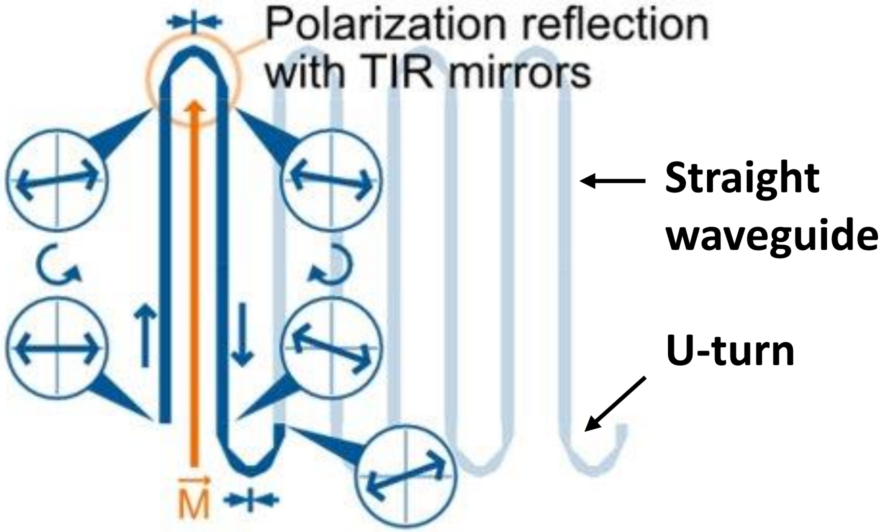
Multiple components needed for a sensor

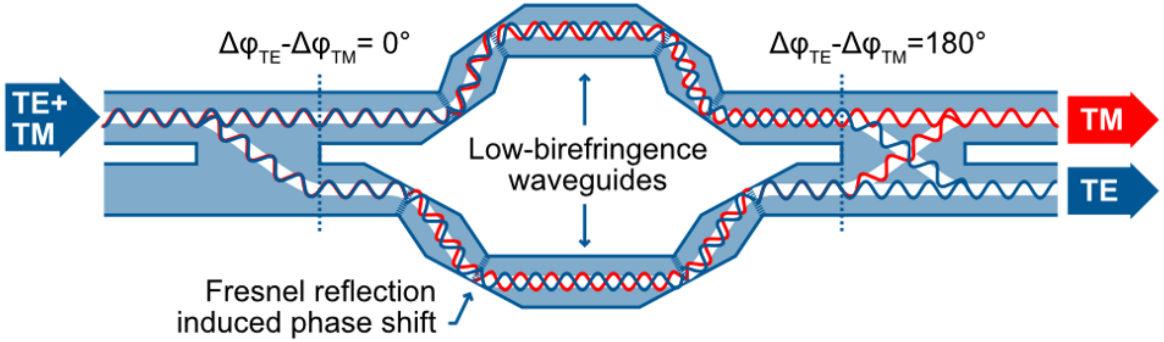
Faraday rotator based on

- **Straight waveguides** with dimensions and coating optimized for **zero birefringence**
- **Folded waveguides with U-turns** based on total internal reflection (TIR) mirrors

Polarisation splitter at the input and output of the Faraday rotator

- To create linear input polarization
- To measure the amount of Faraday rotation

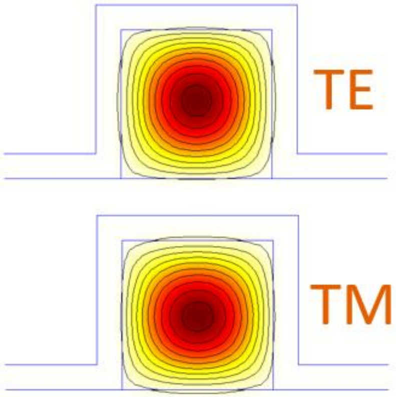


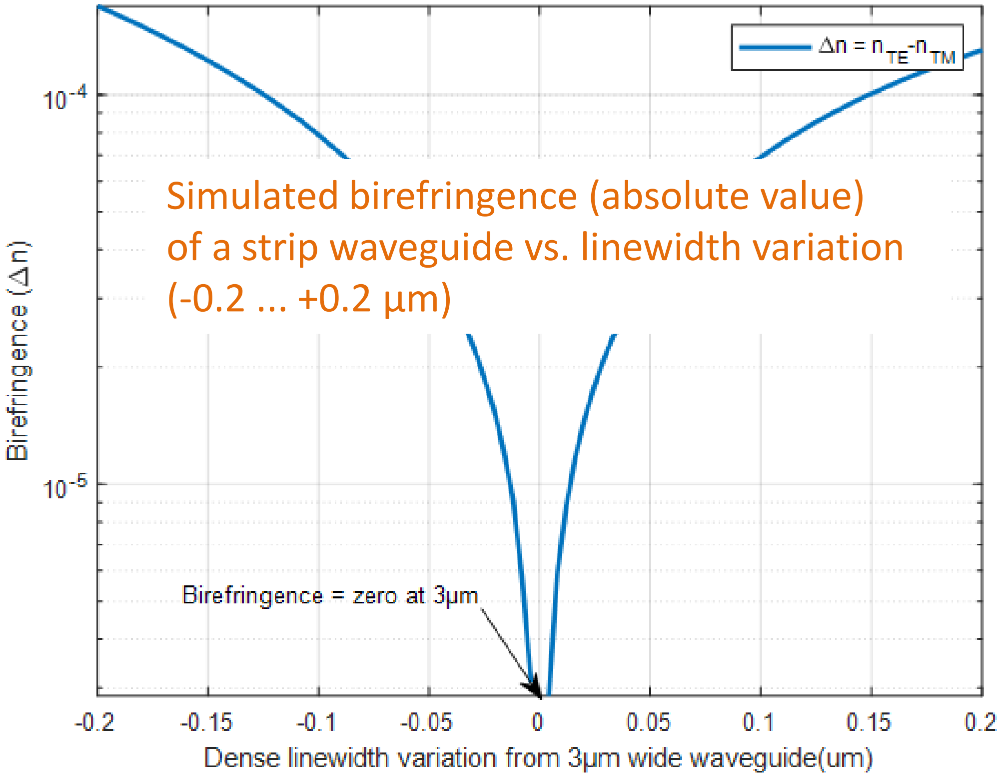


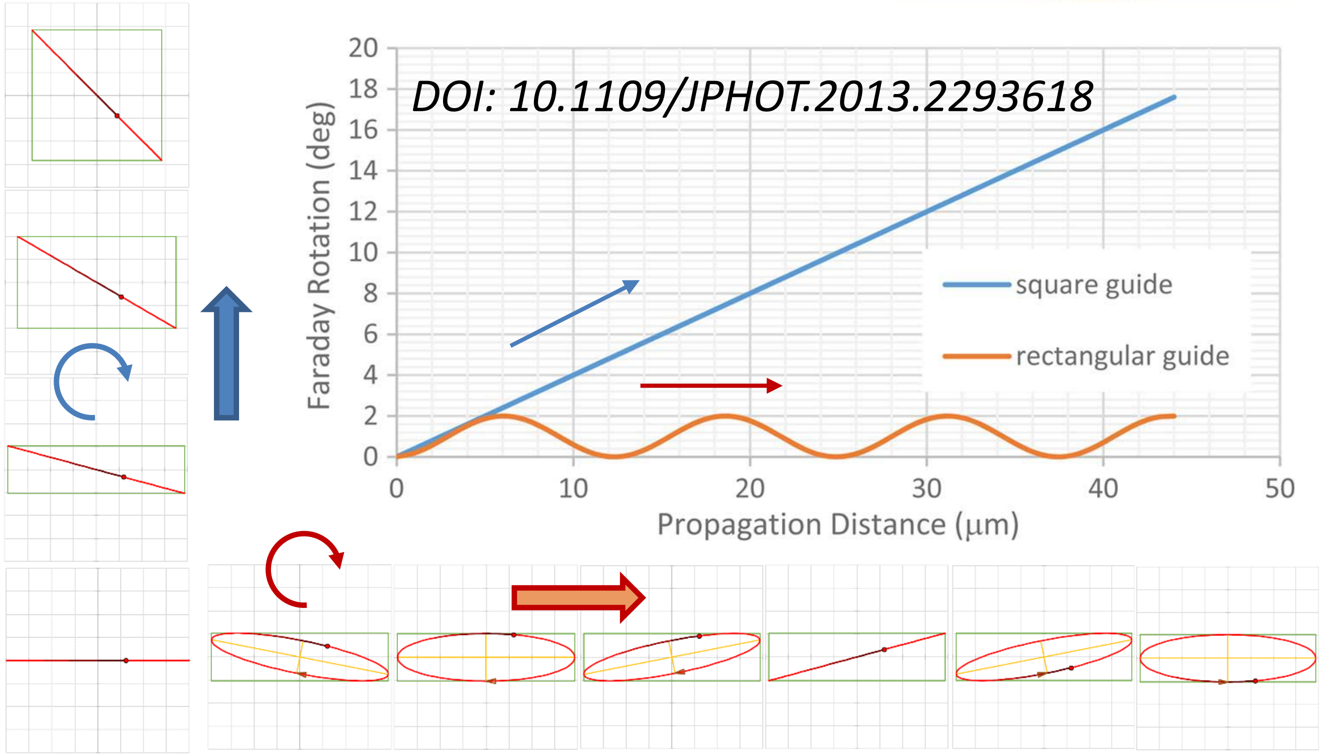
~Zero birefringence waveguides

VTT

- Zero birefringence of waveguides is needed for efficient Faraday rotation (as in the blue line)
- Stress free 3 µm wide strip waveguide can produce zero birefringence, but needs good linewidth control



