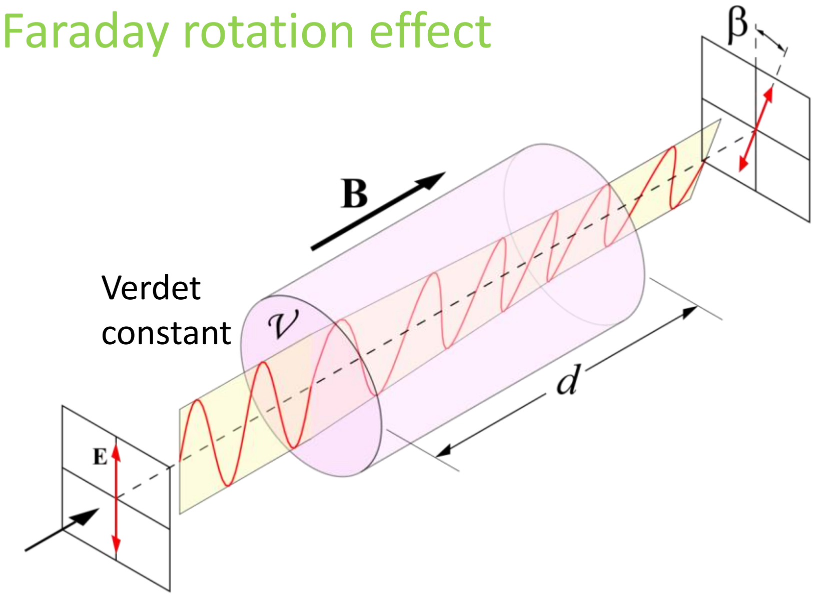
Enabling research: Silicon optics steady state magnetic field sensor

A. Salmi, T. Aalto, K. Bryant, S. Dura, A. Hokkanen, M. Kapulainen, C. Matteo, F. Sun, T. Tala, B. Wälchli, M. Jessen, T. Jensen, J. Rasmussen, S. Kragh Nielsen

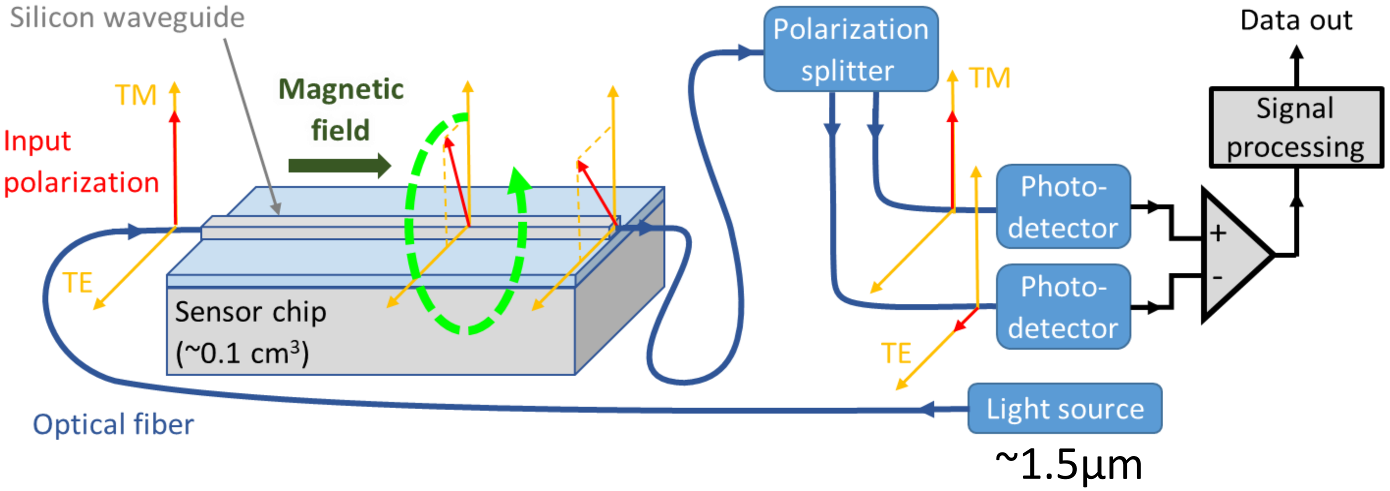
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Measurement concept

