EUROfusion

Enabling research: Silicon optics steady state magnetic field sensor

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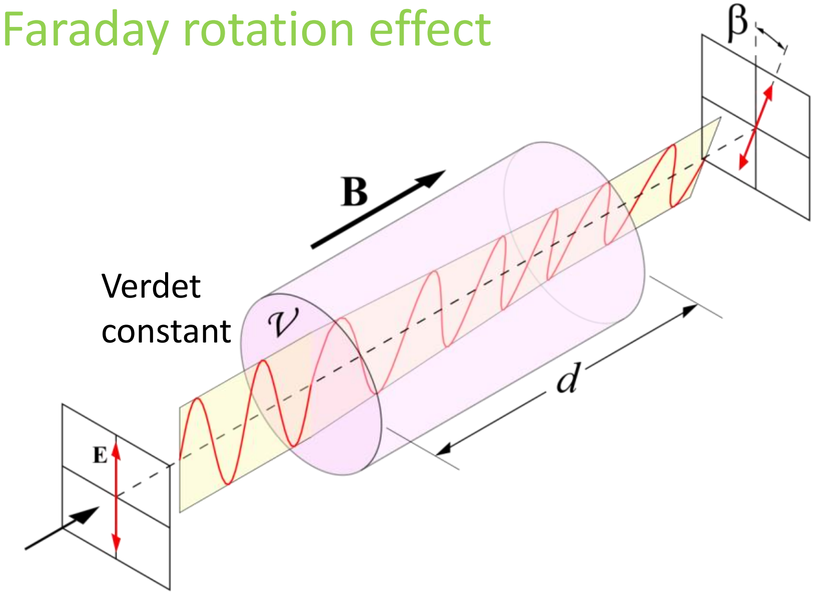
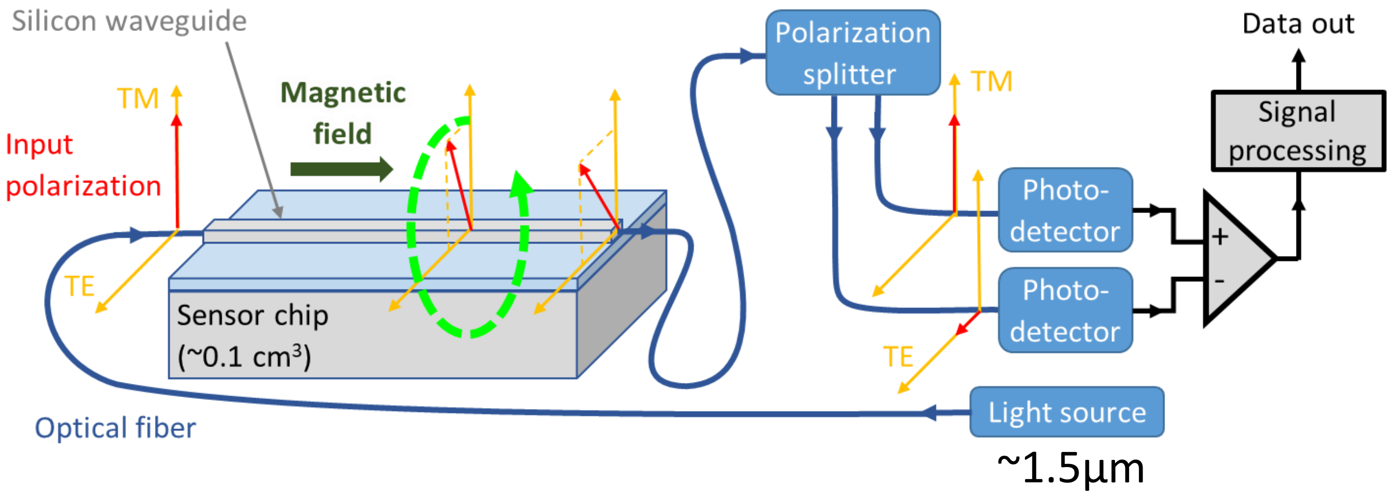
Measurement concept

Faraday rotation effect



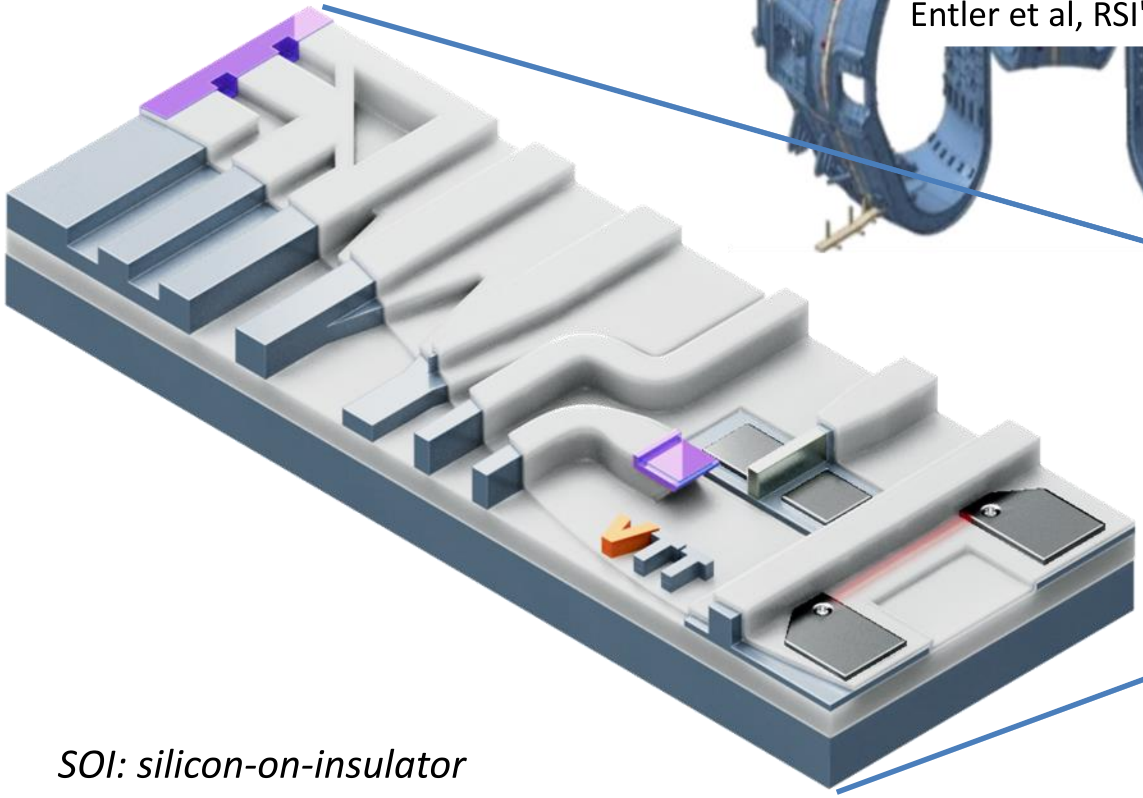
Sensor on silicon (simplified schematic)



- **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)



