Pr16: Silicon optics steady state magnetic field sensor

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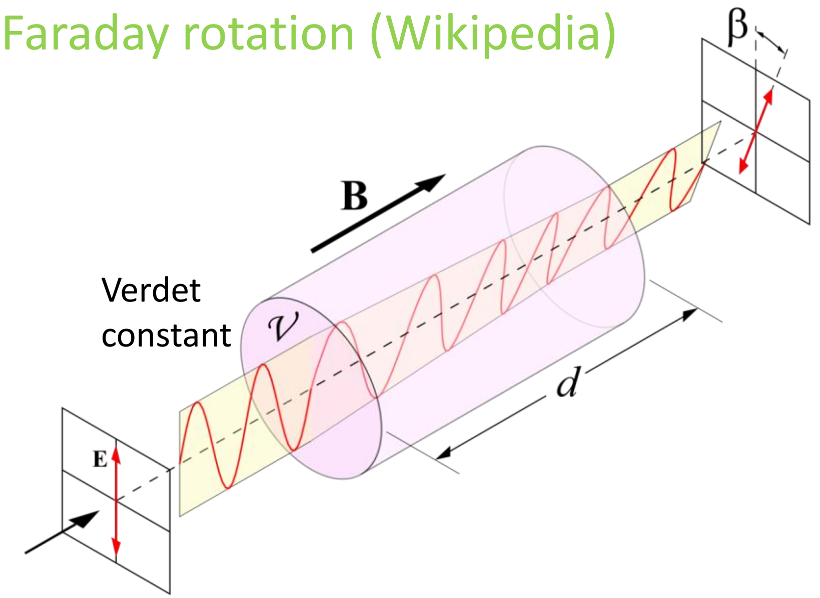
Present status in a nutshell

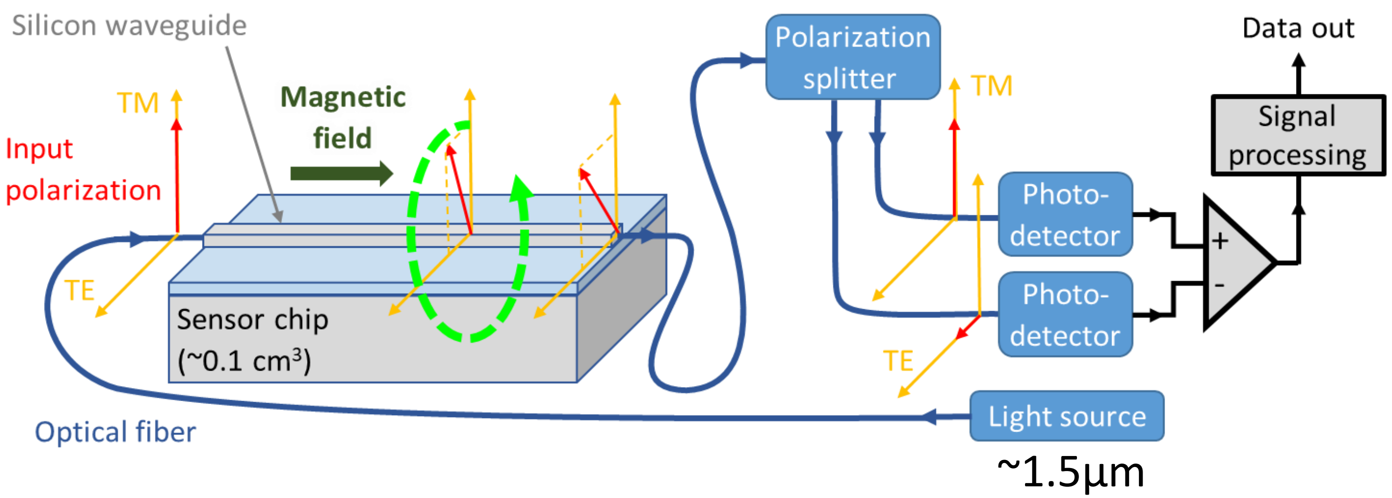
- 1.5 years from project initiation (April 2021)
- ~6 months behind schedule (and clocked PPMs) due to the lack of human resources
  - Particularly experimental characterisation of the components was lagging
- Recruited one new person to help with measurements
  - Now progressing well but still lagging due to the initial delay
- Difficult to catch up even with additional efforts due to the multi project wafer scheduling constraints, and serial nature of the research
- Current project end (Mar 2024) is proposed to be extended until end of 2024

Measurement concept

Faraday rotation (Wikipedia)



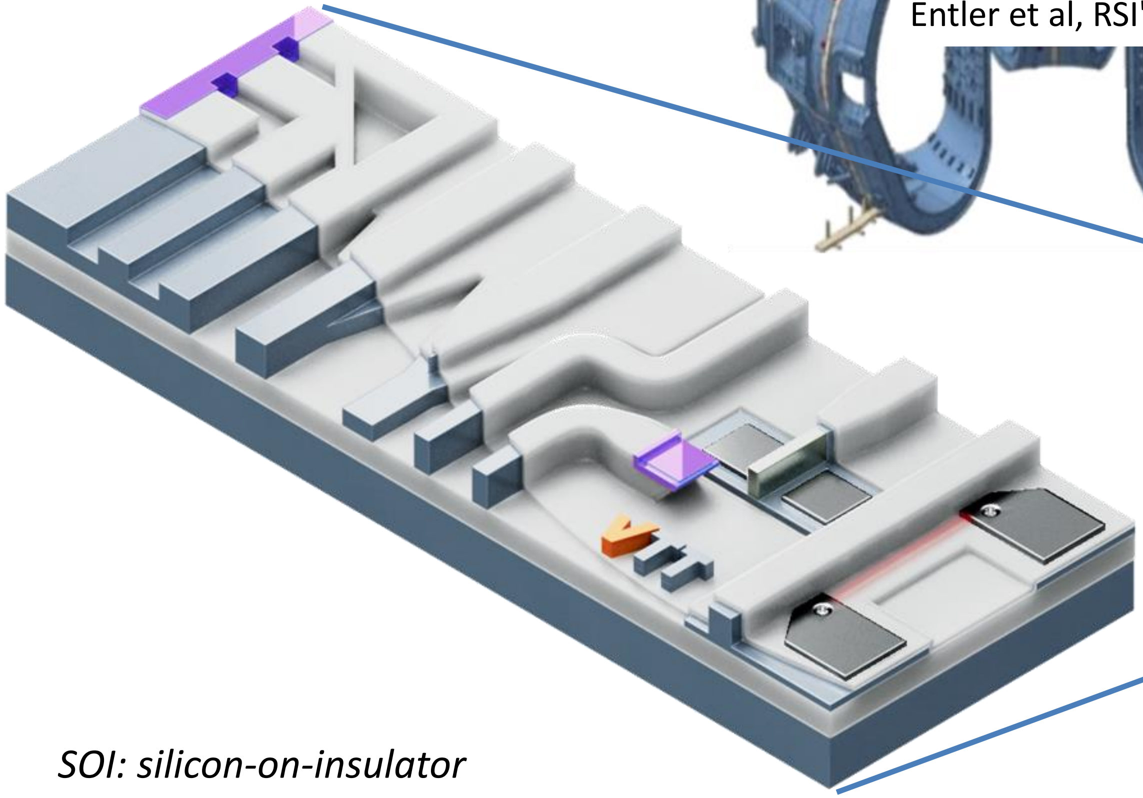
Sensor on silicon (simplified schematic)



- **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)



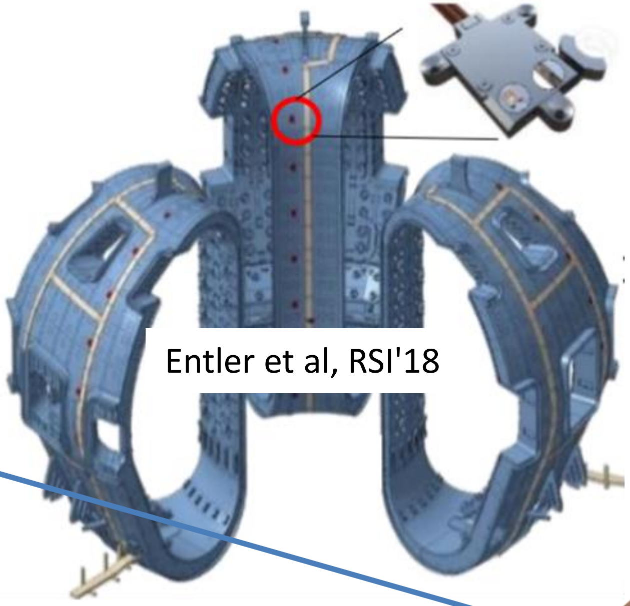
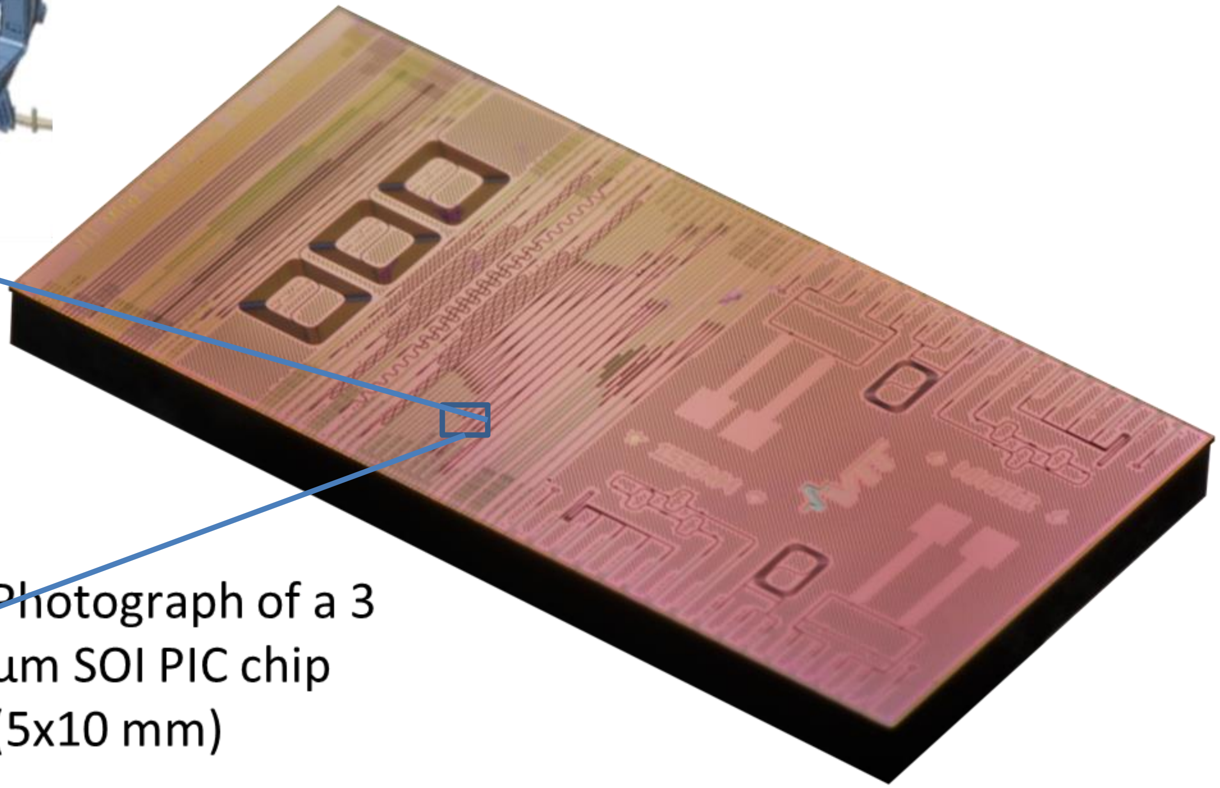