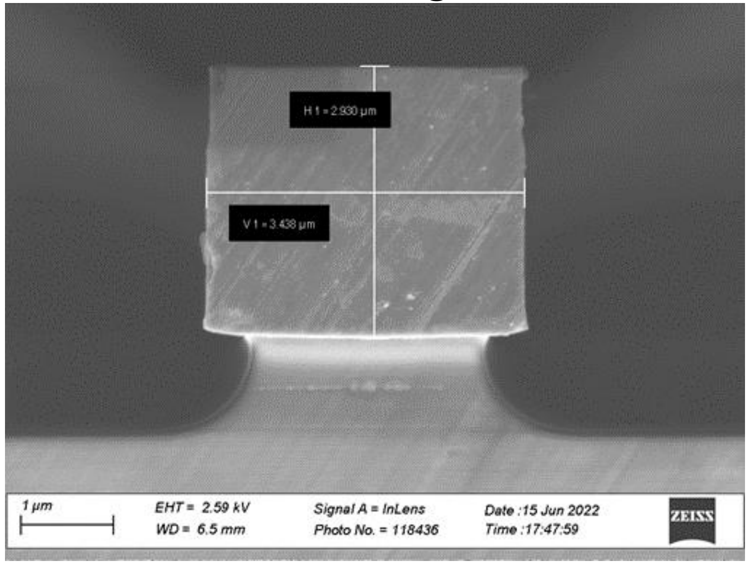


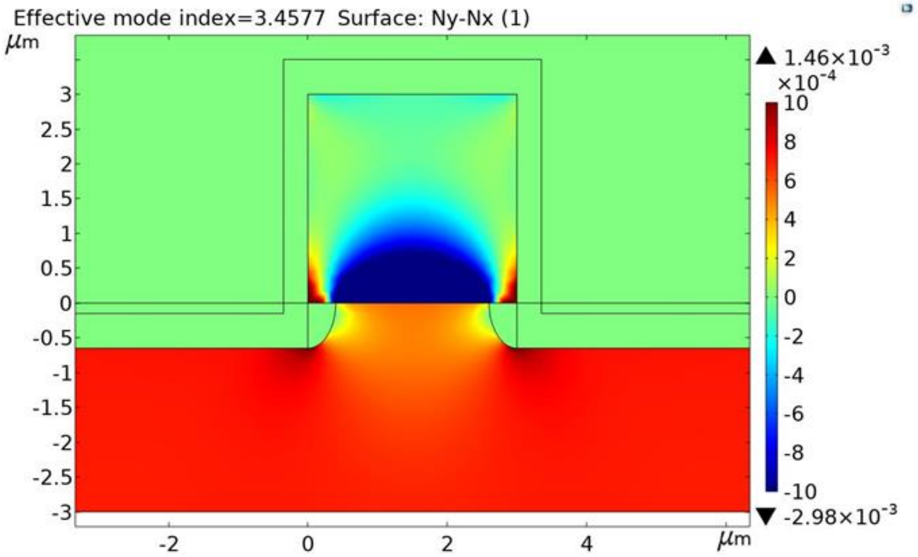


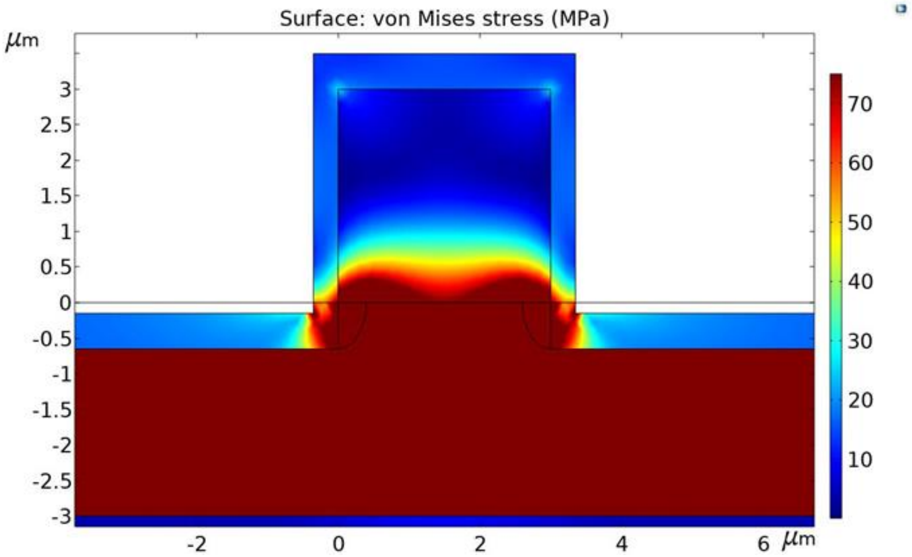
COMSOL® modelling of birefringence

- For theoretical insight COMSOL multi-physics modelling has been performed for birefringence
  - Input parameters (internal stress obtained from literature, may vary depending on manufacturing process, thus only rough estimates)

SEM image







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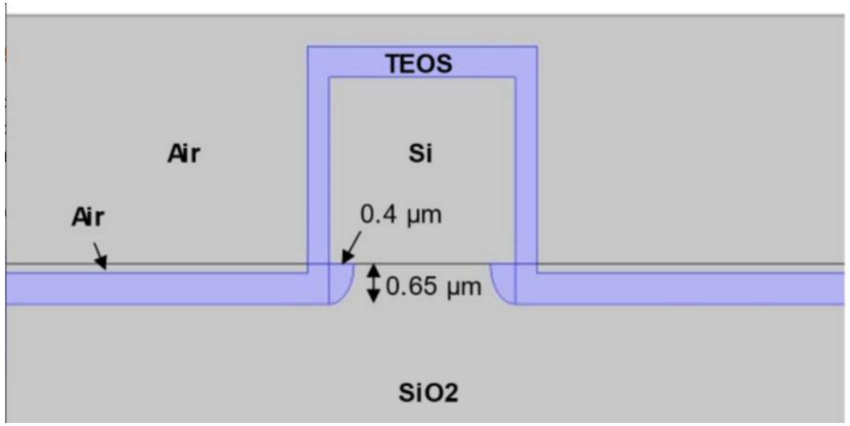
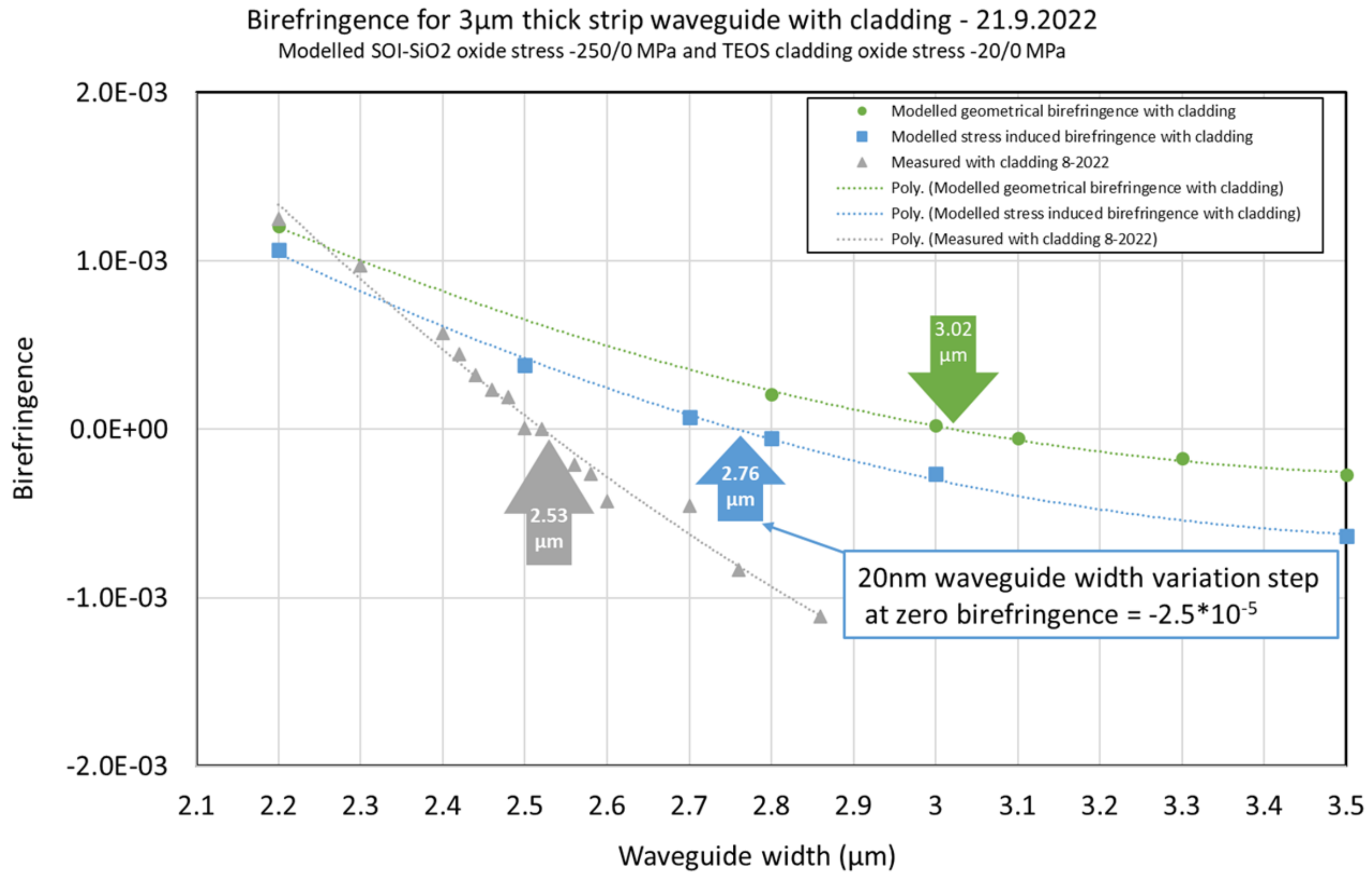
Birefringence origins

- Birefringence is caused by geometry and material (internal & external) stress

- Fair qualitative agreement between modelling and measurements
- Simulated birefringence is less sensitive on width variation than measurements