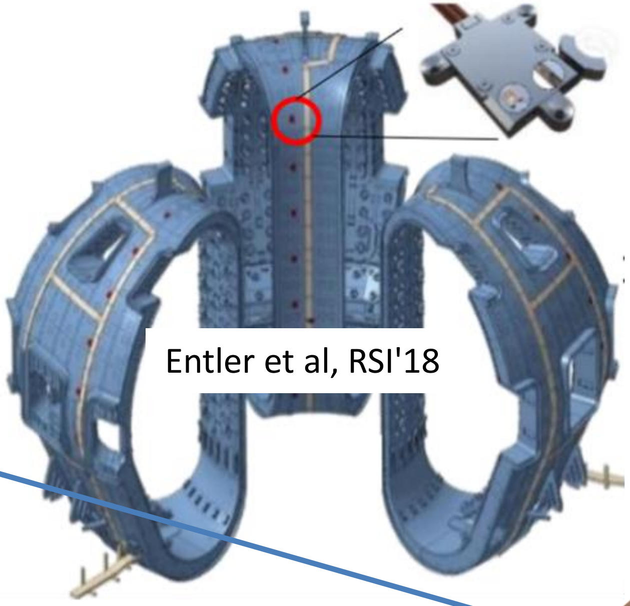
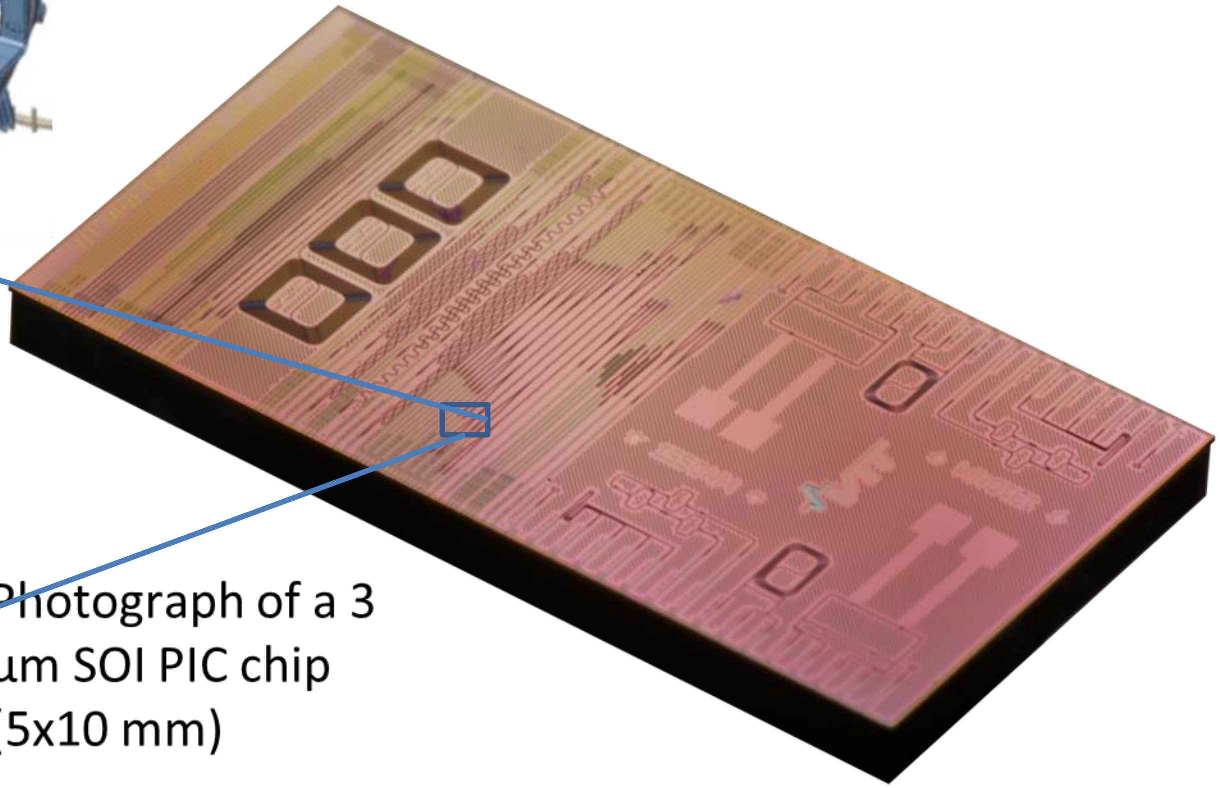


Illustration of a tokamak reactor with a (conventional) magnetic field sensor in one potential place for magnetic field measurement



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

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

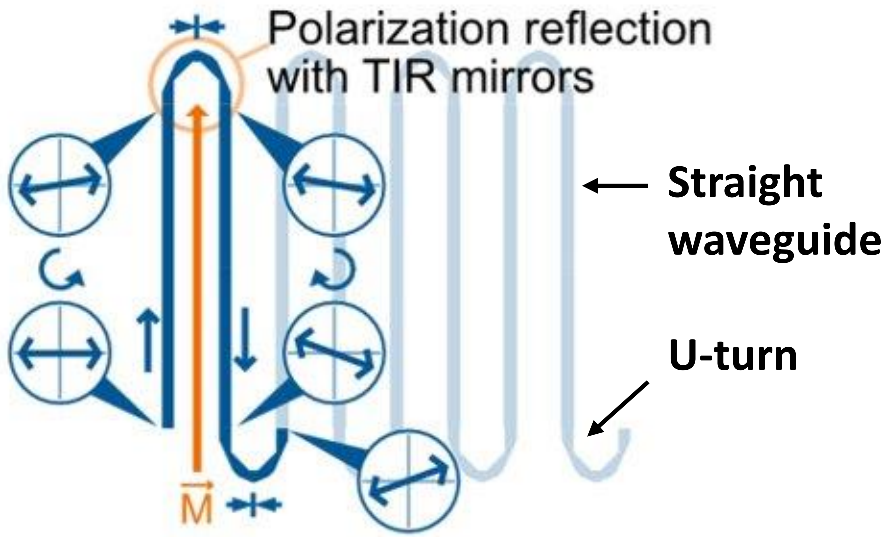
Multiple components needed for a sensor

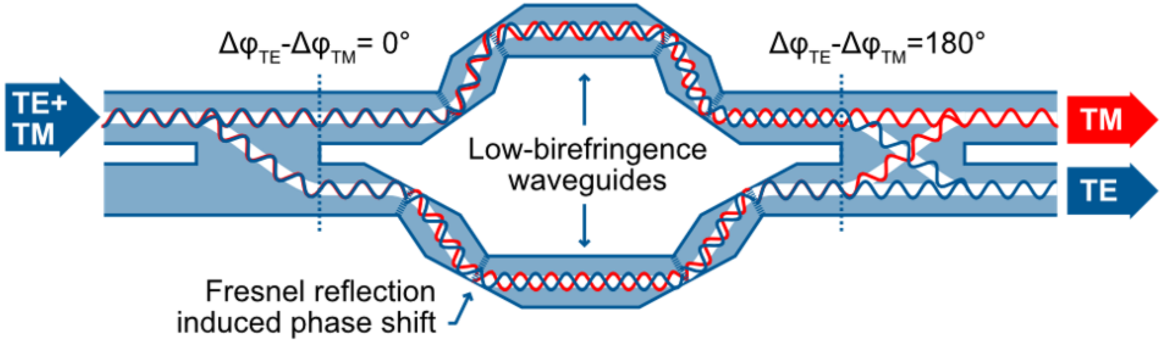
Faraday rotator based on

- **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

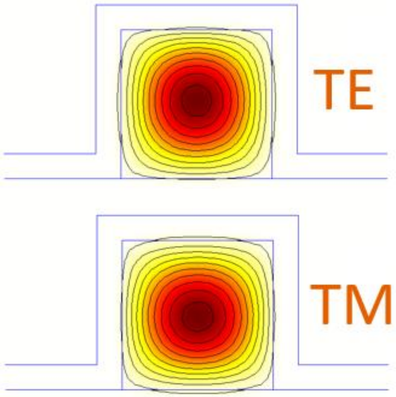
- To create linear input polarization
- To measure the amount of Faraday rotation