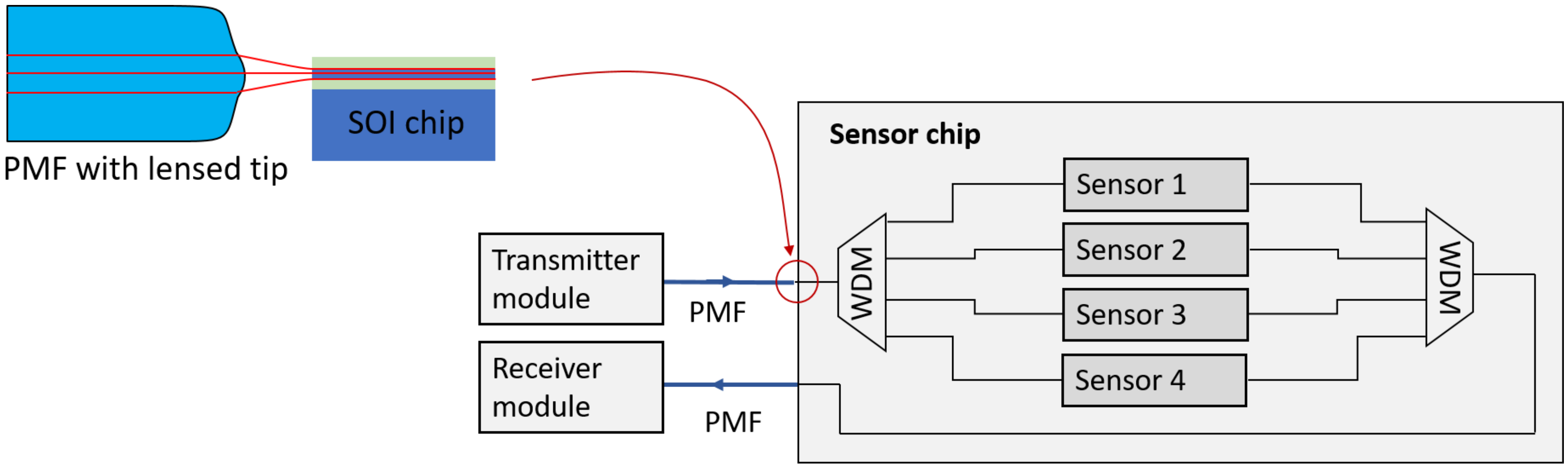
Illustration of a tokamak reactor with a (conventional) magnetic field sensor in one potential place for magnetic field measurement



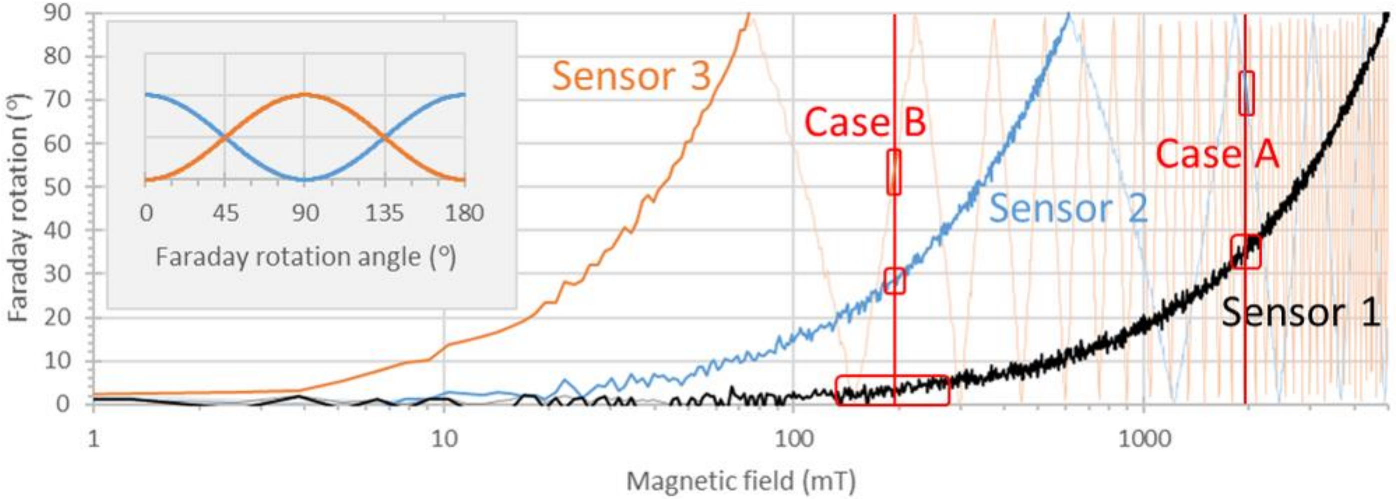
Photograph of a 3 µm SOI PIC chip (5x10 mm)

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

Multiple sensors for resolution



- Faraday rotation should be in the range of 1-89 degrees for unambiguous magnetic field measurement in one sensor
- Need to use 3-4 sensors to obtain targeted performance (5T +/- 4mT)



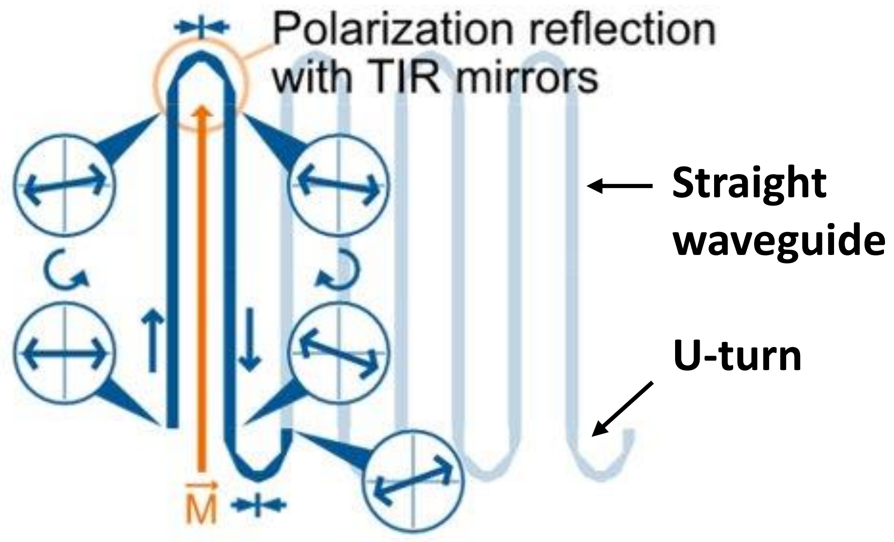
Multiple components needed for a sensor

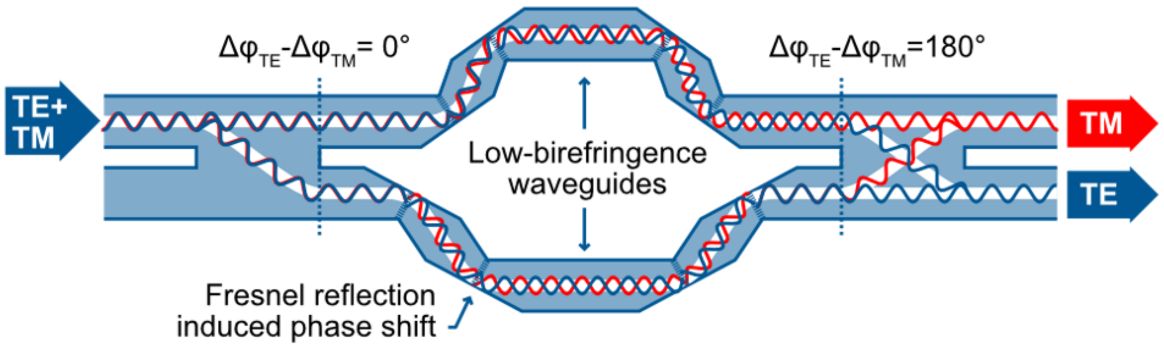
Faraday rotator based on

- **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

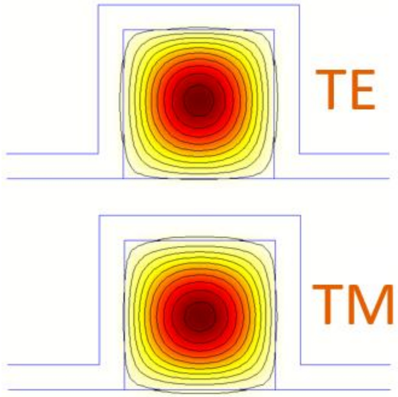
- To create linear input polarization
- To measure the amount of Faraday rotation