COMSOL model





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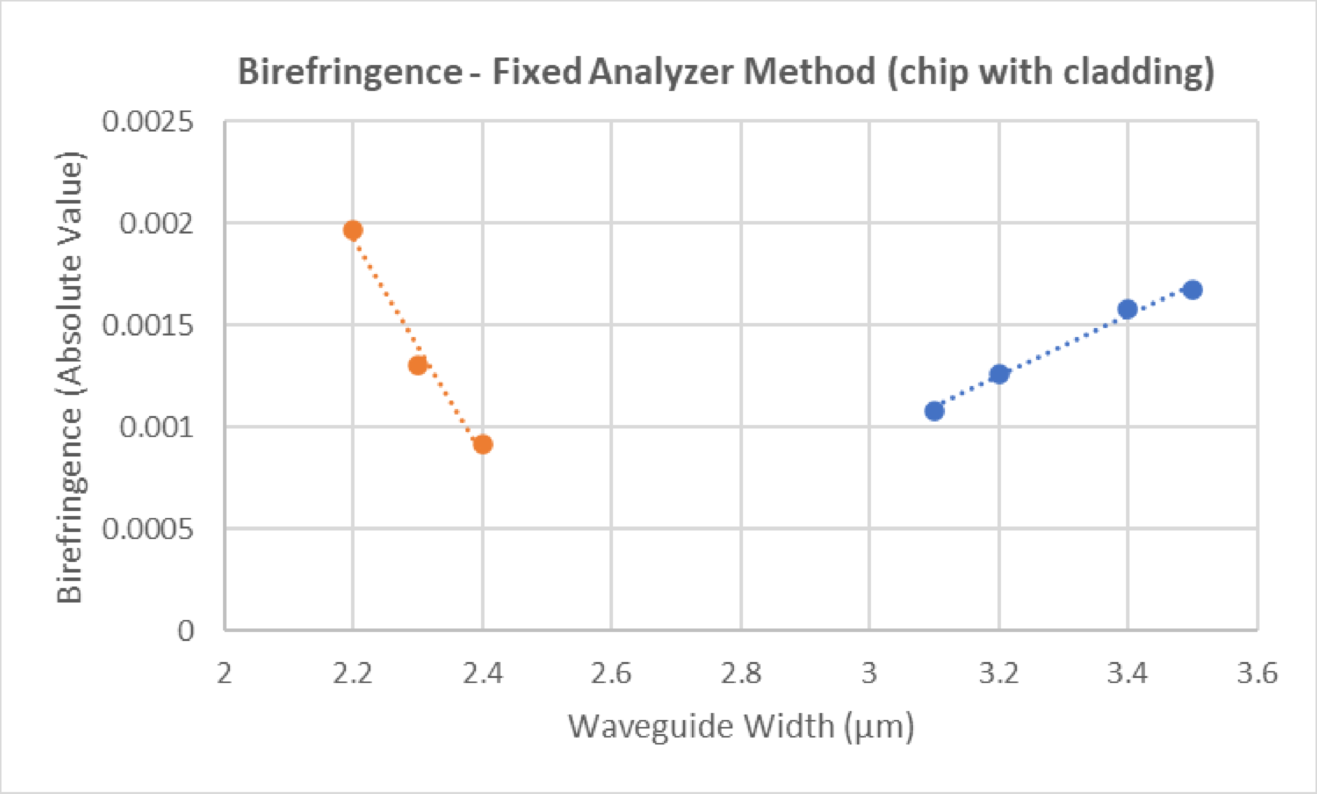
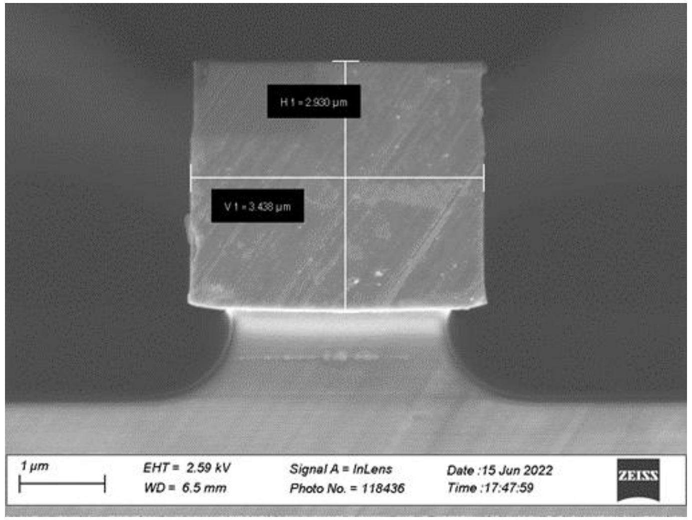
Birefringence measurement

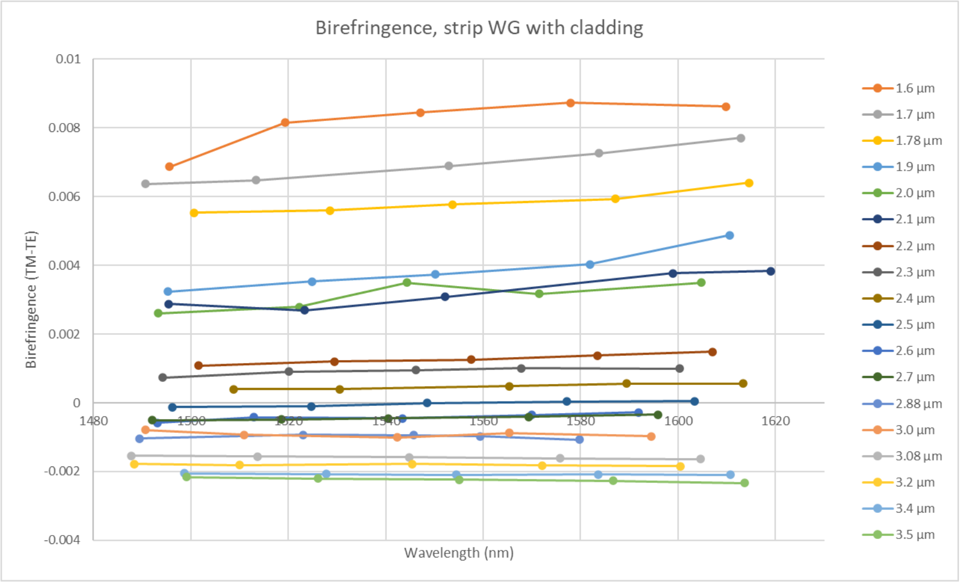
- Routinely used “Fixed analyzer” method data is not sensitive enough to locate optimal width
- Extrapolation suggests lowest birefringence @ ~2.5-2.7 µm width

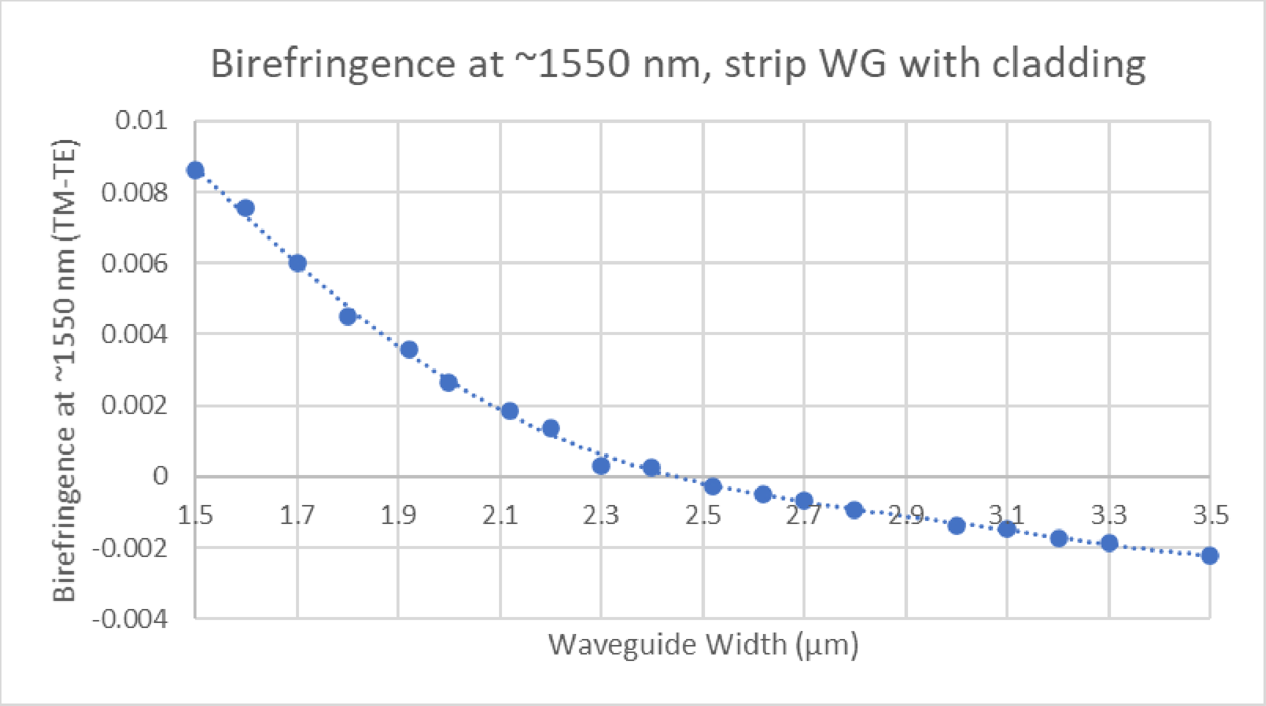


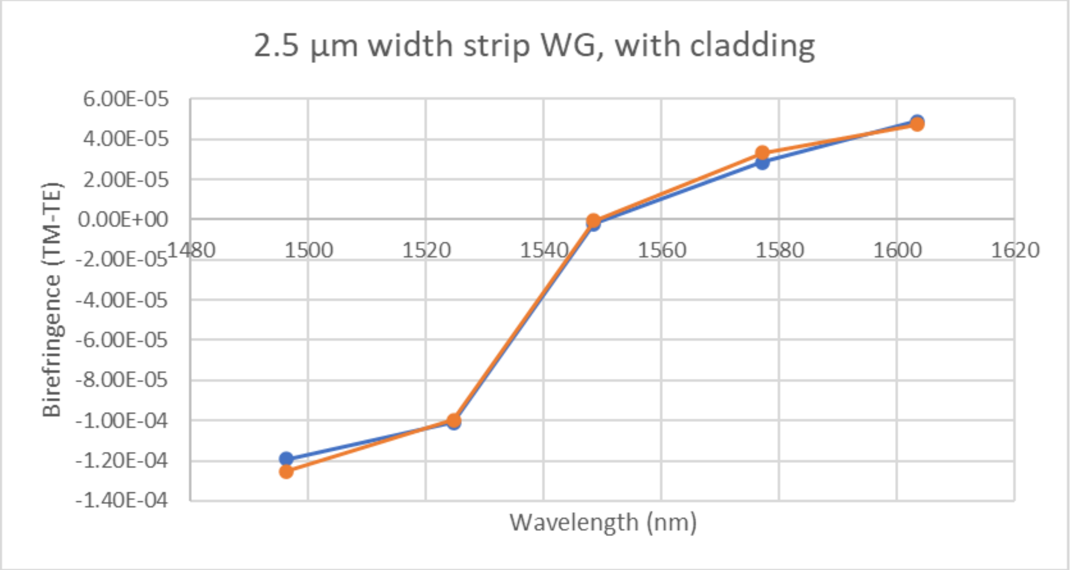


Fabry-Perot birefringence measurement

- More sensitive scheme based of Fabry-Perot method was set up and used to obtain more accurate estimates (though only a proxy)