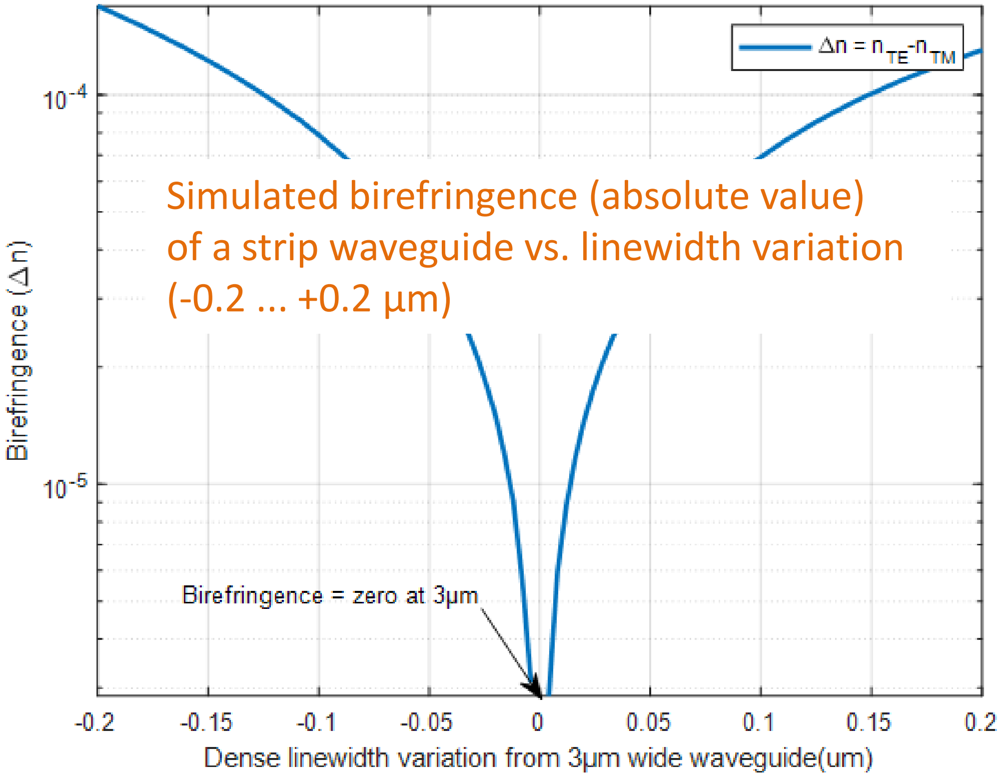


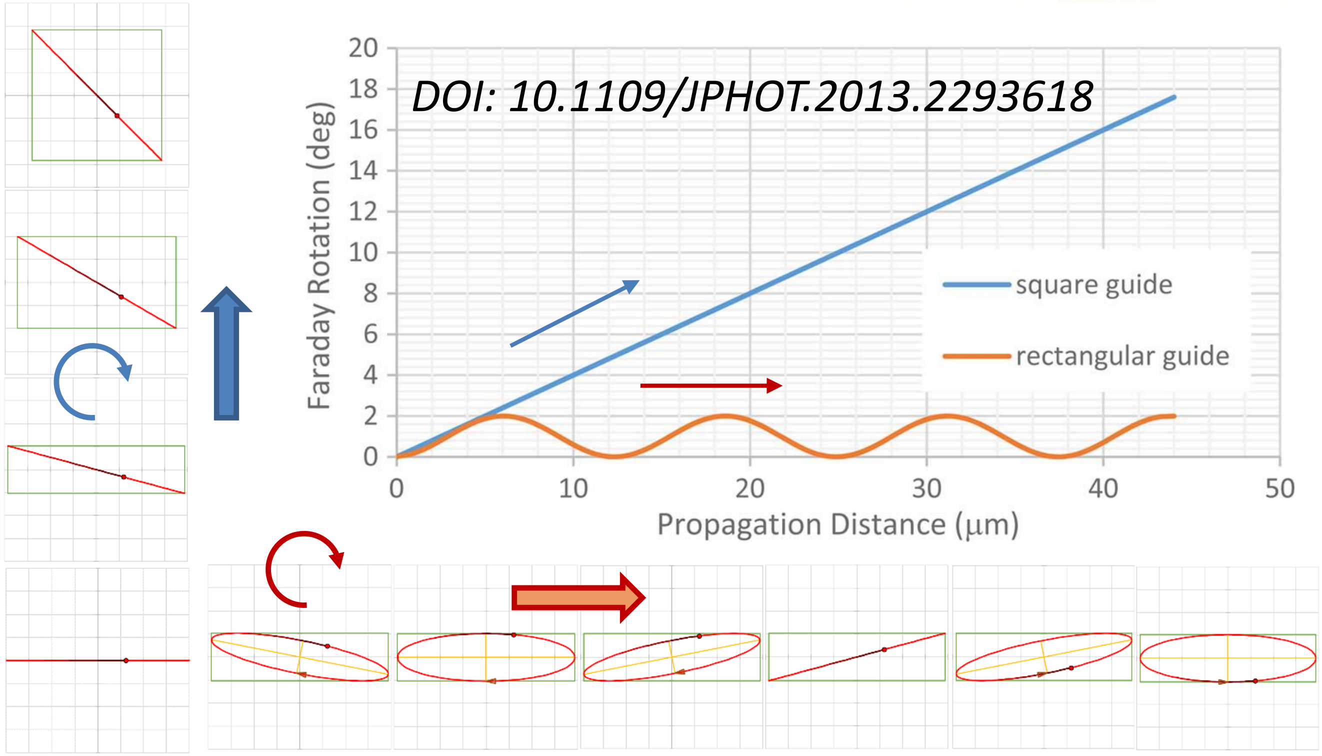


~Zero birefringence waveguides

- 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



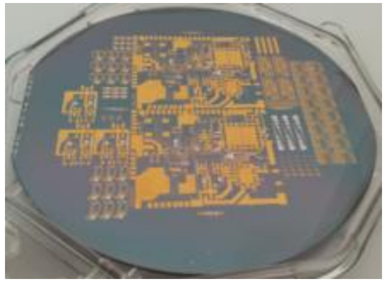


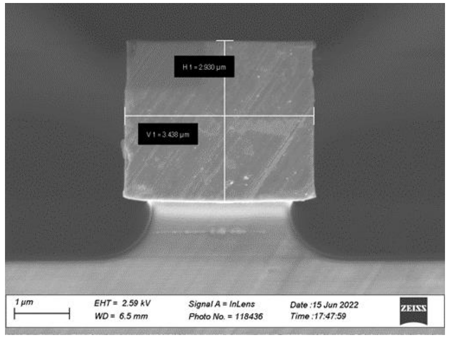


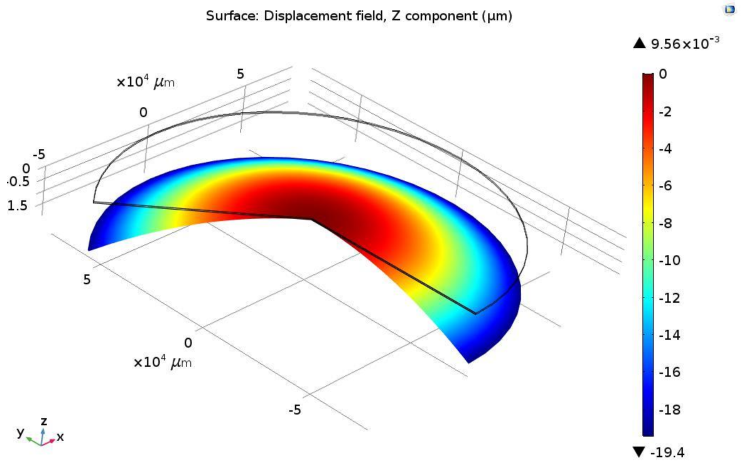
Experimentally inferred oxide stress values

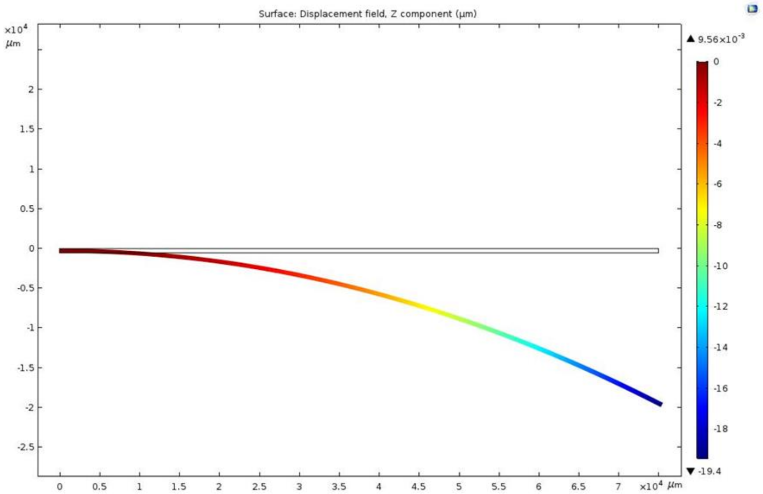
- Oxides on silicon monitor wafers
  - Bow measurements before and after oxide deposition
  - COMSOL modelling to define corresponding wafer bending value

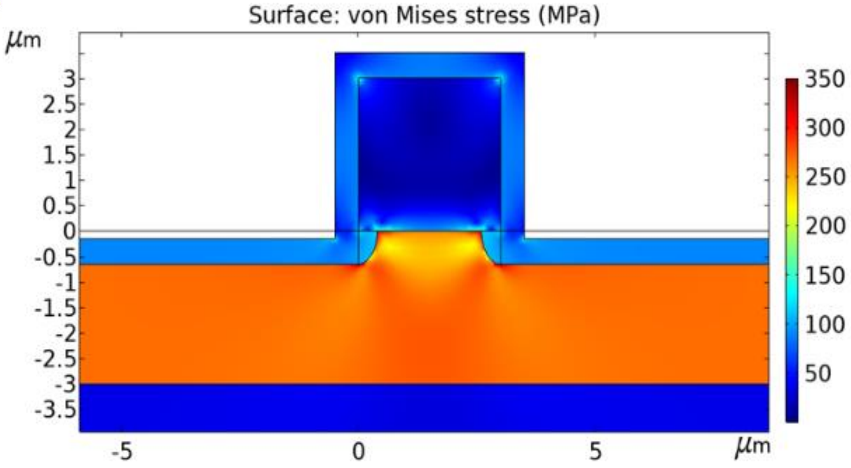
  $\Rightarrow$ Experimentally defined stress value