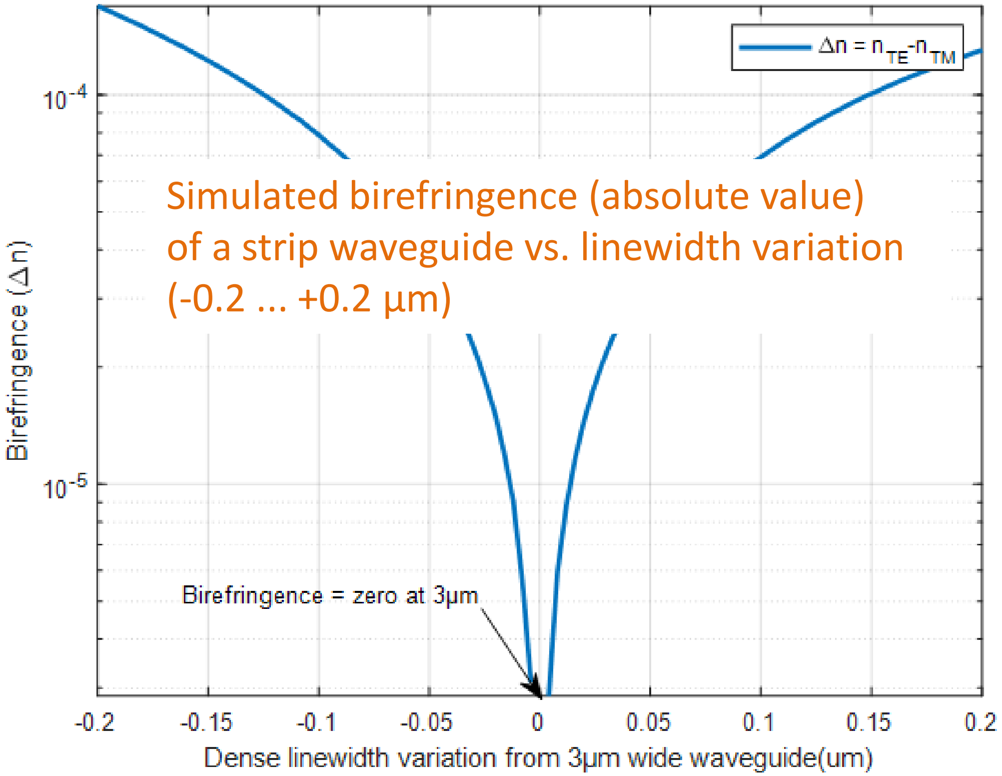


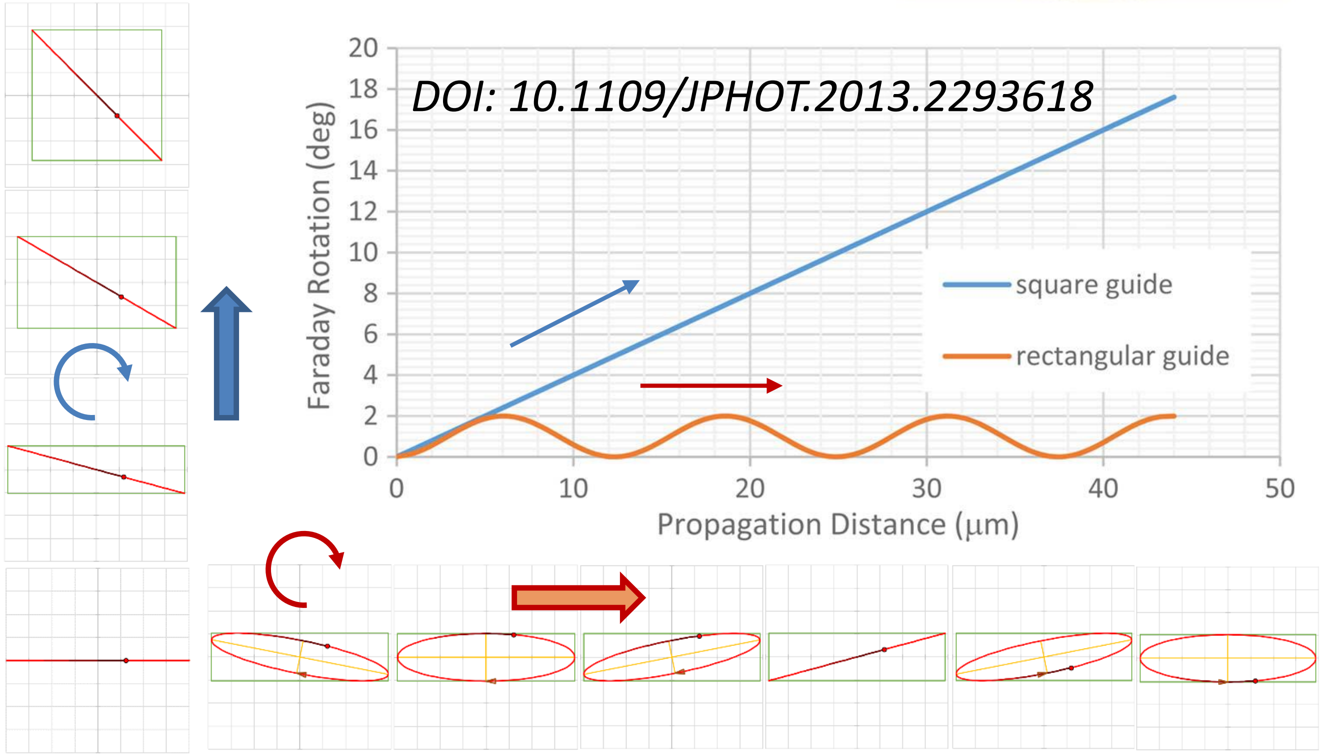


~Zero birefringence waveguides

- 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

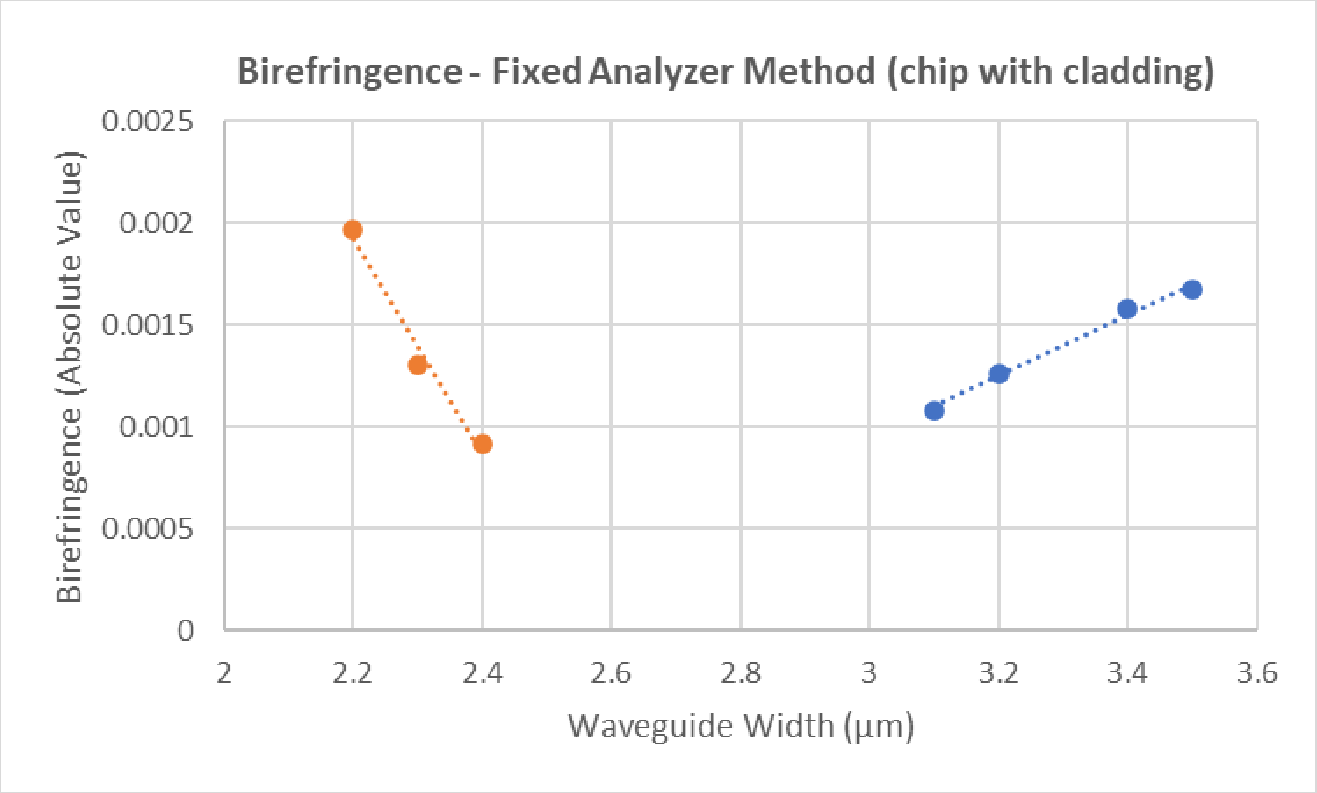




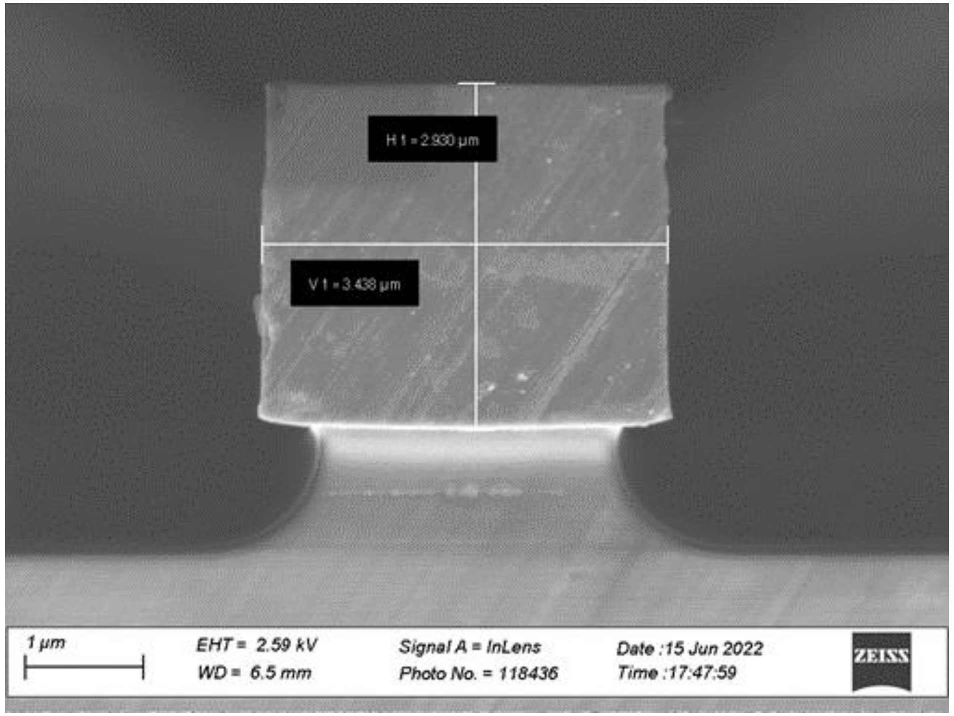


Birefringence measurement