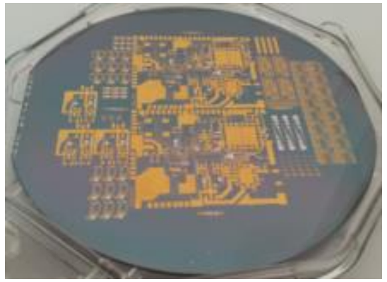




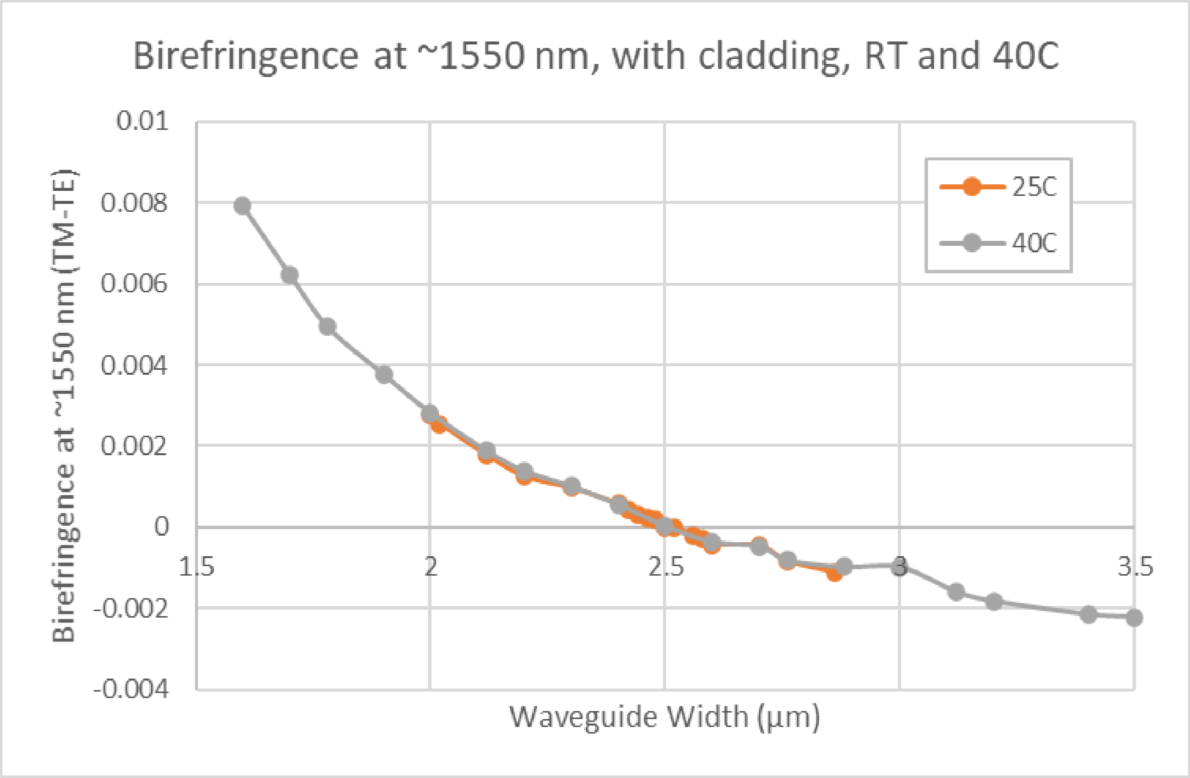


Moderate sensitivity to temperature

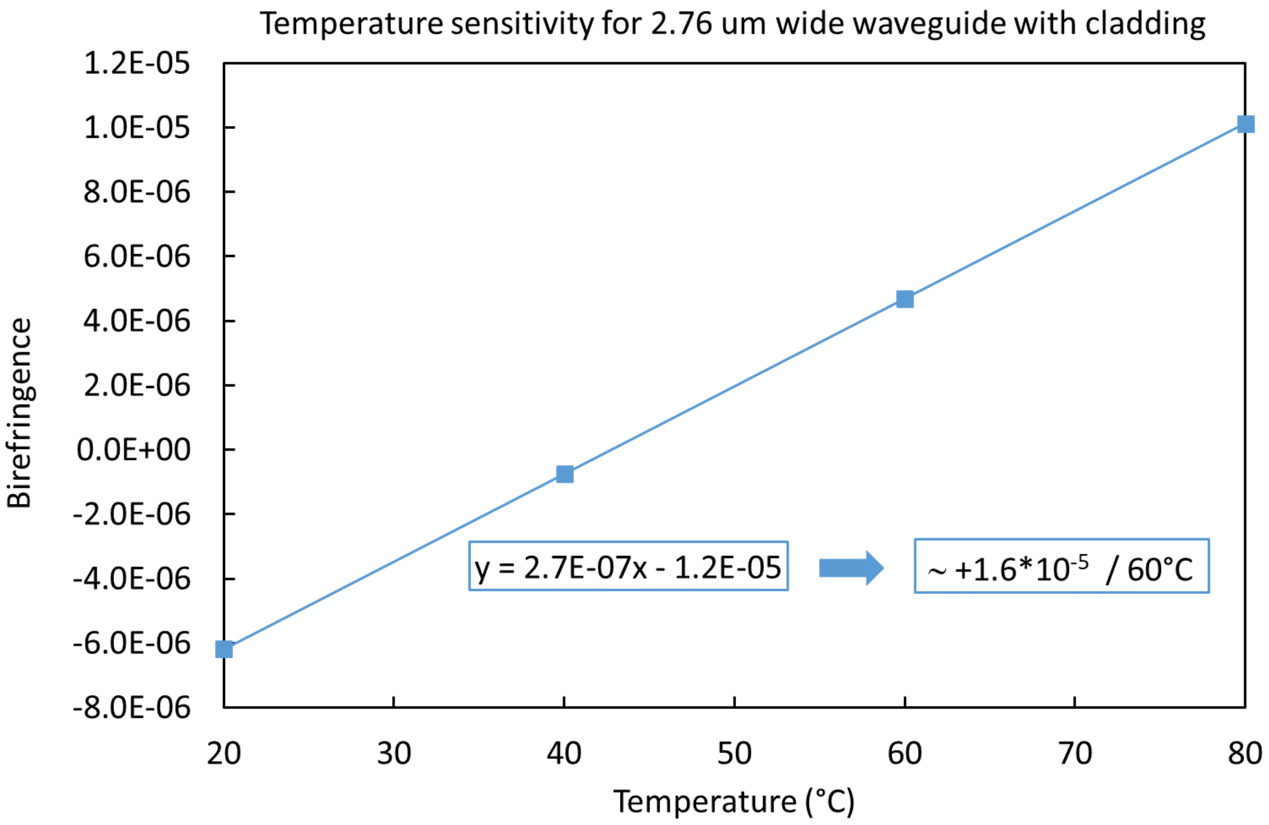
- Initial measurements are consistent with COMSOL calculations showing relatively weak birefringence dependency on temperature
  - Consistent with modelling, allows measurements in different temperatures