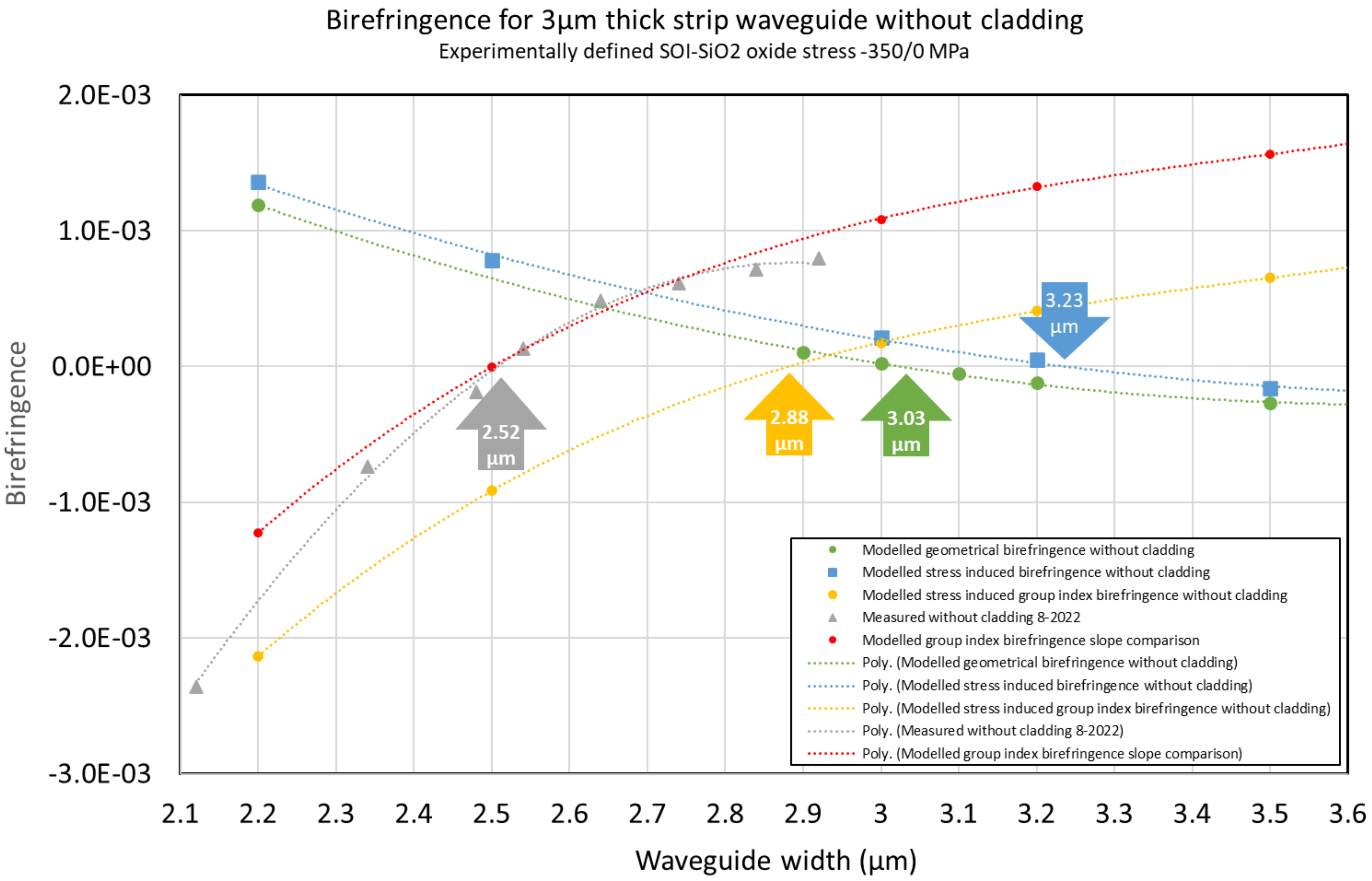




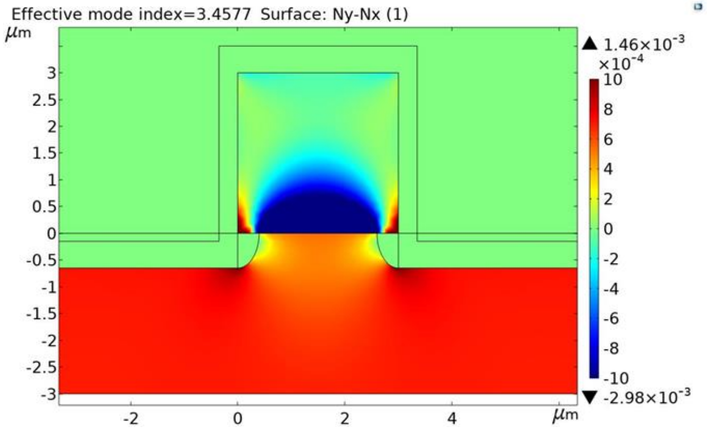
3D axisymmetric model

Simulated birefringence

- Experimentally defined SOI-SiO2 BOX oxide stress -350 MPa

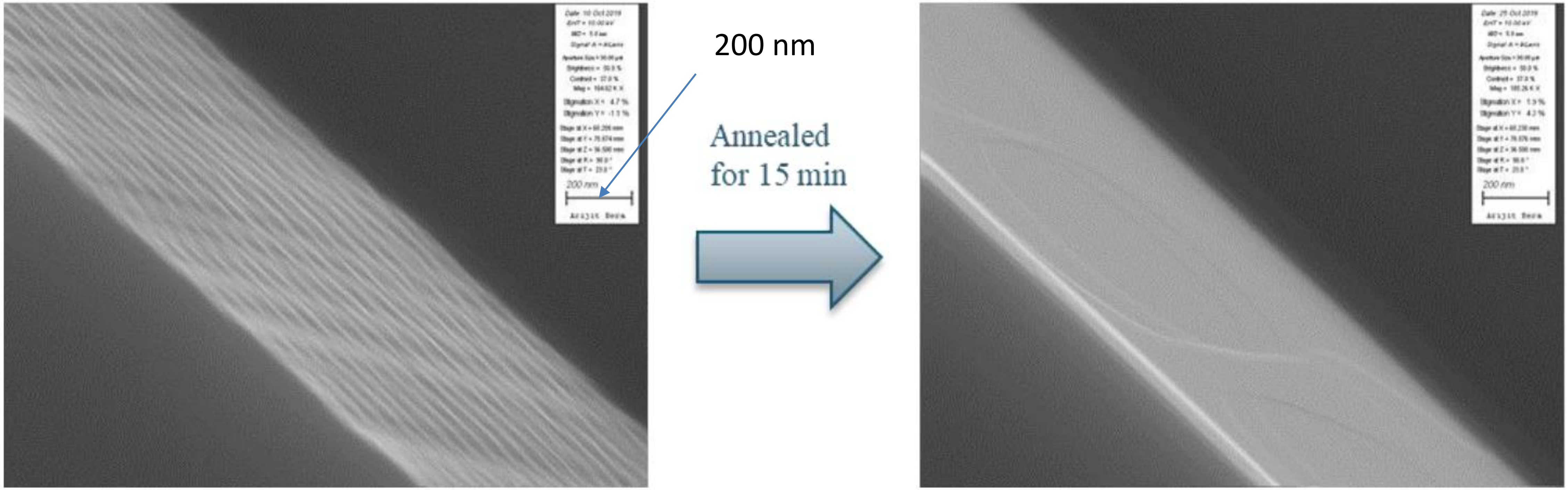


$$n_g = n_{\text{eff}} - \frac{\lambda \mathrm{d}n_{\text{eff}}}{\mathrm{d}\lambda}$$