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

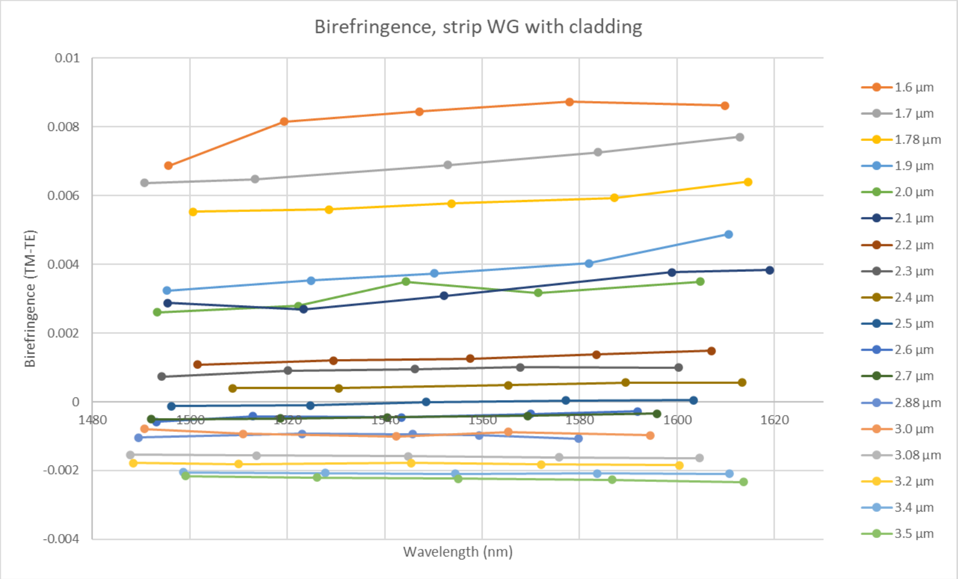


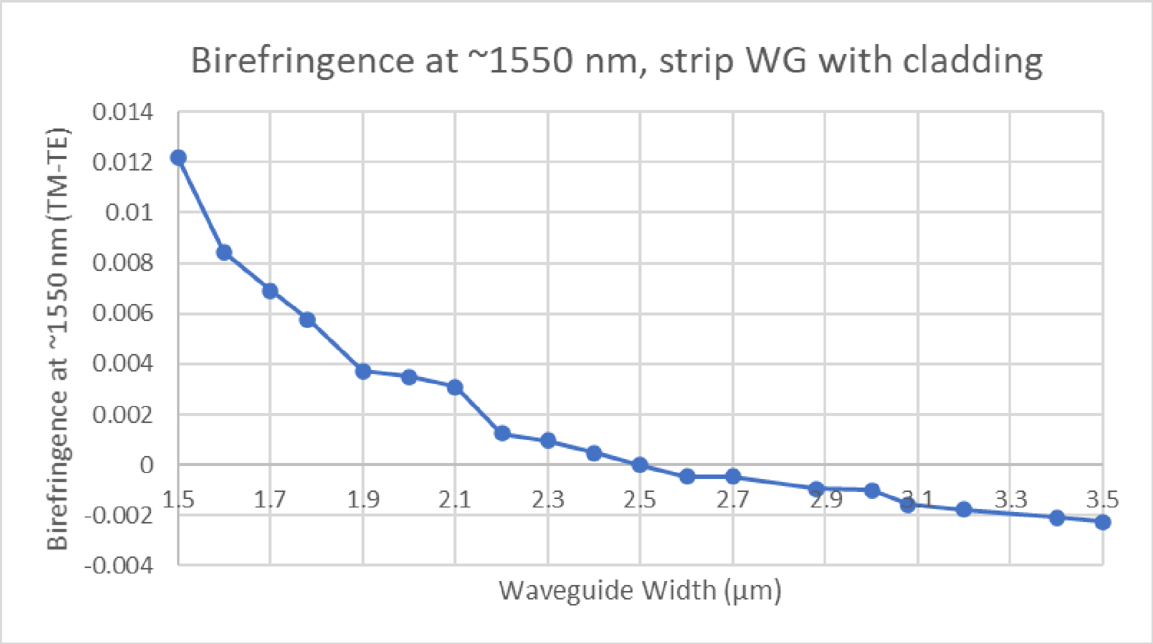
SEM image

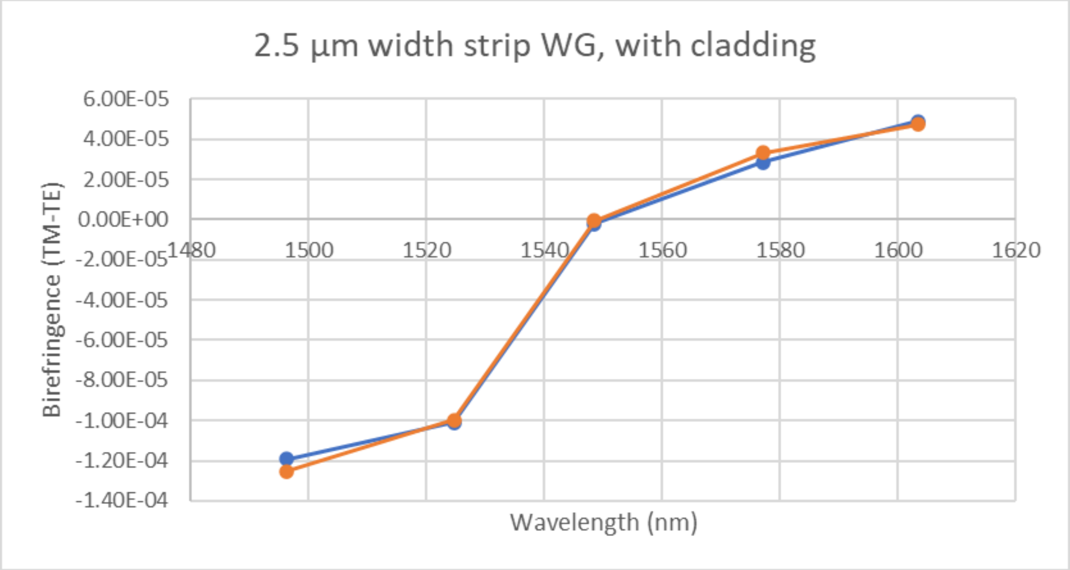


Fabry-Perot birefringence measurement

- More sensitive scheme based of Fabry-Perot method was setup and used to obtain more accurate estimates