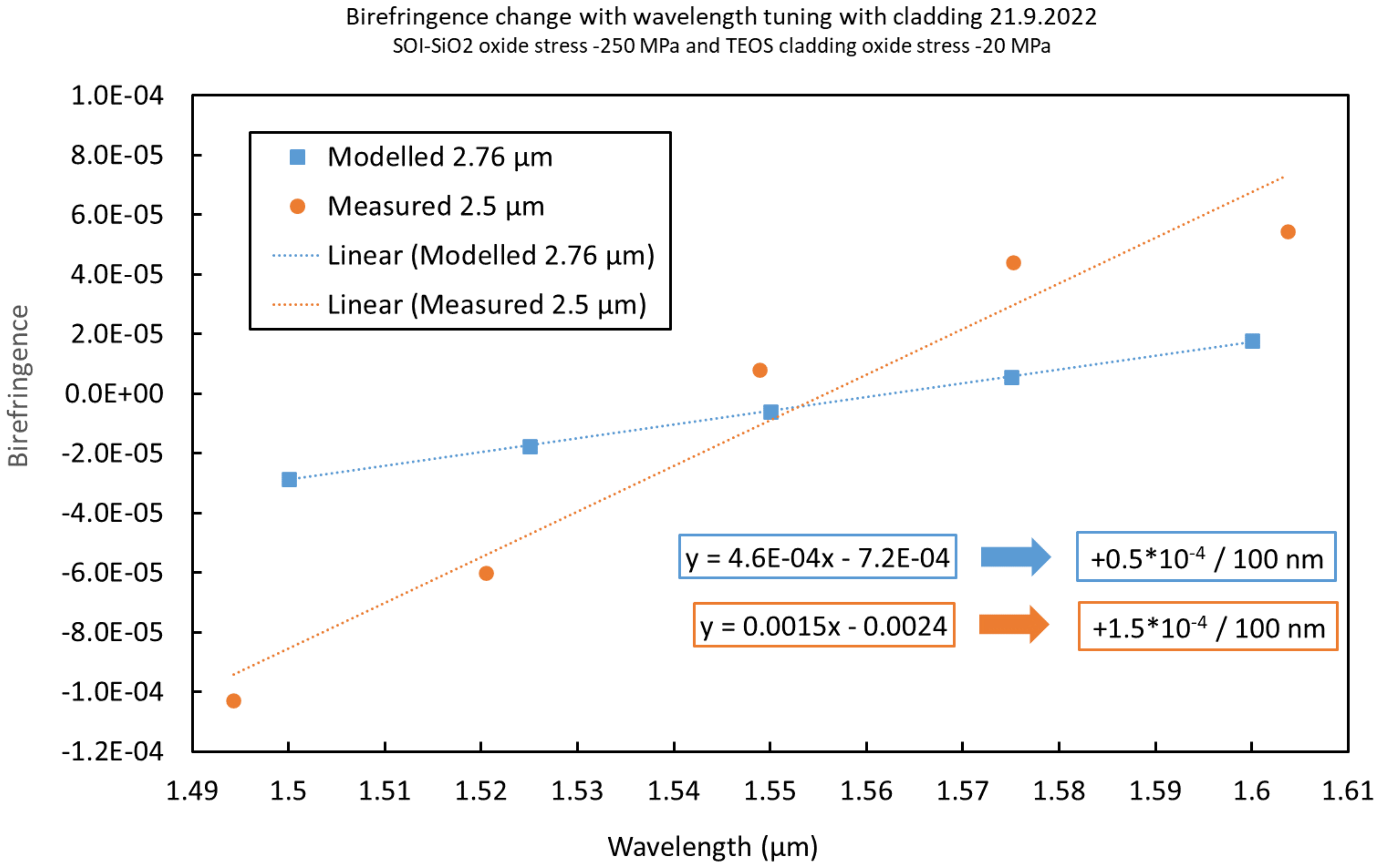
Fabry-Perot birefringence measurements



COMSOL modelling



Simulations v measurements

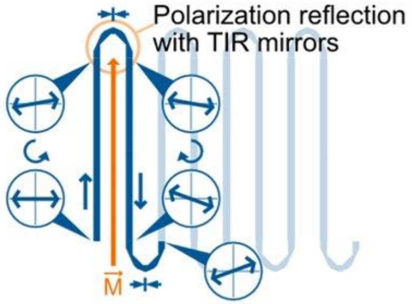


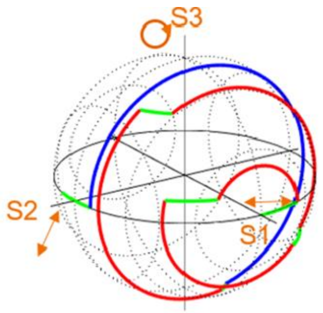
Measurements show ~3x stronger wavelength dependence than modelling

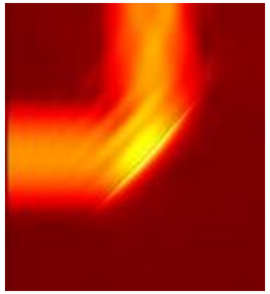
➔ Wavelength tuning can be used to minimise birefringence

U-turn design

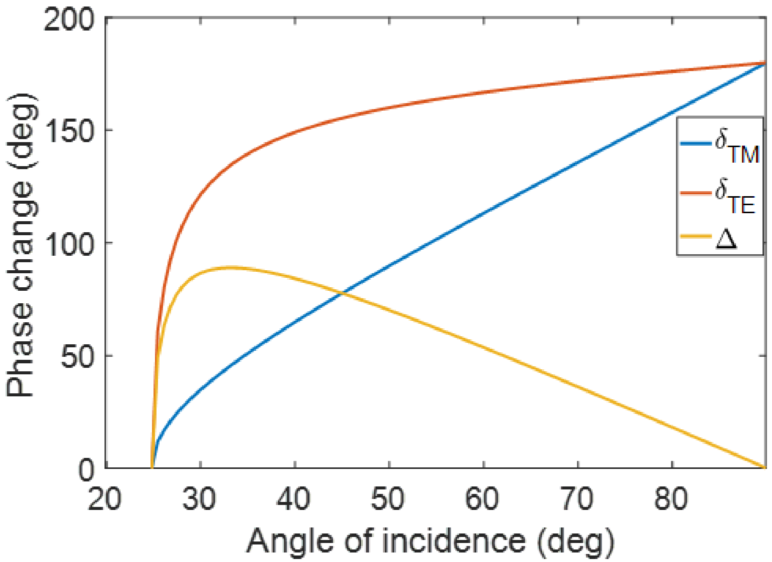
- Many options are being considered
- Physical constraint: 180° U-turn needed
- Phase change $\Delta \sim n\pi$ with n = odd integer
- Small losses needed
- Total internal reflection (TIR) mirrors are not wavelength dependent

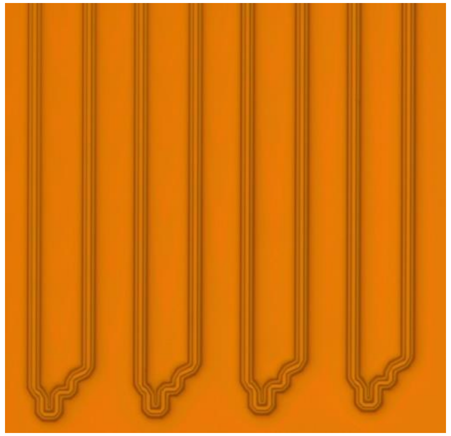


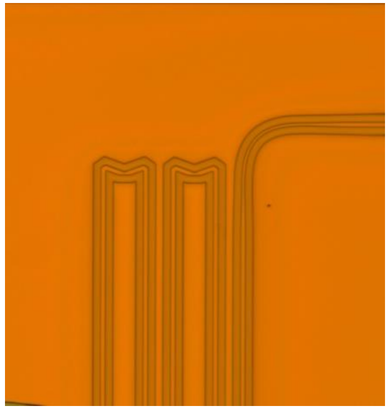




Fresnel equations:



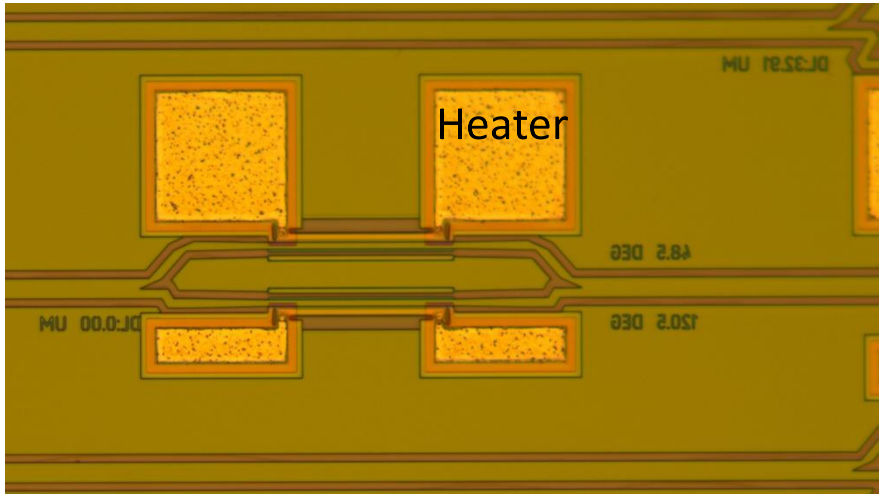


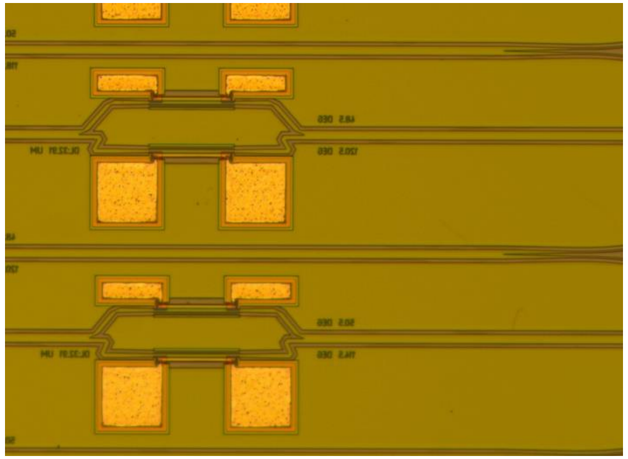


TIR mirror-based polarization splitter

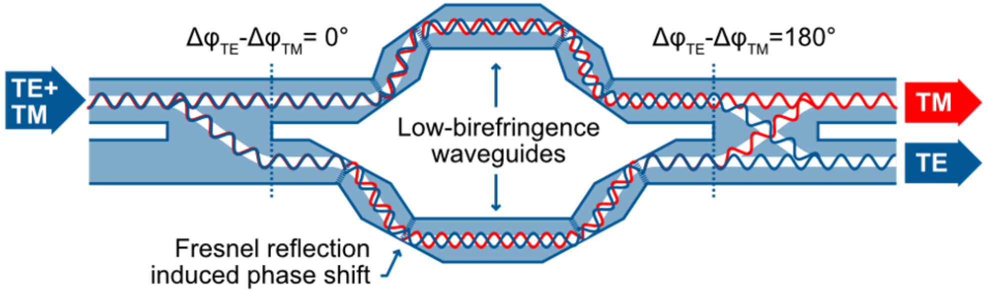
- Novel polarization beam splitter (PBS)
  - Separates TE and TM polarizations
  - Based on wavelength-independent and polarization-dependent phase shifts in total internal reflection (TIR) mirrors