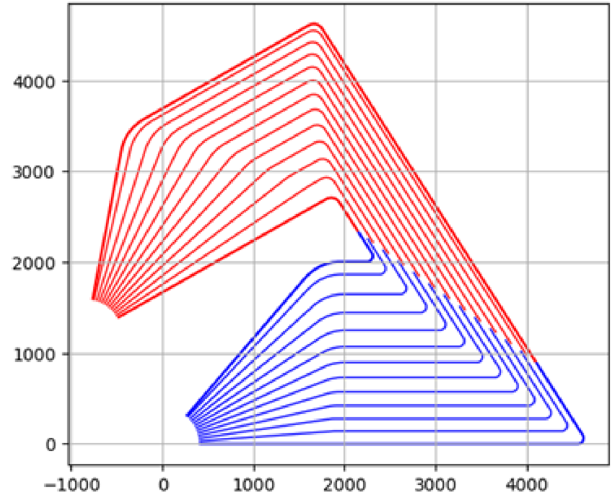
Hydrogen annealing for smoother waveguides

- SEM images of Hydrogen annealed waveguide surface after 15 min treatment
- Measurements show 75% improvement in polarisation extinction ratio and attenuation down to 4 dB/m



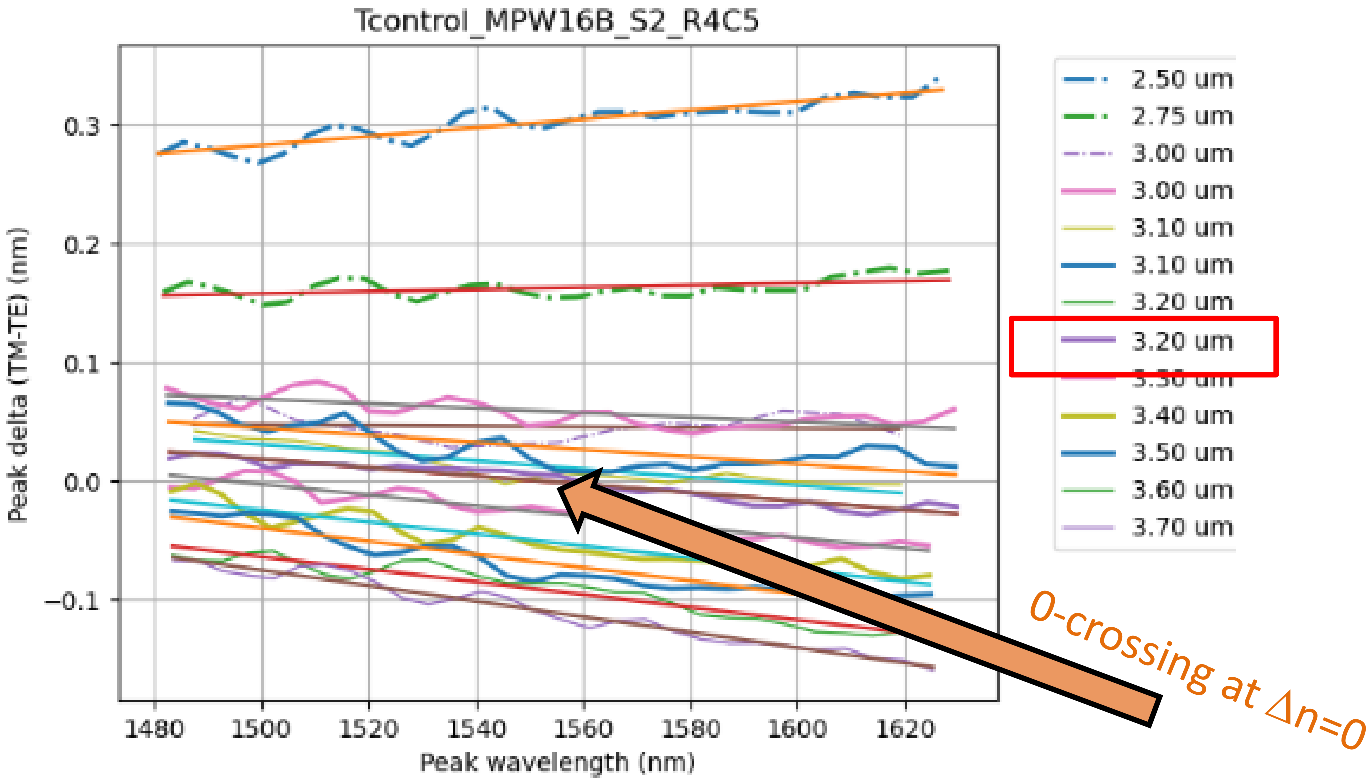
Birefringence measurements

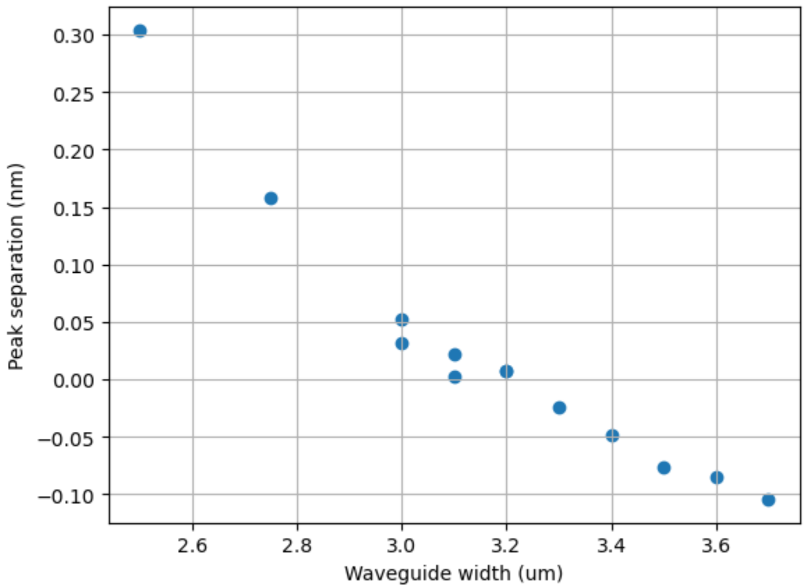
- Effective index birefringence cannot be measured from a single waveguide
  - Specific test structures are needed for each waveguide dimension of interest
- Two approaches utilised
  - Arrayed waveguide gratings (AWG)
  - Folded waveguides with a 3-point scan in straight section lengths

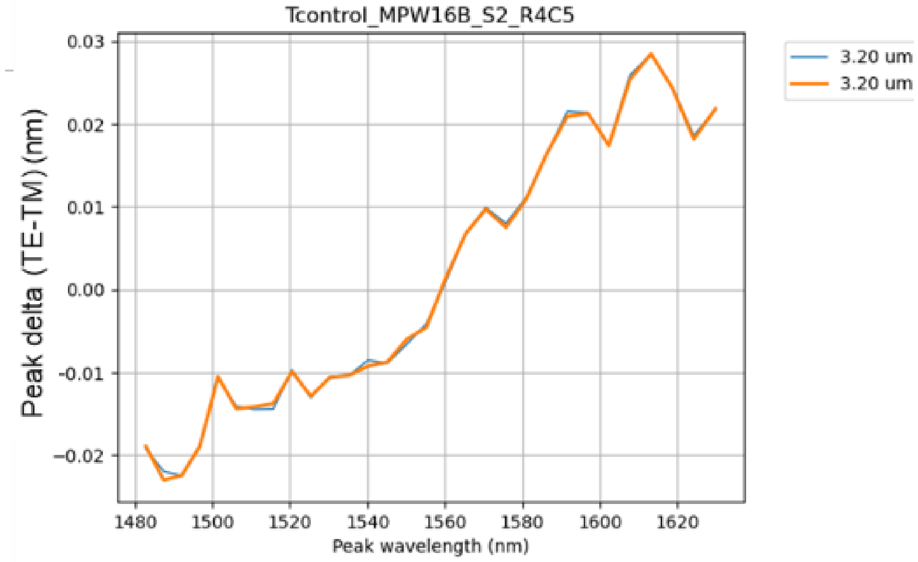


AWG measurements

- Rough scan of waveguide widths point to 3.2µm
- Measurement noise is small as seen from repeat measurement
  - Small scale variation likely due to 3D roughness of the waveguide surfaces