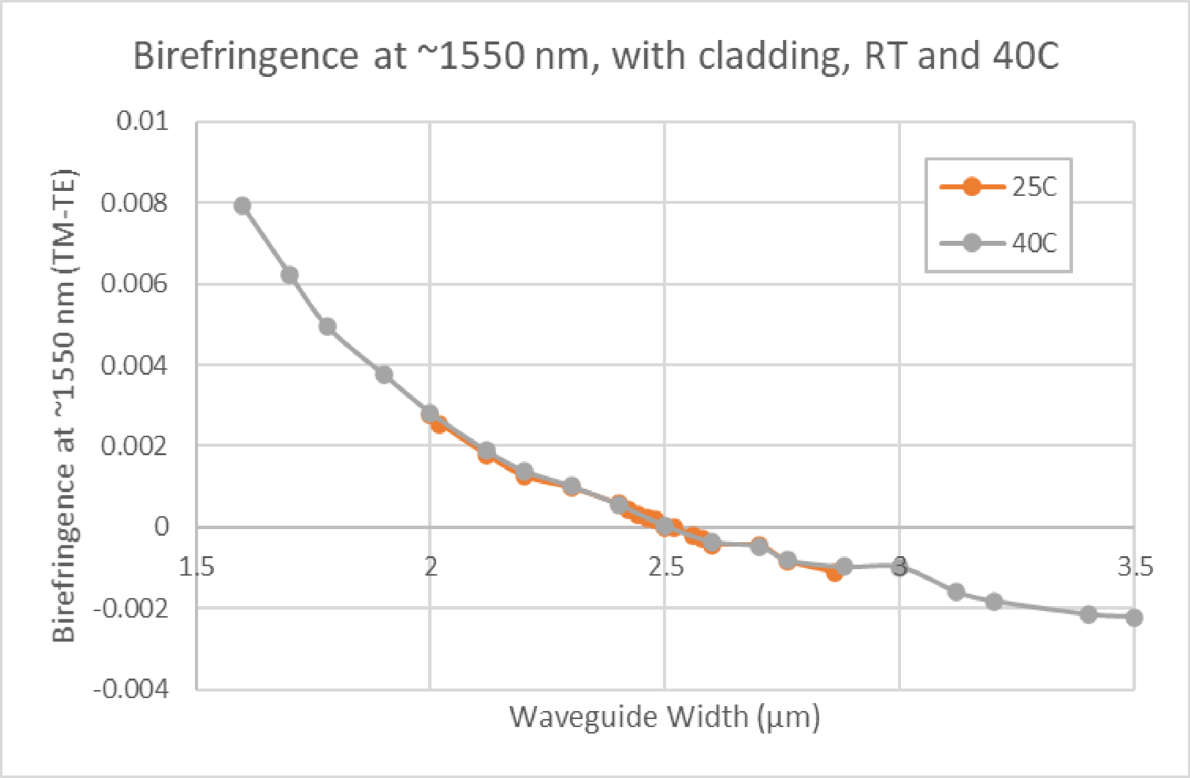




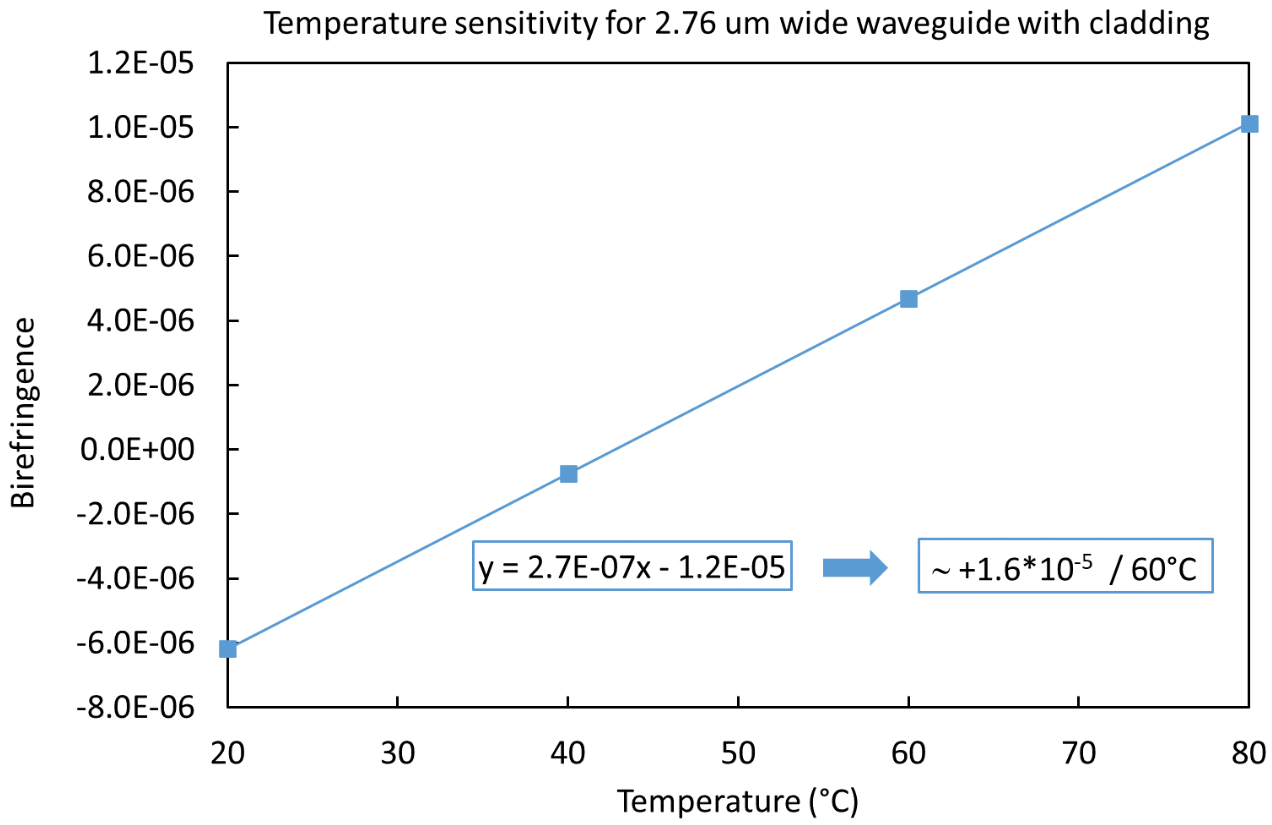
Moderate sensitivity to temperature

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

Fabry-Perot birefringence measurements



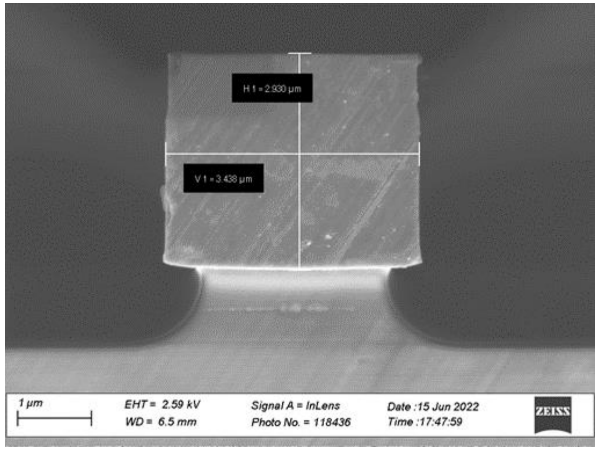
COMSOL modelling

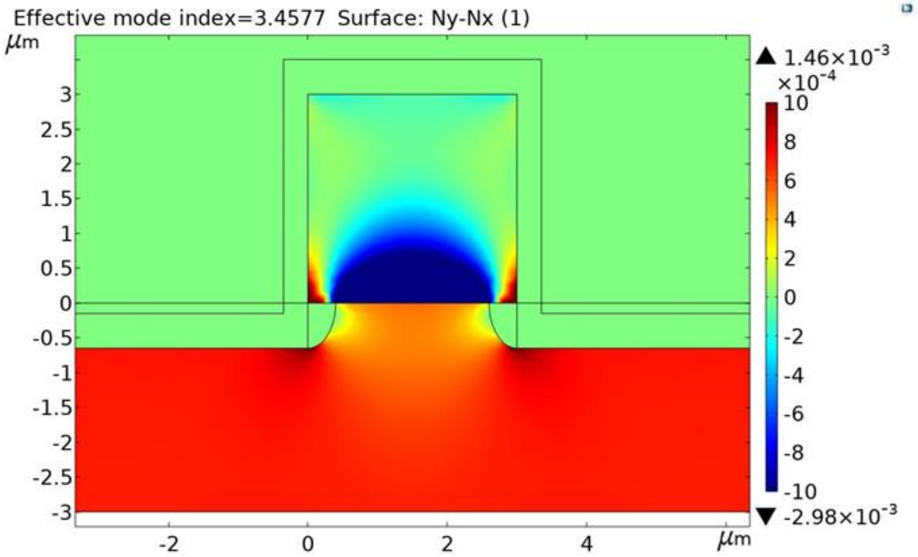


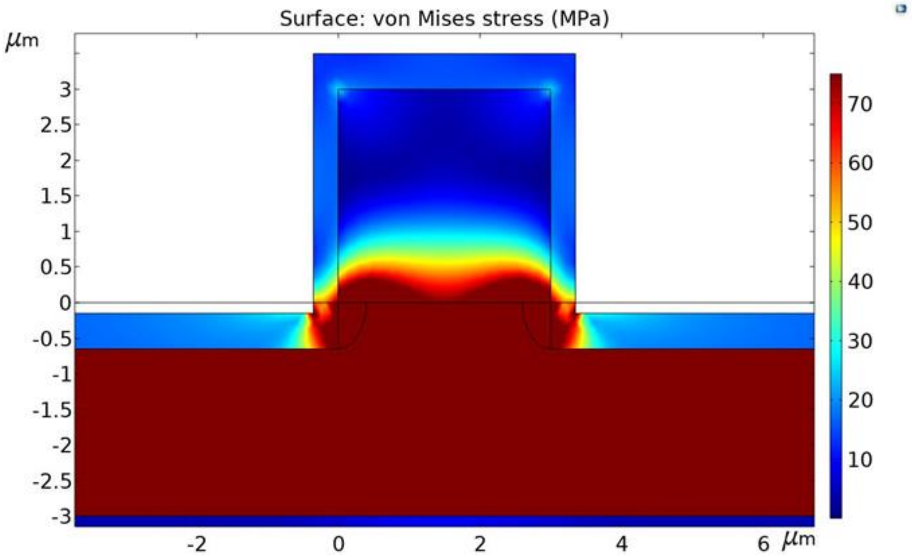
COMSOL® modelling of birefringence

- 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





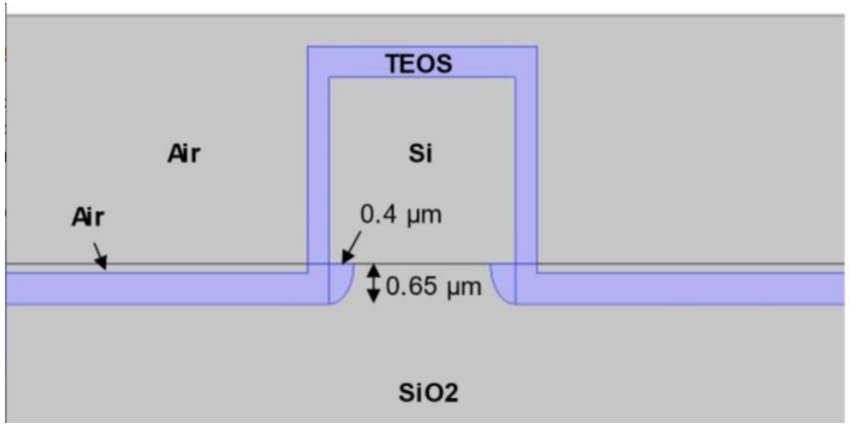


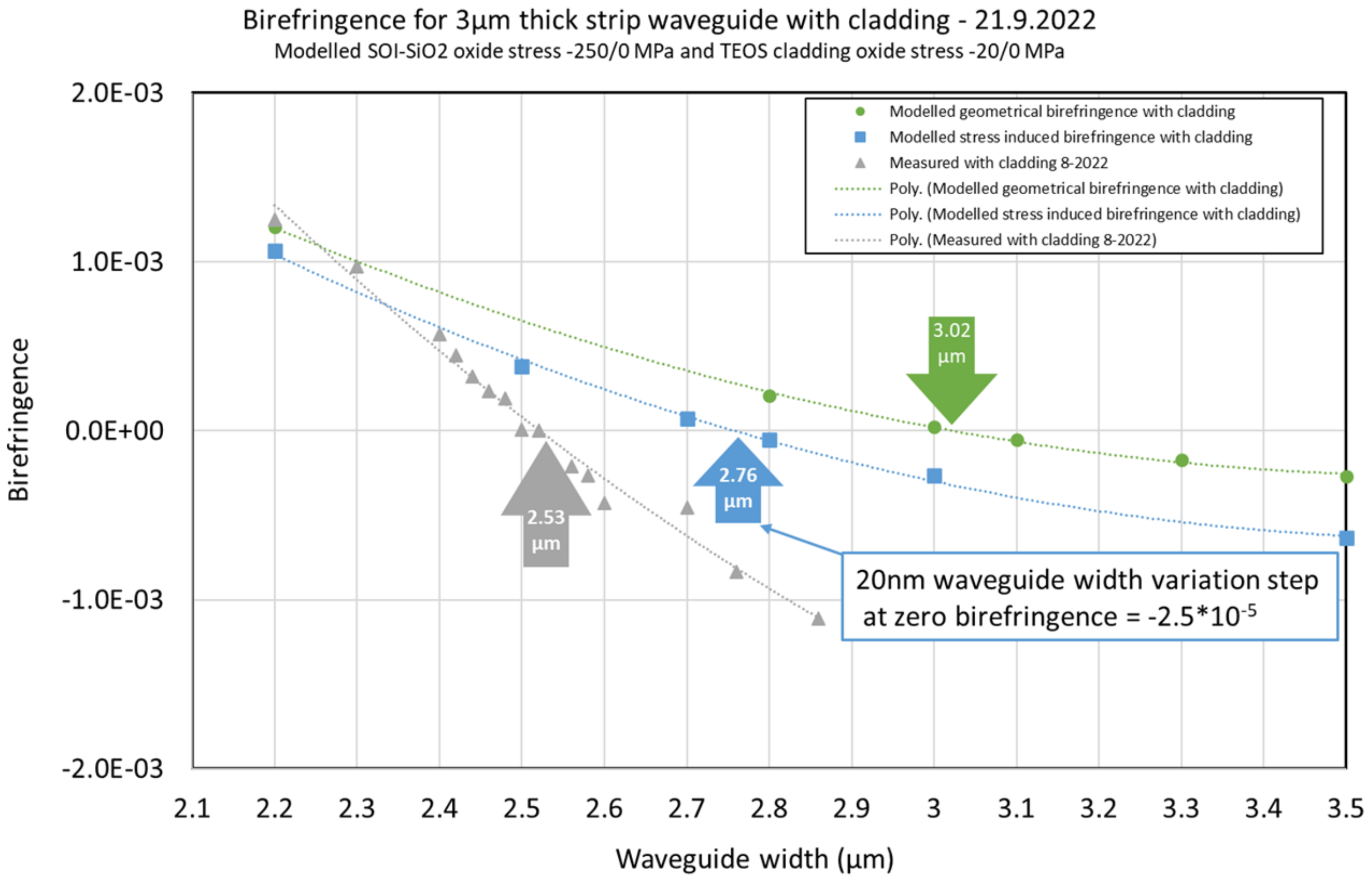
Birefringence origins

- Birefringence is caused by geometry and material (internal & external) stress
- Stresses depend on process temperature history