Fabricated test structures



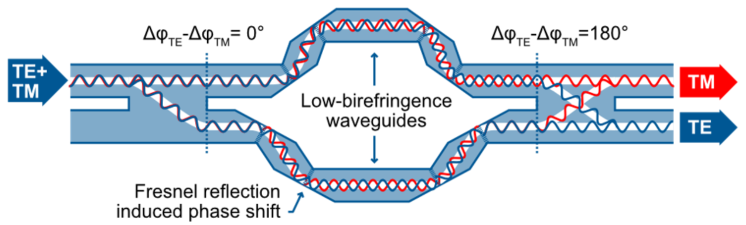


Schematic of TIR based polarization splitters

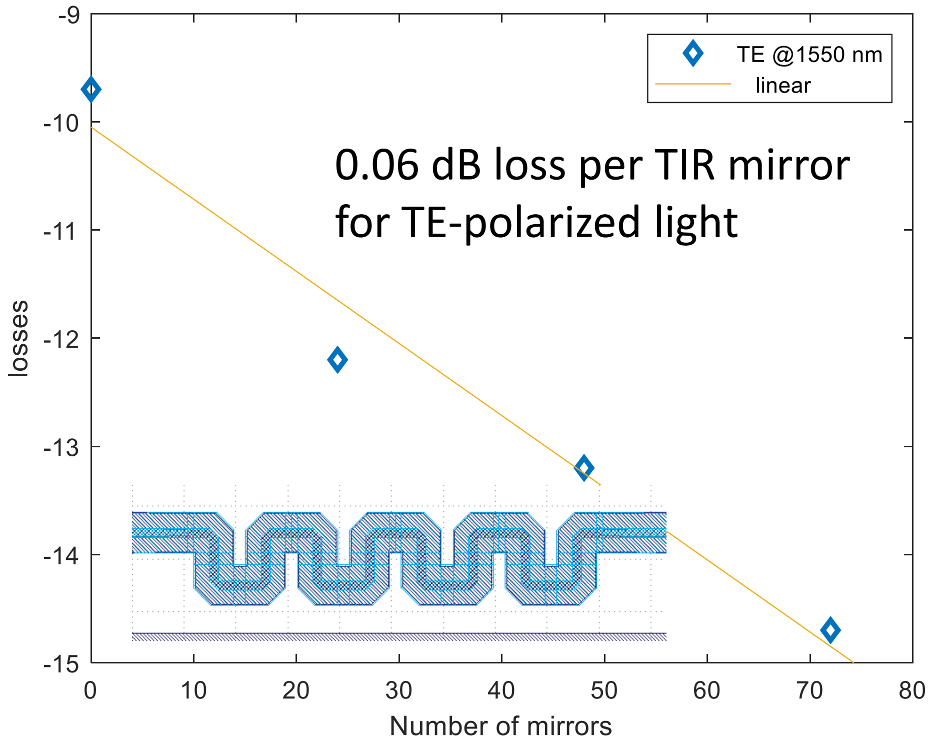


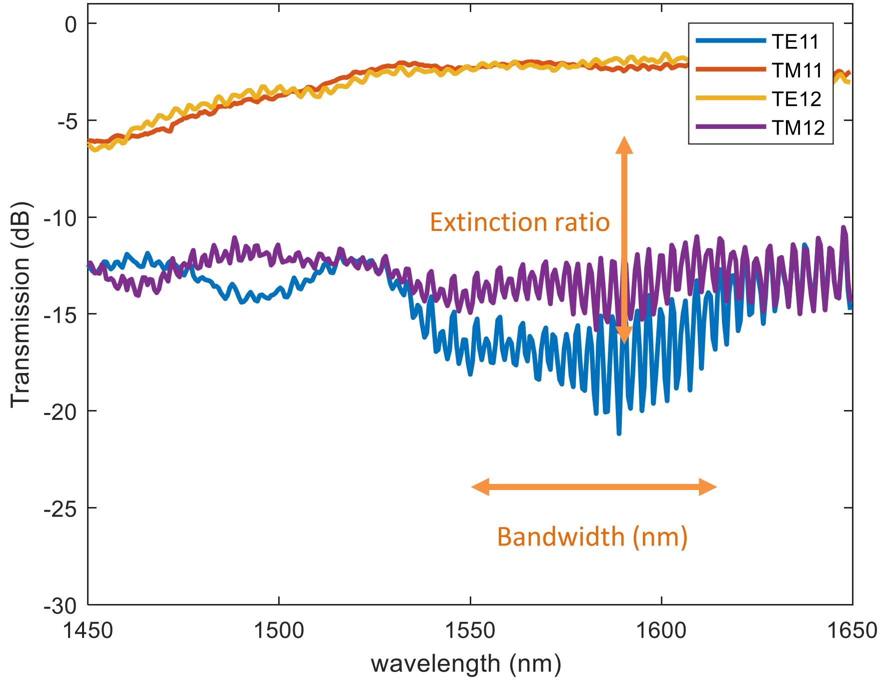
TIR mirror-based polarization splitters

- Two performance metrics
  - Mirror performance (need low losses)
  - Extinction ratio (polarisation purity)
- High bandwidth with TIR approach



- Maximum ER 19 dB for 50nm for both polarizations.
- 15dB ER @ 100 nm for both polarizations.





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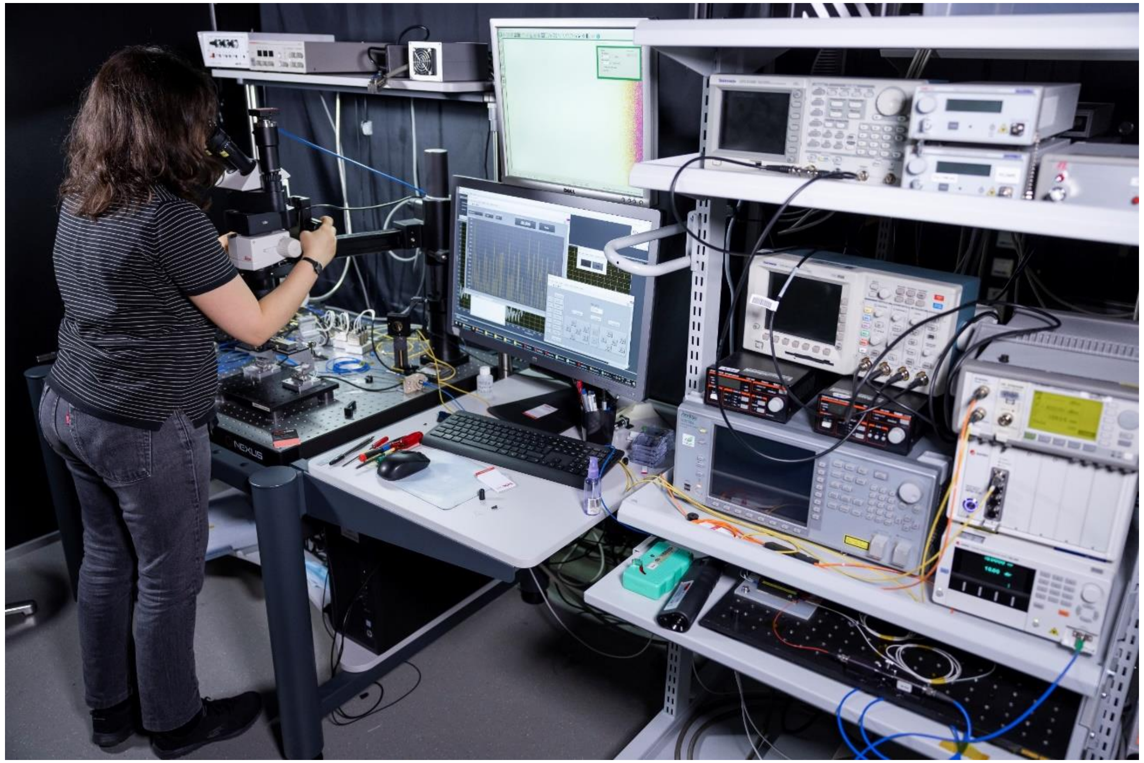
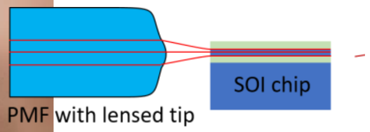
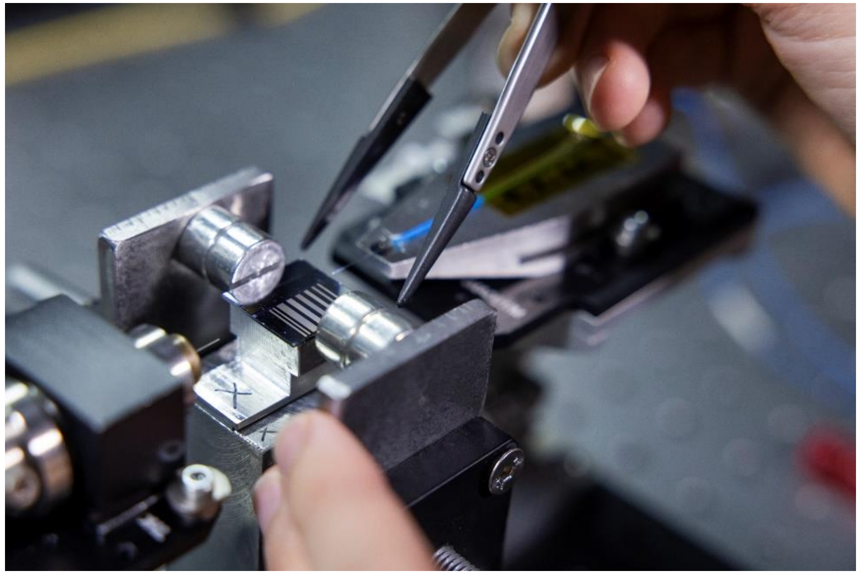
Optics laboratory setup

- Component characterisation, fibre splicing, done at home lab with watchmaker precision
  - Equipped with microscope, spectrometers, light sources, polarizers, …