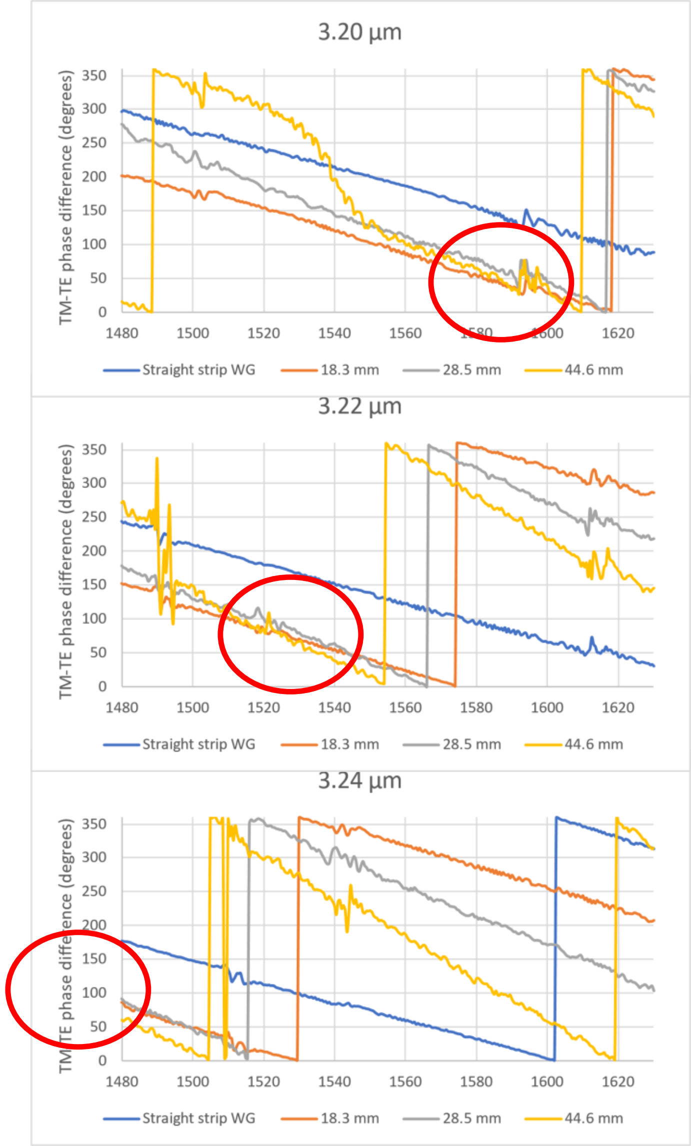






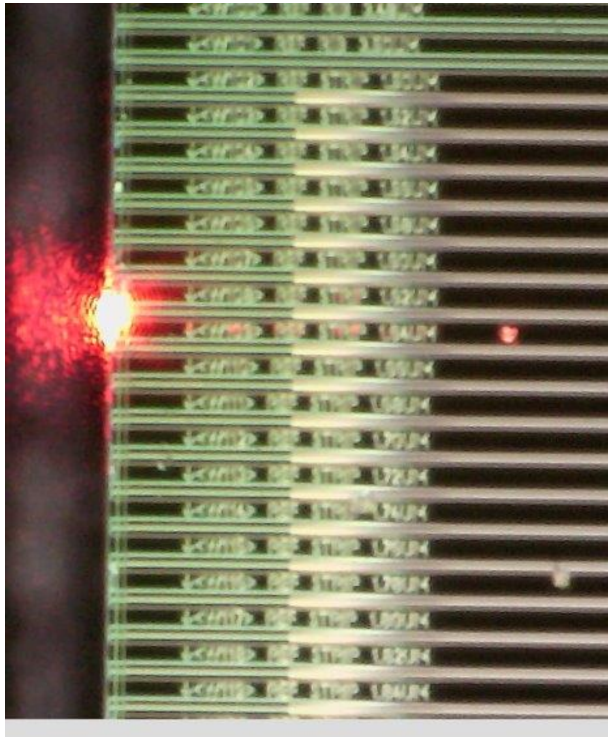
Folded waveguide

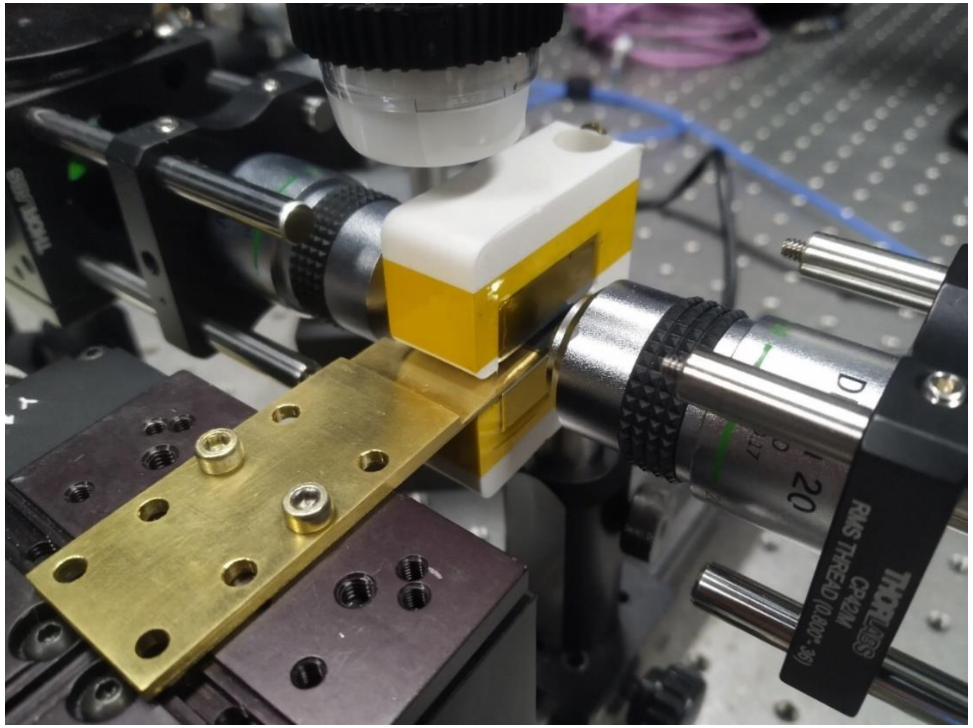
- Test structures from the same wafer show the same width for the minimum birefringence ~3.2µm
- The location of the 3-way crossing point moves to smaller wavelength with increasing width similar to AWG measurements
- NB: waveguides from another processing run have the crossing near ~3.1µm indicating sensitivity to the exact manufacturing ‘recipe’

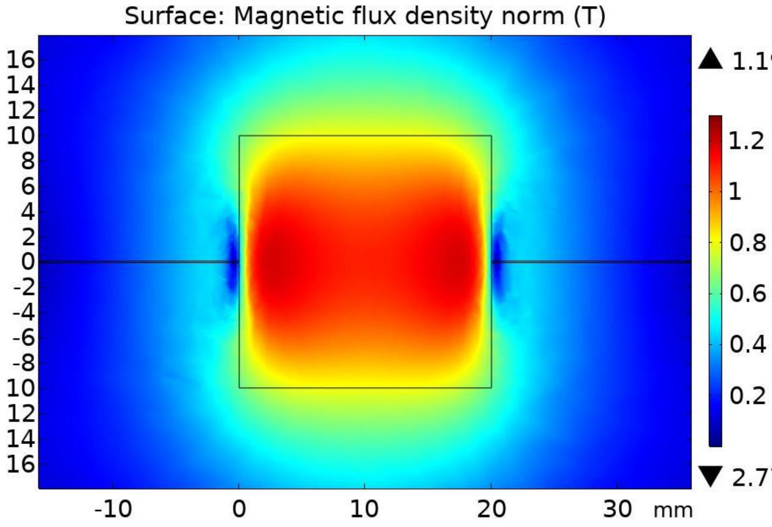


Faraday rotation measurement setup

- Movable permanent magnet with 1 T allows clean measurement of with and without magnetic field
  - COMSOL calculations confirm magnetic field uniformity