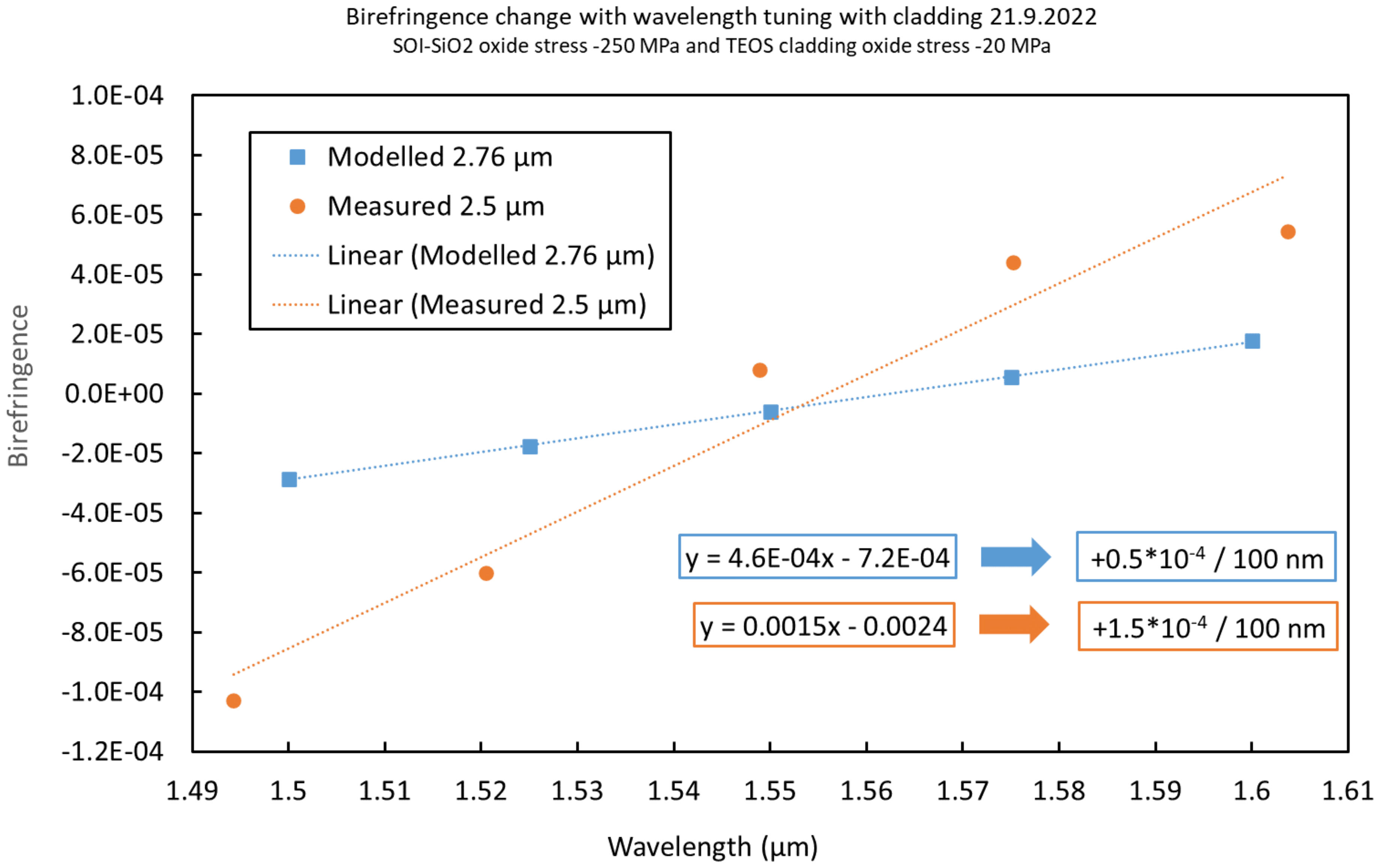
- Fair qualitative agreement between modelling and measurements
- Experimentally stress seems to play more significant role than small width variations

COMSOL model





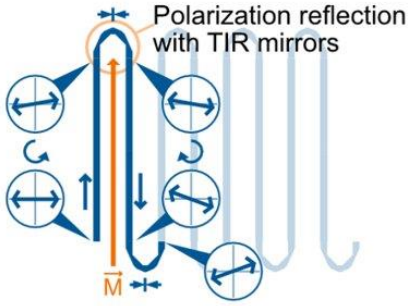
Simulations v measurements

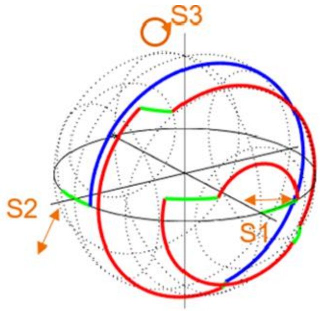


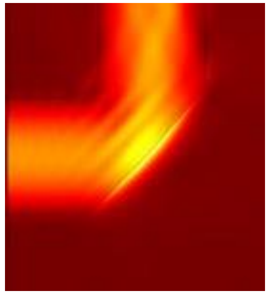
Measurements show ~3x stronger wavelength dependence than modelling

U-turn design

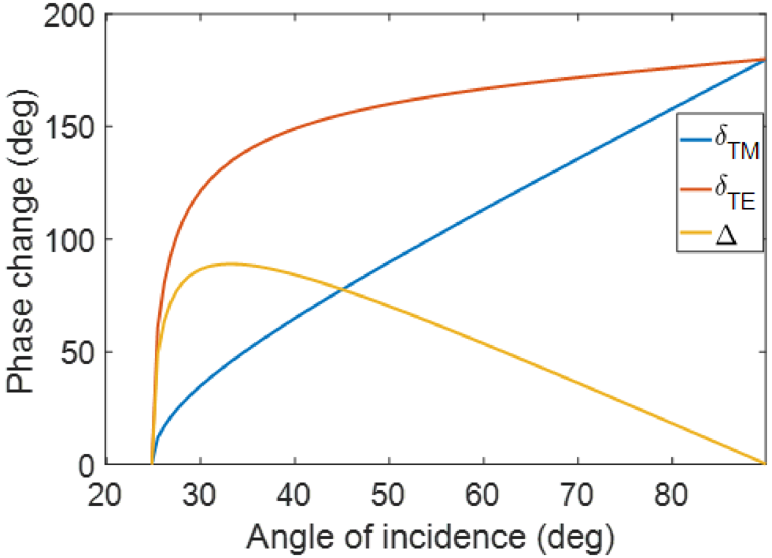
- Many options are being considered
- Physical constraint: 180° U-turn needed
- Phase change $\Delta \sim n\pi$ with n = odd integer
- Small losses needed
- Total internal reflection (TIR) mirrors are not wavelength dependent

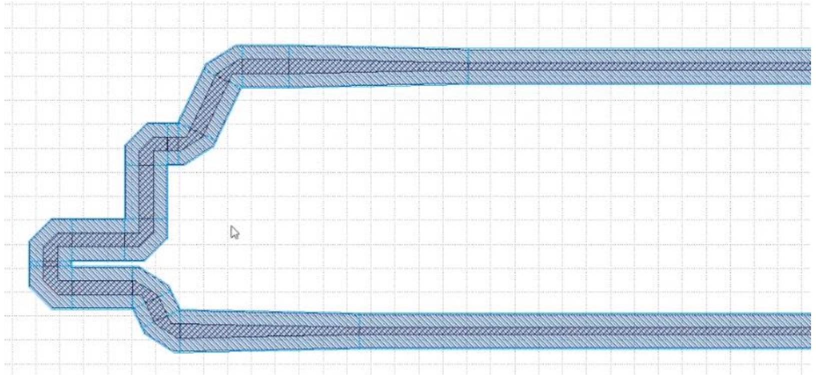


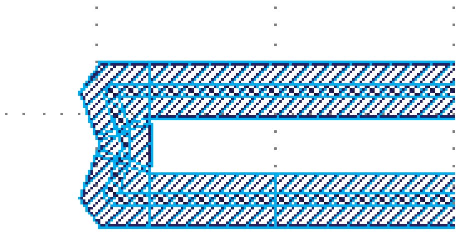




Fresnel equations:



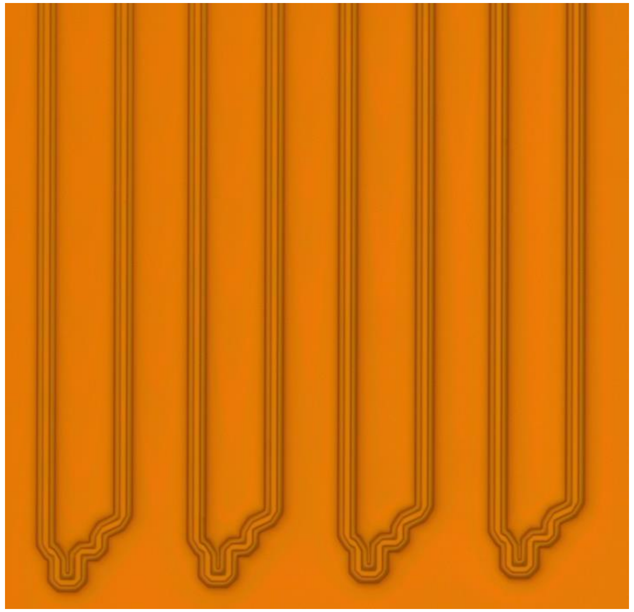


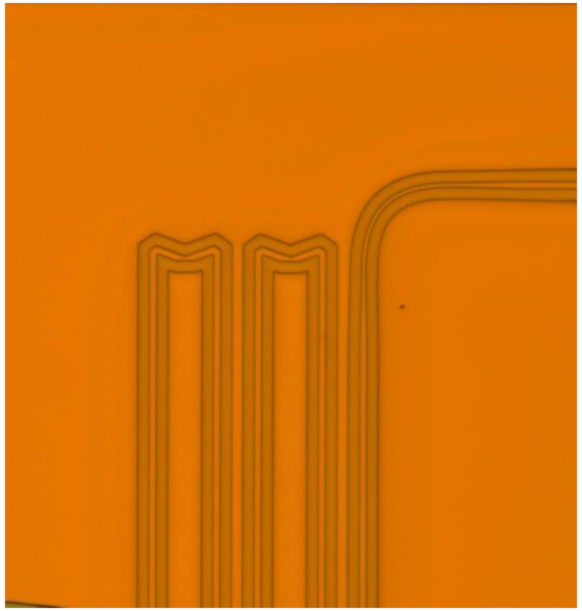


Fabricated Faraday rotator structures

- Devices for multiple u-turns with odd π phase shifts are successfully fabricated.
- Devices for multiple u-turns with compensated mirror structures are successfully fabricated.

8 mirror design yielding 3π phase shift



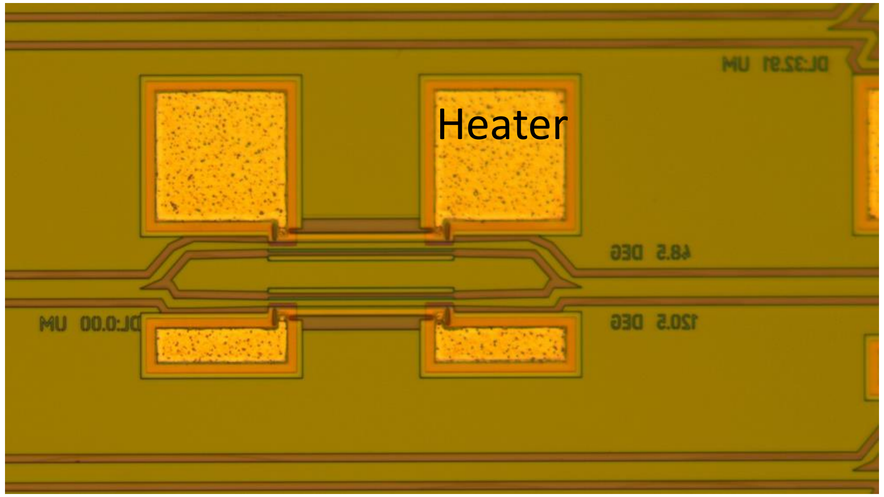


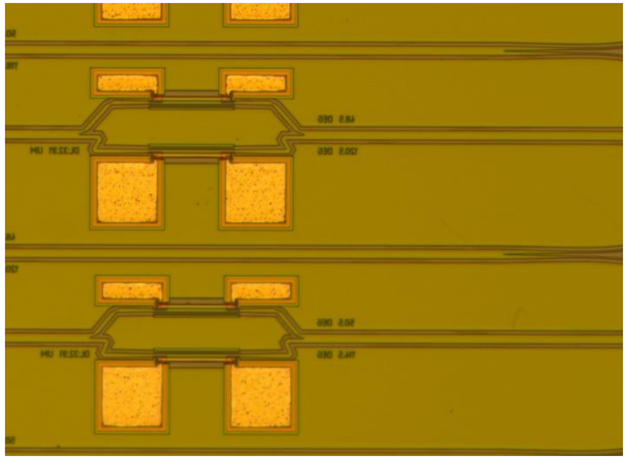
M shaped TIR mirrors: producing phase compensation to achieve 1 x π phase shift over two U-turns