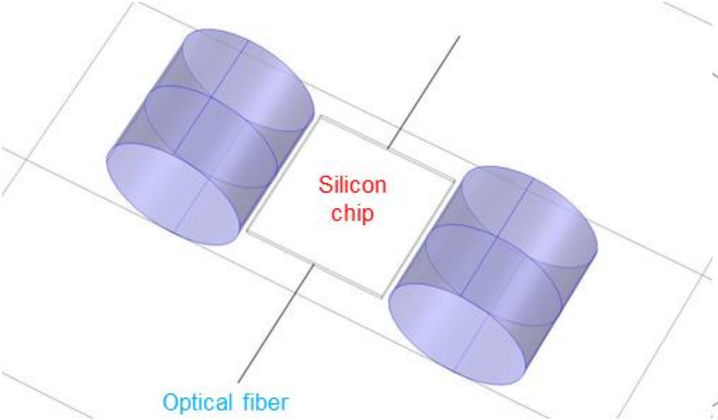


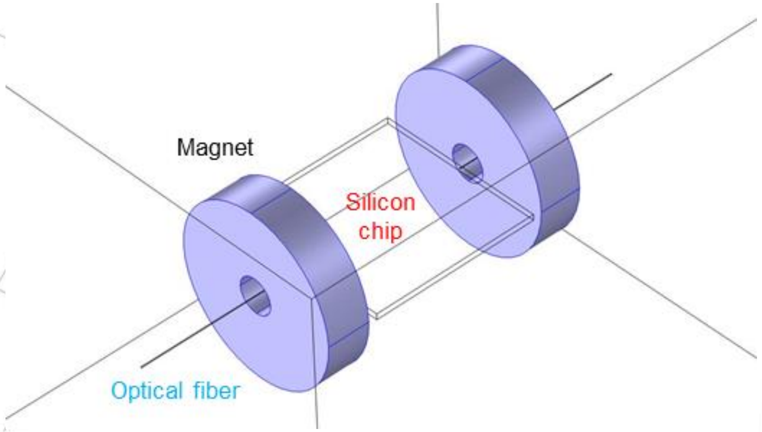


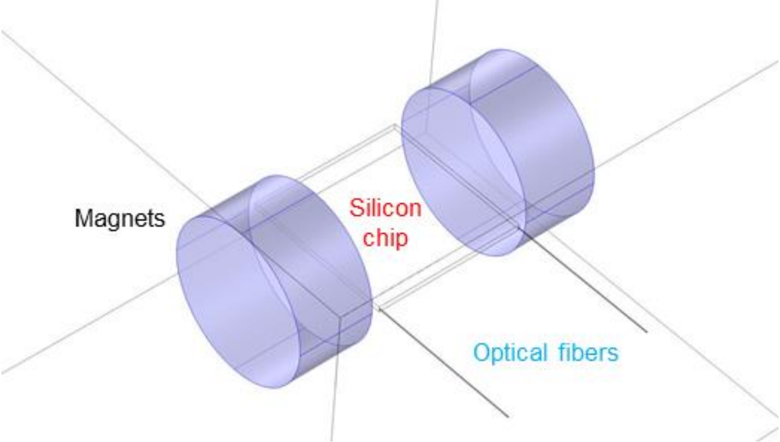


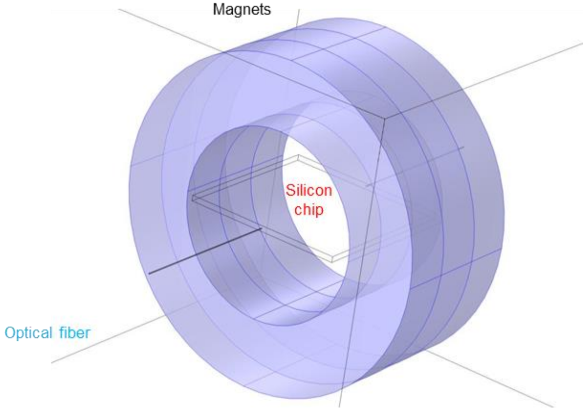
In-situ magnetic field setup

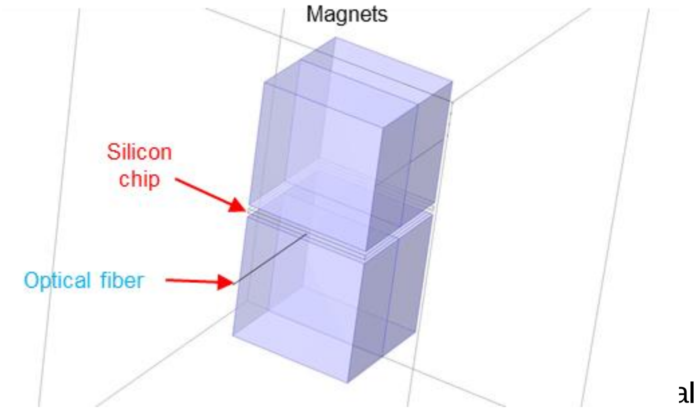
- Many constraints from available space, access and safety in setting up adequate in-situ magnetic field for component characterisation and Faraday rotation measurements
- Several permanent magnet options and configurations modelled with COMSOL to find the optimal