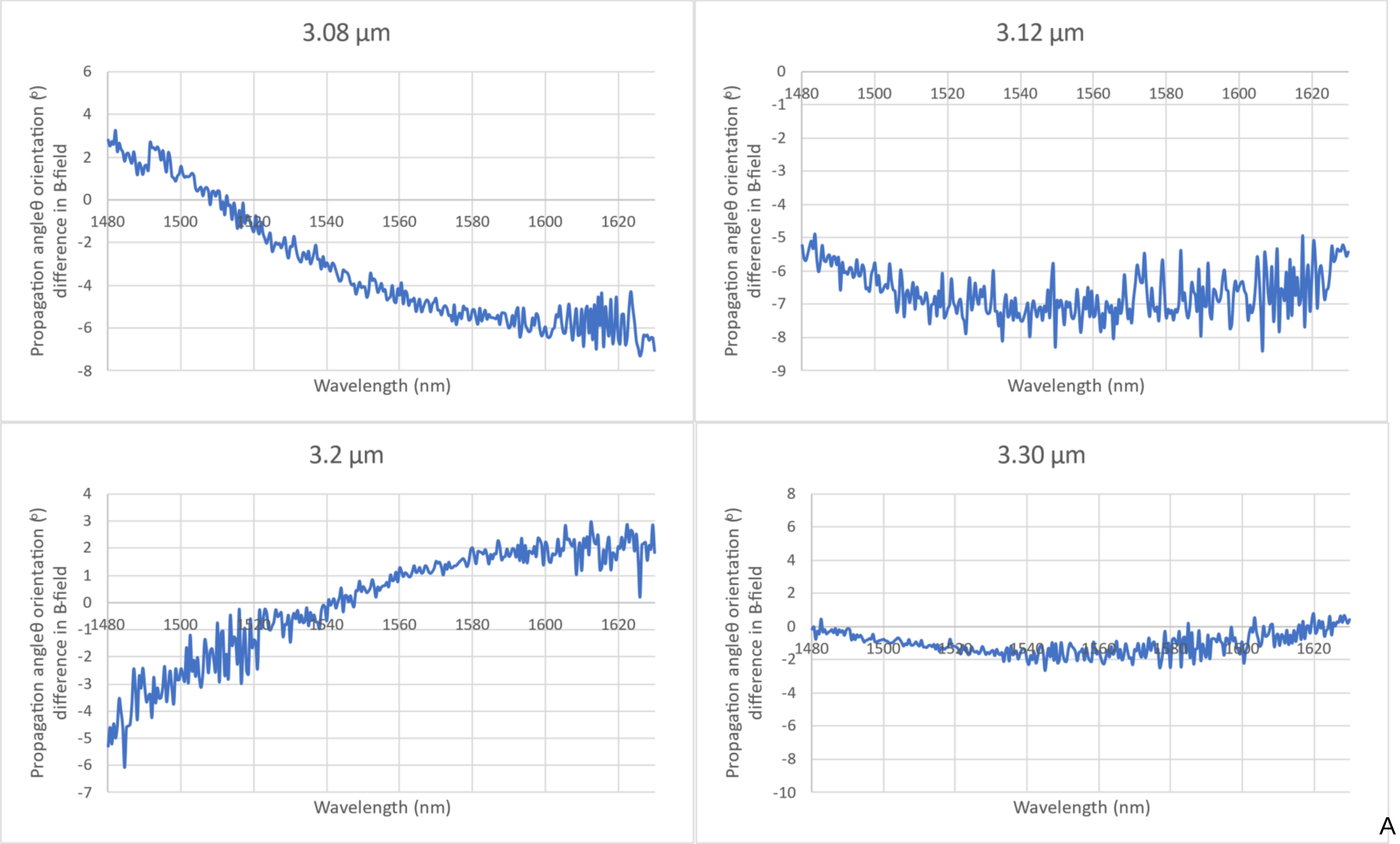


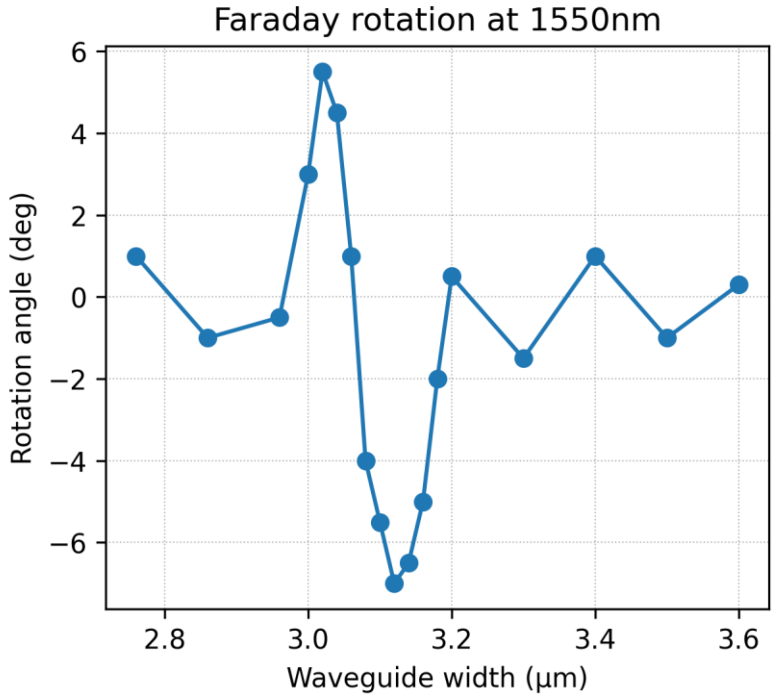




Rotation angle difference measurement @1T

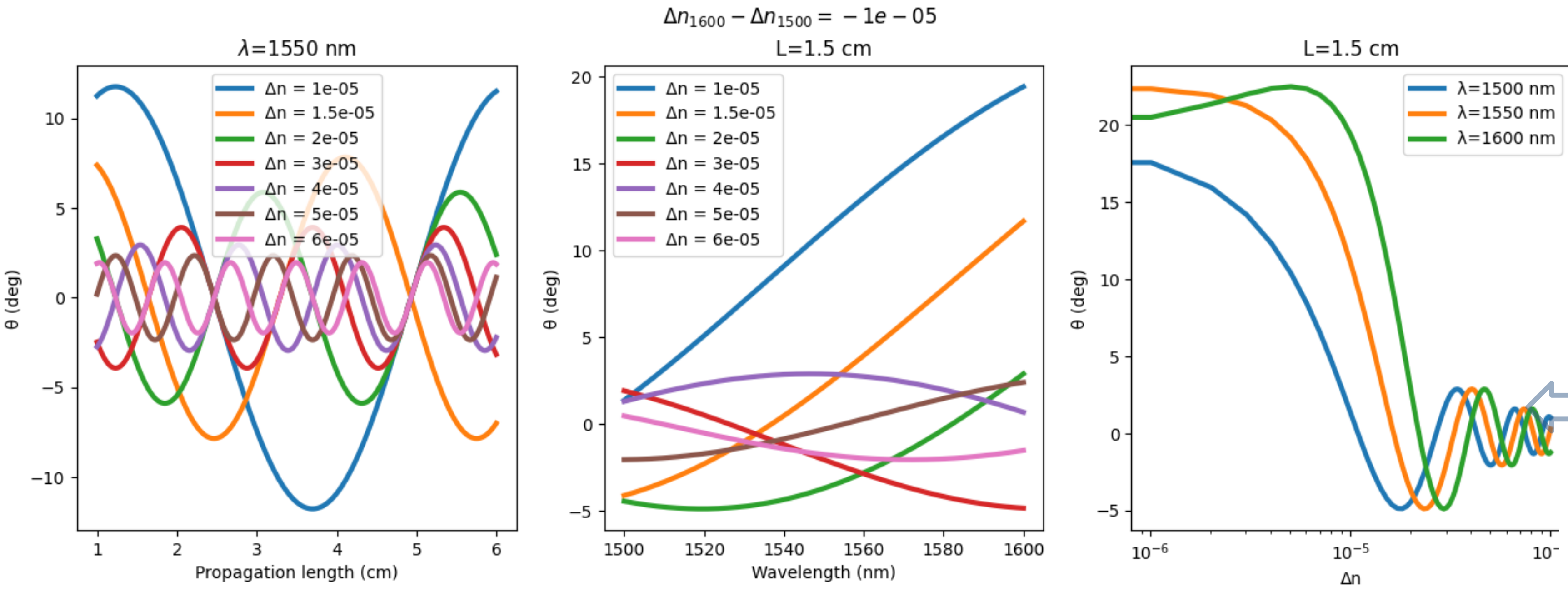
- Rotation angle should be ~22.5deg for *Verdet constant* 15 [deg/T/cm] at zero birefringence
- Is this Faraday rotation?