TIR mirror-based polarization splitter

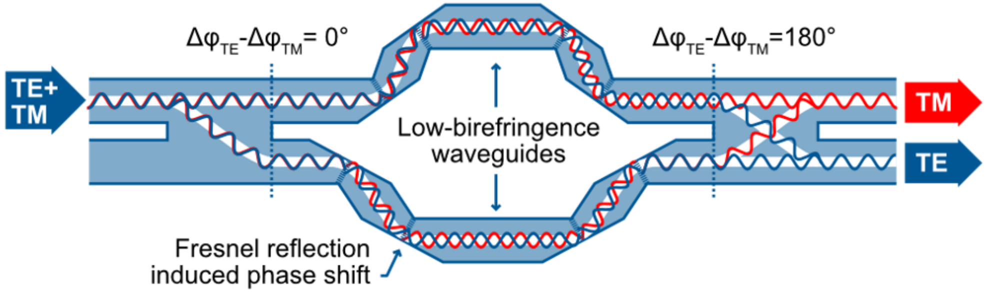
- Novel polarization beam splitter (PBS)
  - Separates TE and TM polarizations
  - Based on wavelength-independent and polarization-dependent phase shifts in total internal reflection (TIR) mirrors

Fabricated test structures



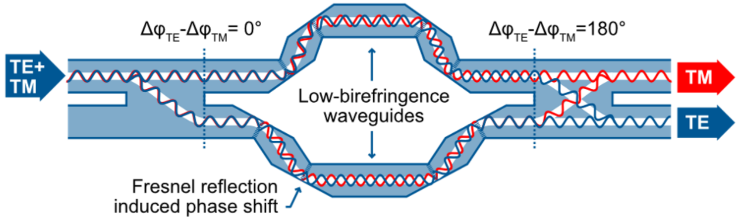


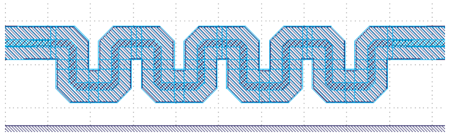
Schematic of TIR based polarization splitters



TIR mirror-based polarization splitters

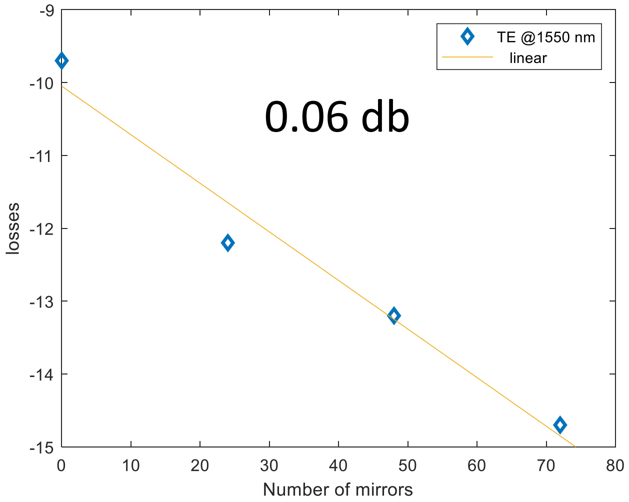
- Two performance metrics
  - Mirror performance (need low losses)
  - Extinction ratio (polarisation purity)



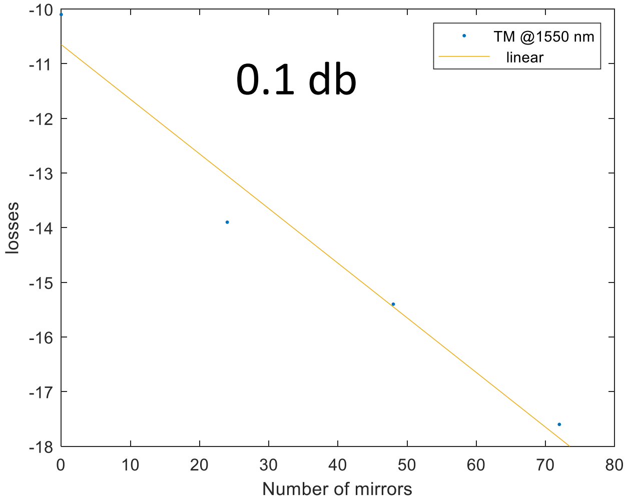


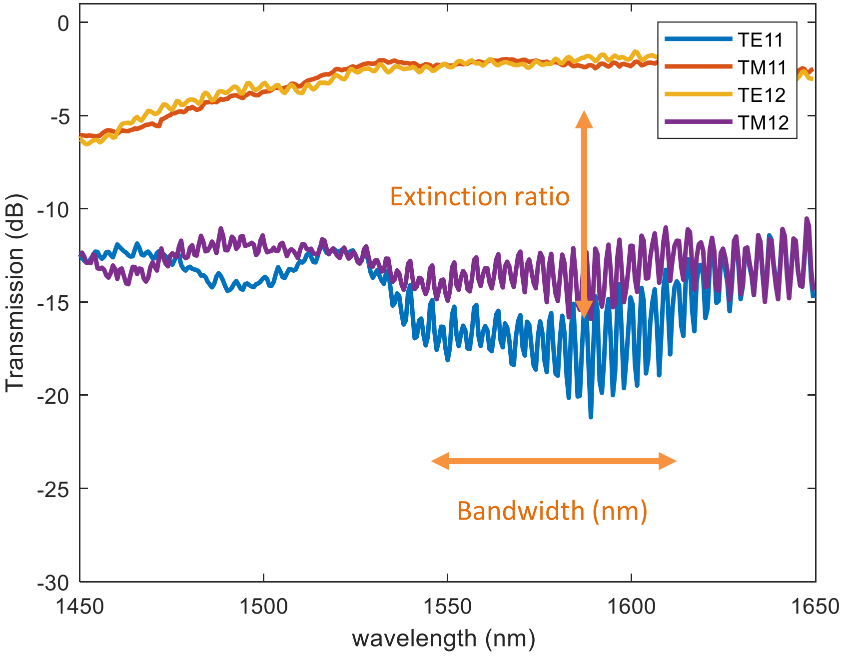
- Maximum ER 19 dB for 50nm for both polarizations.
- 15dB ER @ 100 nm for both polarizations.

0.06 dB loss per TIR mirror for TE-polarized light



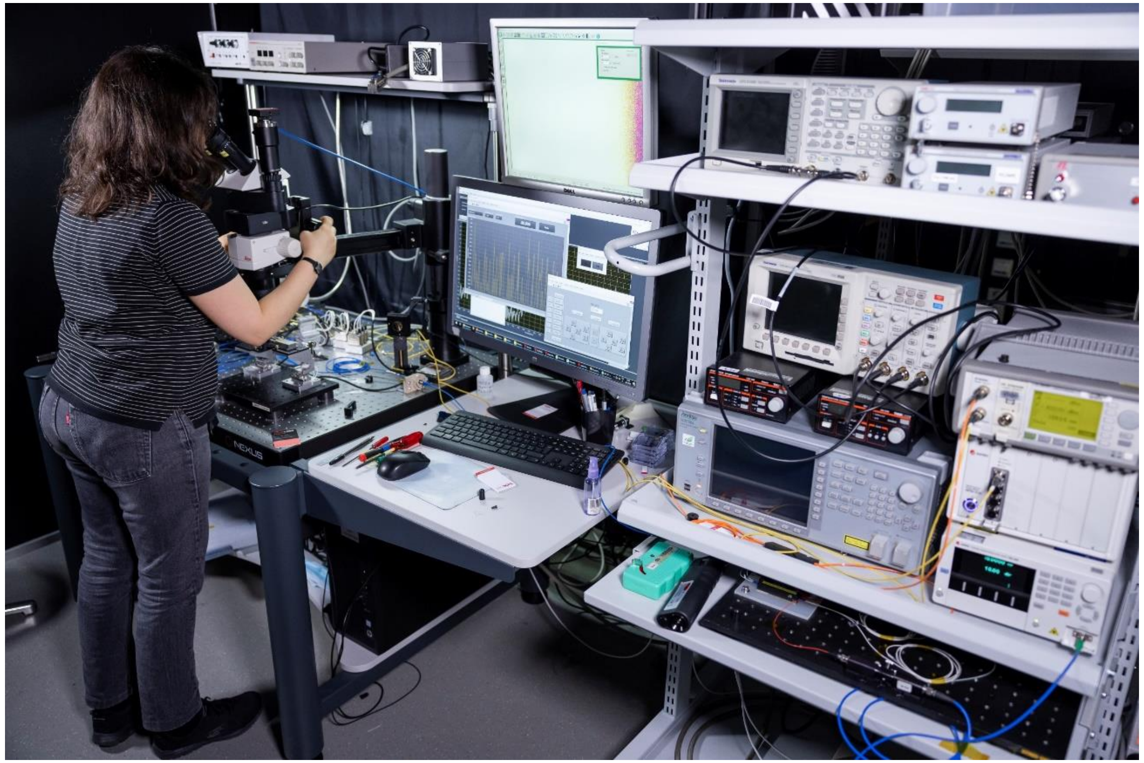
0.1 dB loss per TIR mirror for TM-polarized light