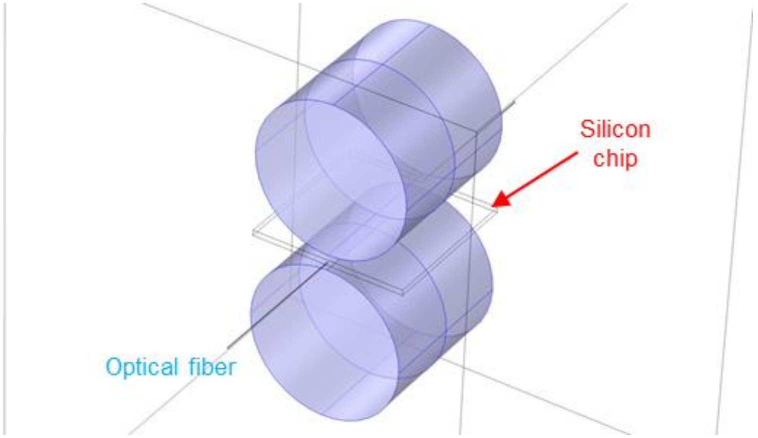




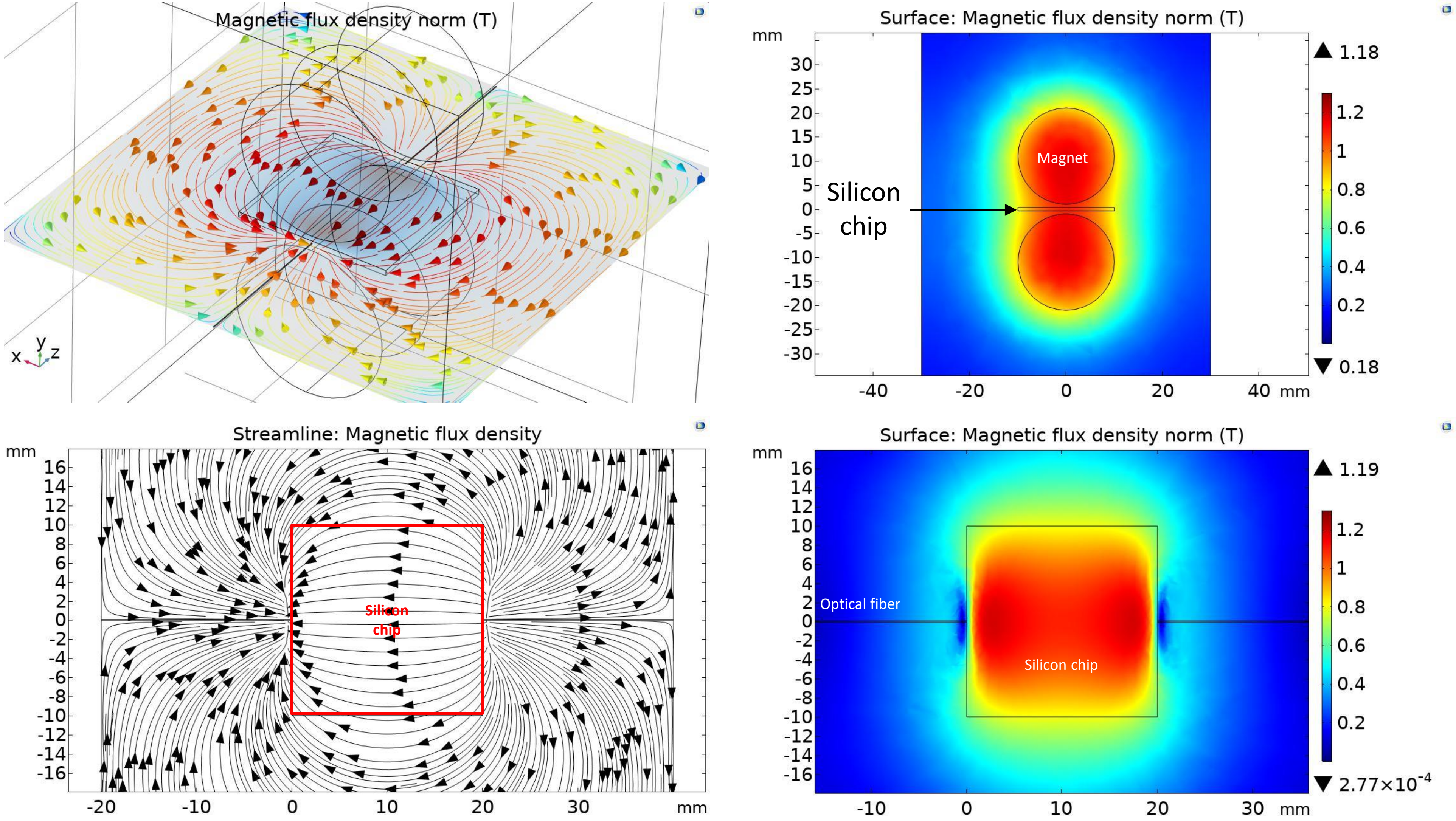








Strong & uniform magnetic field selected



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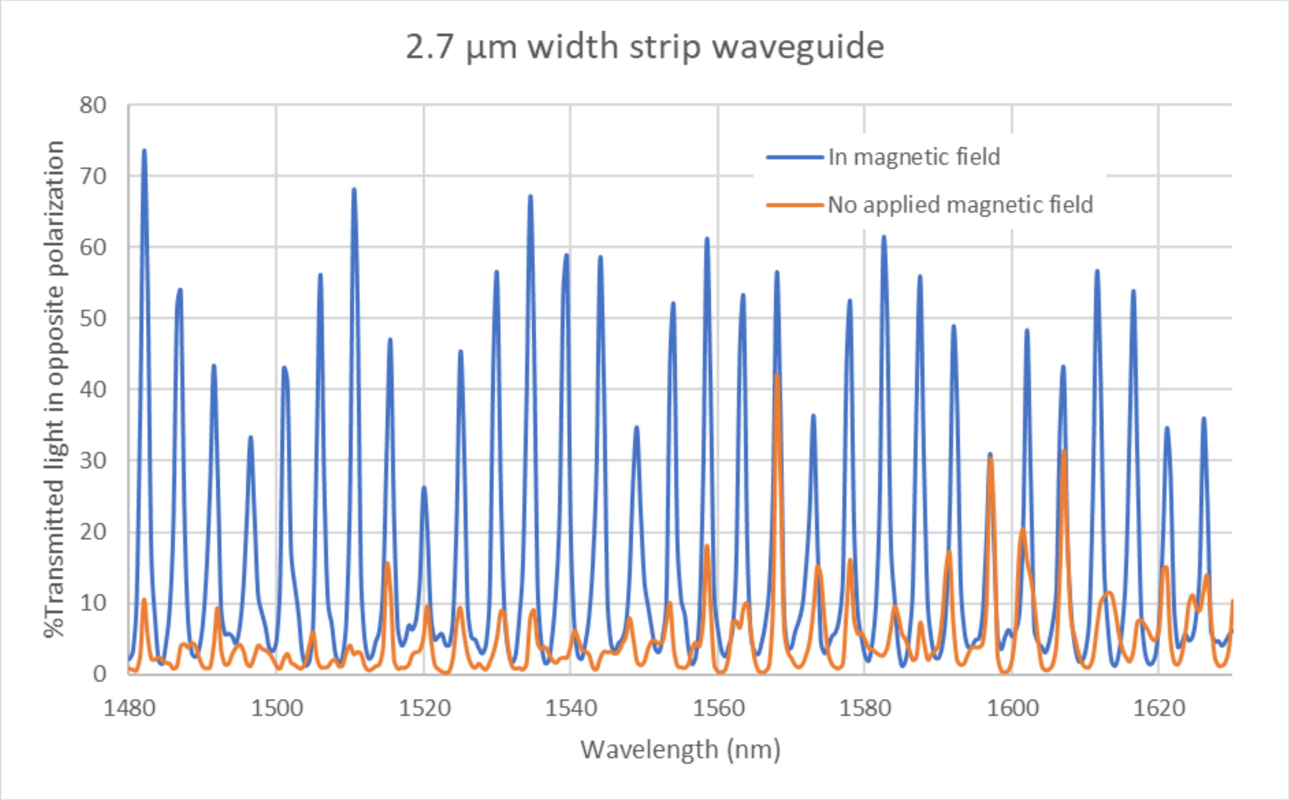
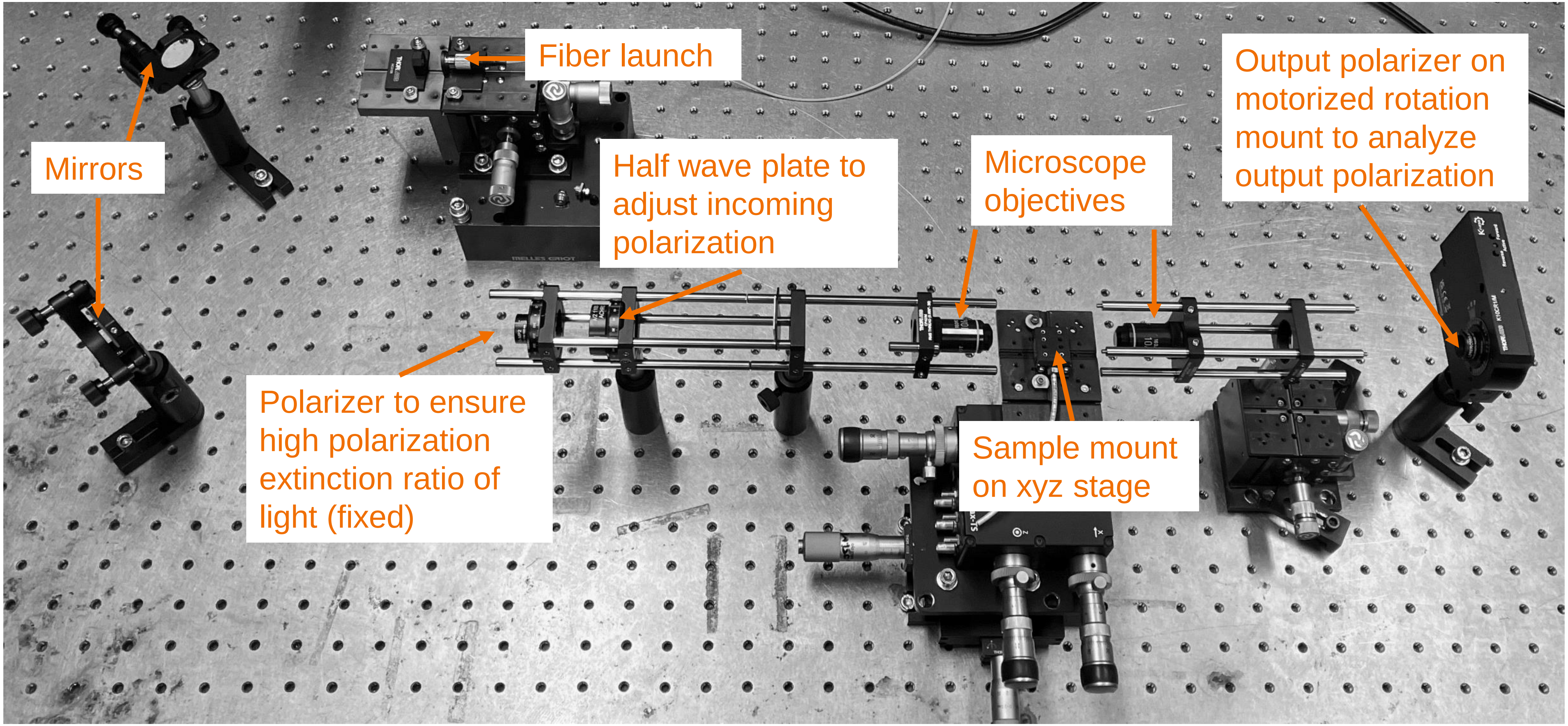
Indication of Faraday rotation in waveguide

- Faraday rotation is indicated in 2.7 µm width waveguide.
- The percent of transmitted light in the opposite polarization is much higher in the presence of a magnetic field.
- However, it is difficult to say quantitatively what is happening.
- Free-space setup is needed for finer control of input polarization.

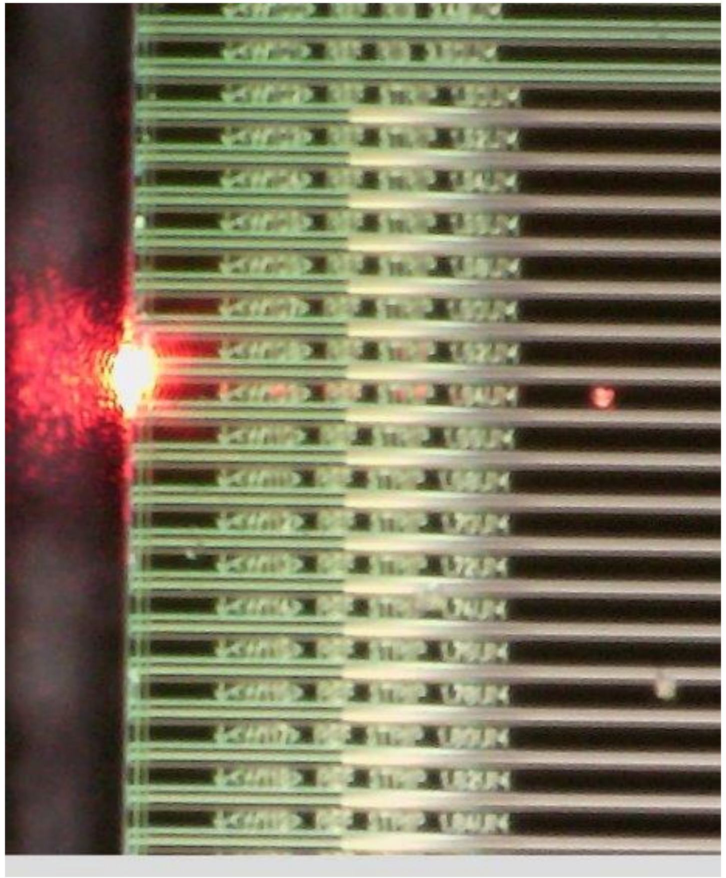


New free-space setup



Alignment and focus

- Visible red laser aligned with the IR laser in order to visualize into which waveguide the IR light is coupled



Waveguide IDs, etched on the silicon chip

Summary

- Achievements so far
  - Lowest birefringence waveguides seem to demonstrate Faraday effect (tentative)
  - Built in-situ magnetic field setup improvements for Faraday rotation demonstration
  - Free space measurement setup being onboarded
  - Verified that TIR mirrors have low losses (0.1dB)
  - Verified consistent measurements across the wafer and day-to-day
  - Achieved 15dB extinction ratio for the TIR based polarisation splitter for both polarisations
  - Designed and manufactured 3µm TIR based U-turns (two flavours)
- Still plenty to do
  - Demonstrate robust Faraday rotation for straight and folded waveguides
  - Optimise U-turns for selected waveguides to allow their characterisation
  - Integrating the components to perform as a sensor

Measurements for integrated package

- Integrated sensor circuits will be characterised using on campus PPMS device capable of
  - B = 0-8T and T = –270 to +127 C automated scans

Effective index measurements using MZI

- Effective index can be calculated from Mach Zehnder interferometer geometry.
- The fabricated devices have same width and different arm length. Due to difference in path length, there is a relative phase shift between two arms.
- Birefringence can be calculated by using this formula.
- $$\Delta n = \left(m + \frac{1}{4}\right) \Delta\lambda / \Delta L$$
- Where m can be in limits of $\mathrm{n_{cladding}} \frac{\Delta L}{\lambda_c} < \mathrm{m} + \frac{1}{2} < \mathrm{n_{core}} \frac{\Delta L}{\lambda_c}$ $\lambda_c = (\lambda^m{}_{TE} + \lambda^m{}_{TM})/2,$

- Measurements are in progress.