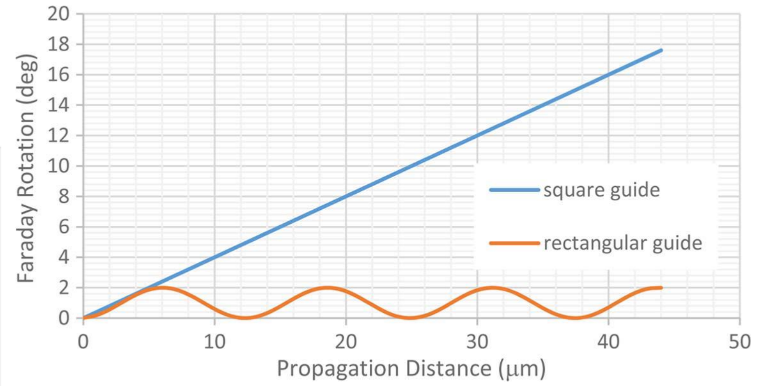


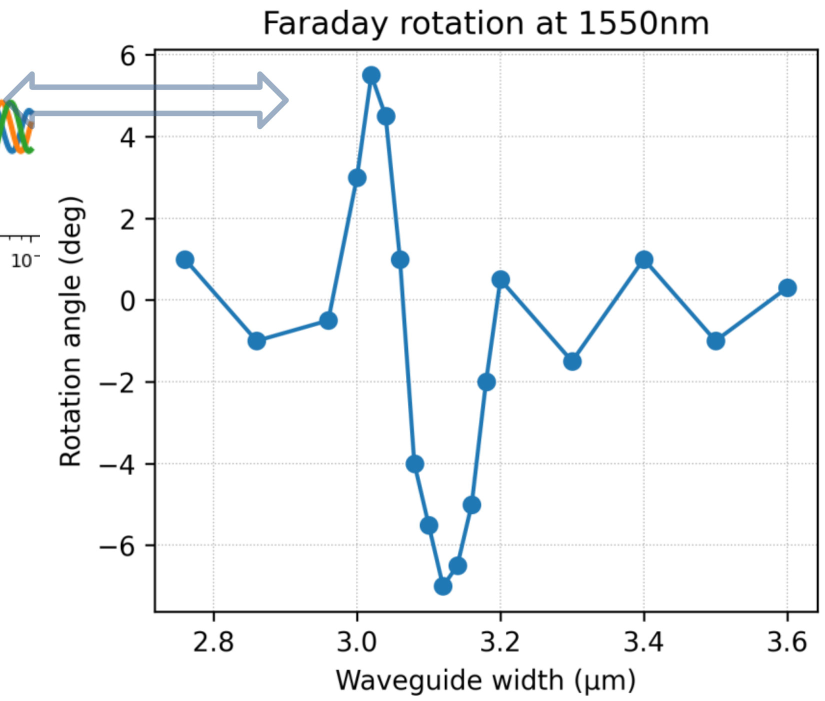
Faraday rotation

- $\theta = B_{field} \cdot L_{ength} \cdot V_{erdet} \cdot \mathrm{sinc}\, f(\Delta n, \lambda, L_{ength})$



2014: Review in Photonics Journal, IEEE

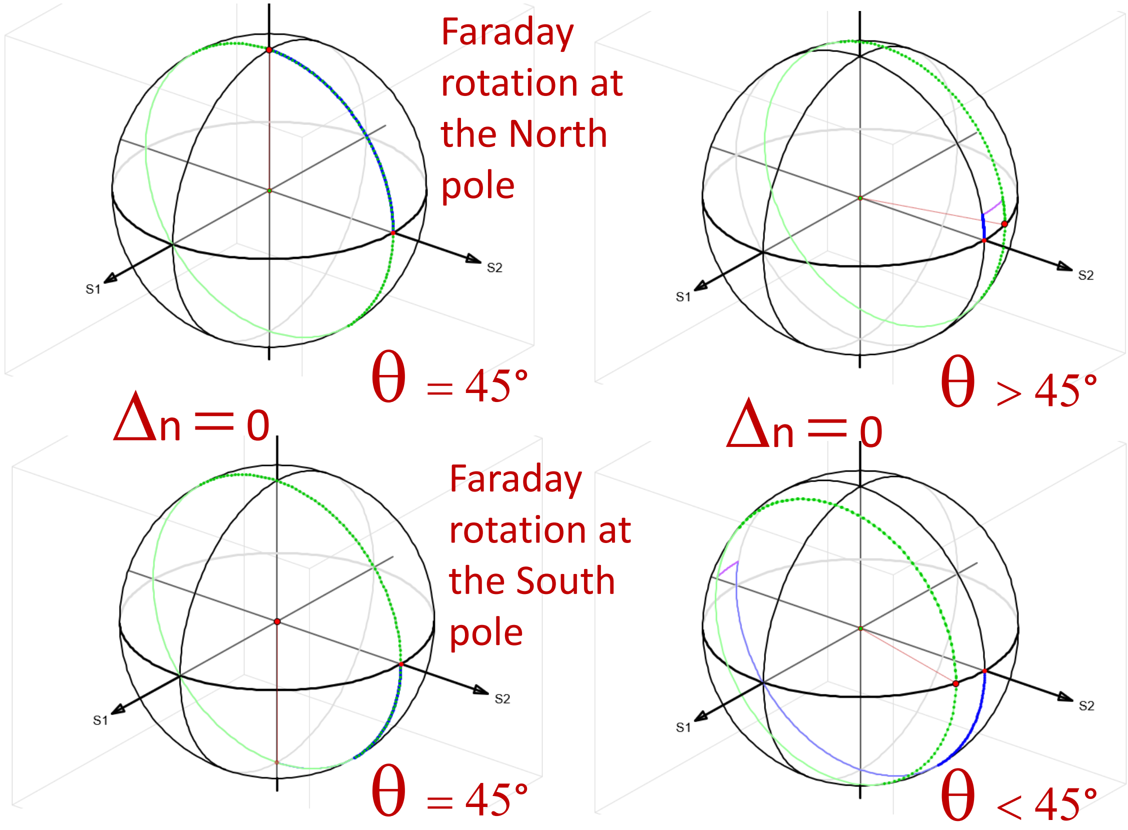




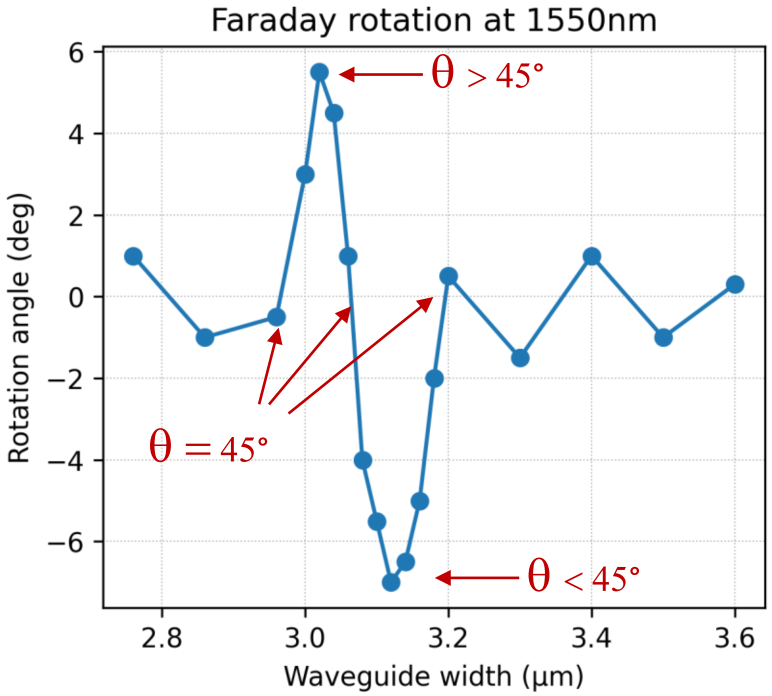
- Clear Faraday rotation measured 👍 but due to too high birefringence variation, rotation does not accumulate but oscillates 👎
- High sensitivity not feasible by increasing waveguide length

Poincare simulation

- Approximately the same Faraday rotation around zero birefringence, but different TE-TM phase differences for different widths
- No Faraday rotation in the North or South pole



Faraday rotation near the equator, but with opposite TE-TM phase differences, leading to opposite changes in θ



Summary

- COMSOL modelling using the inferred stress values are in fair agreement with measurements
- Faraday effect was demonstrated successfully but found to be in the non-ideal regime owing to the sensitivity of Faraday rotation to birefringence.
- The inherently high birefringence variation of the 3µm silicon waveguide makes it difficult to obtain highly sensitive magnetic field sensor as targeted
- TIR mirror based $n \cdot \pi$ phase difference U-bends manufactured exhibited larger loss of light than expected (compared to test structures) for yet unknown reasons