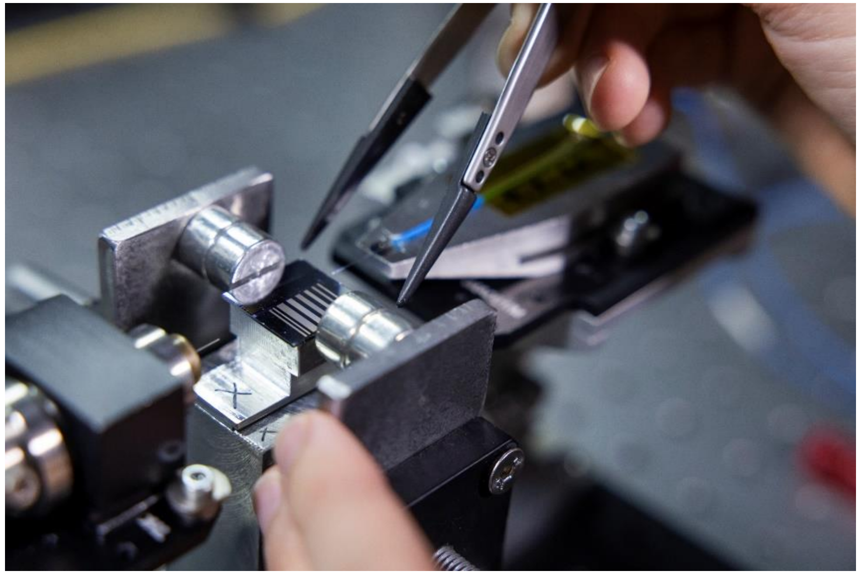




Optics laboratory setup

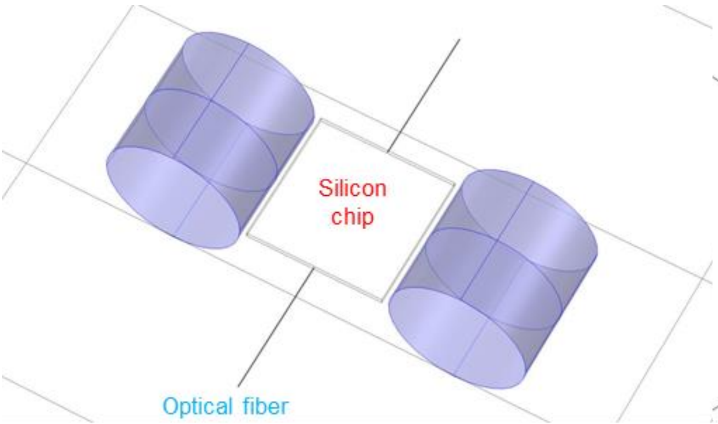
- Component characterisation, fibre splicing, done at home lab with watchmaker precision
  - Equipped with microscope, spectrometers, light sources, polarizers, …

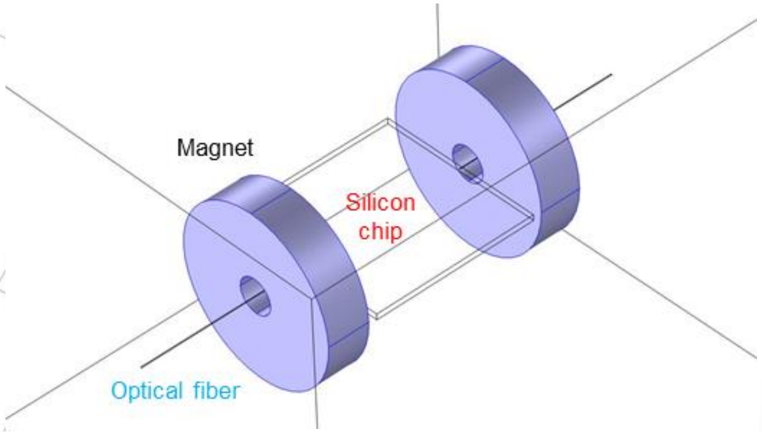


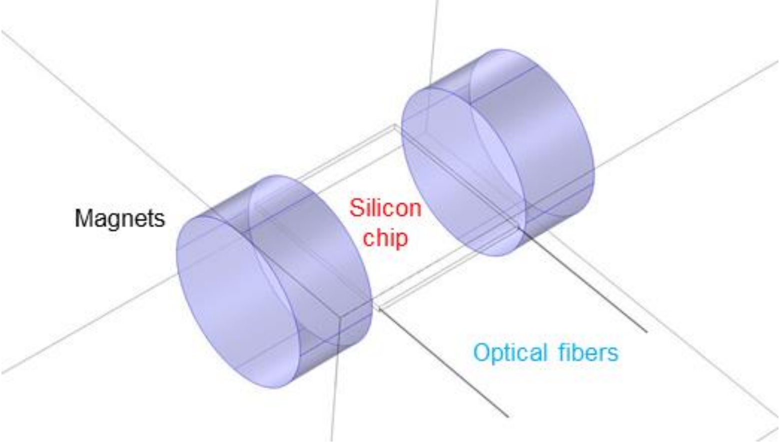


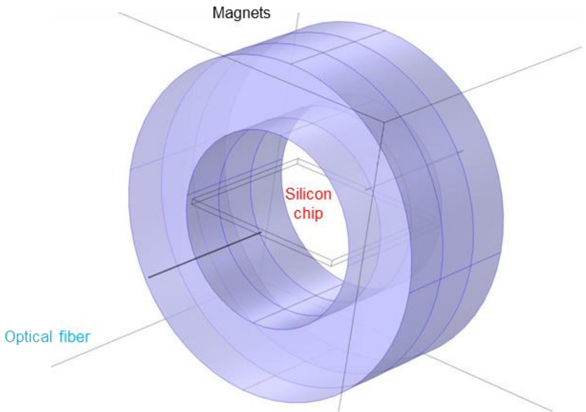
In-situ magnetic field setup

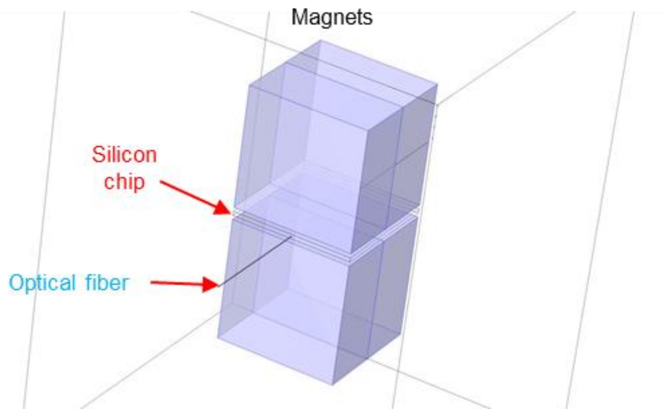
- Many constraints from available space, access and safety in setting up adequate in-situ magnetic field for component characterisation and Faraday rotation measurements
- Several permanent magnet options and configurations modelled with COMSOL to find the optimal

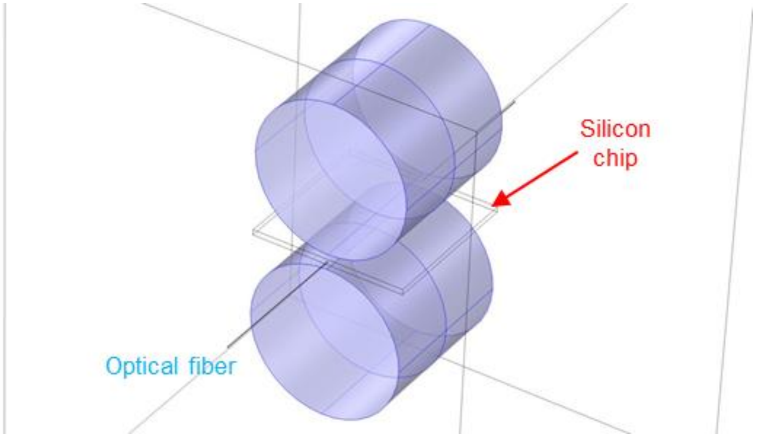




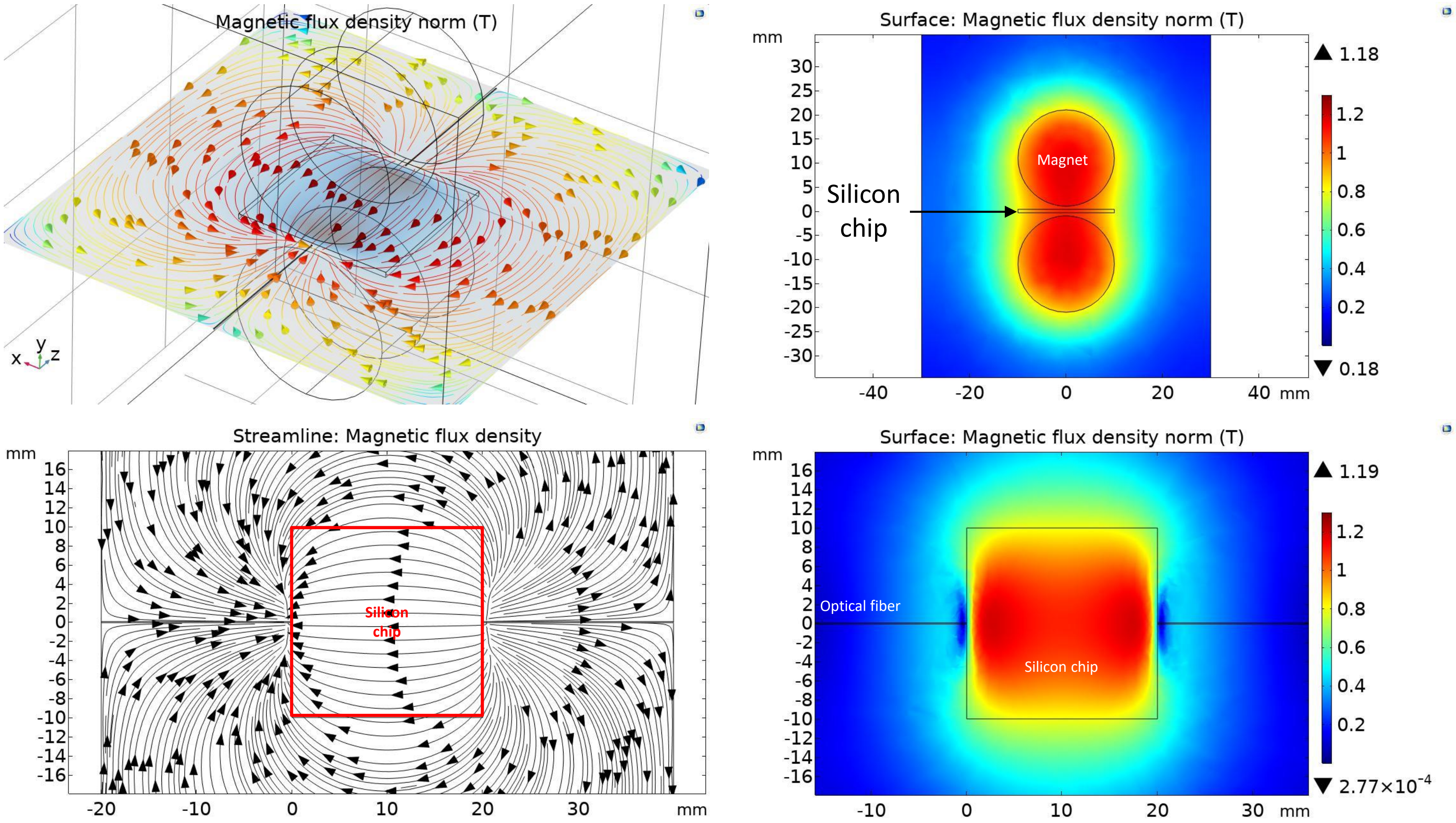








Strong & uniform magnetic field selected



Measurements in-situ and for integrated package

3D printed twin-magnet holder
(stack two for full effect)

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

Summary

- Despite the slow start we have
  - Obtained low enough birefringence waveguides that allow Faraday rotation
  - Built in-situ magnetic field setup for Faraday rotation demonstration
  - Verified that TIR mirrors have low losses (0.1dB)
  - 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 strong Faraday rotation for straight and folded waveguides
  - Optimise U-turns for 2.5µm wide waveguides to allow their characterisation
  - Integrating the components to perform as a sensor
- Project DL extension requested