Faraday rotation effect

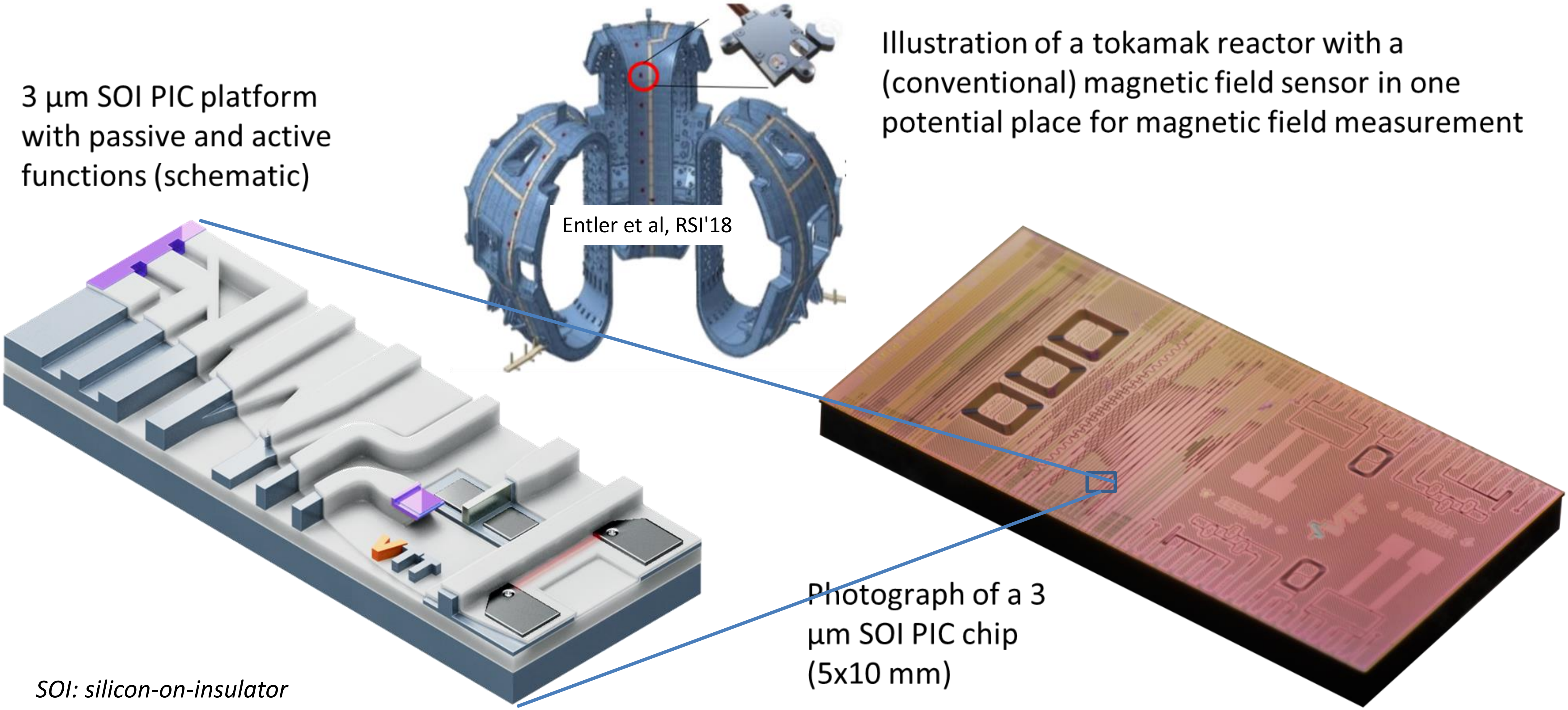


Sensor on silicon (simplified schematic)



- **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

Entler et al, RSI'18

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

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

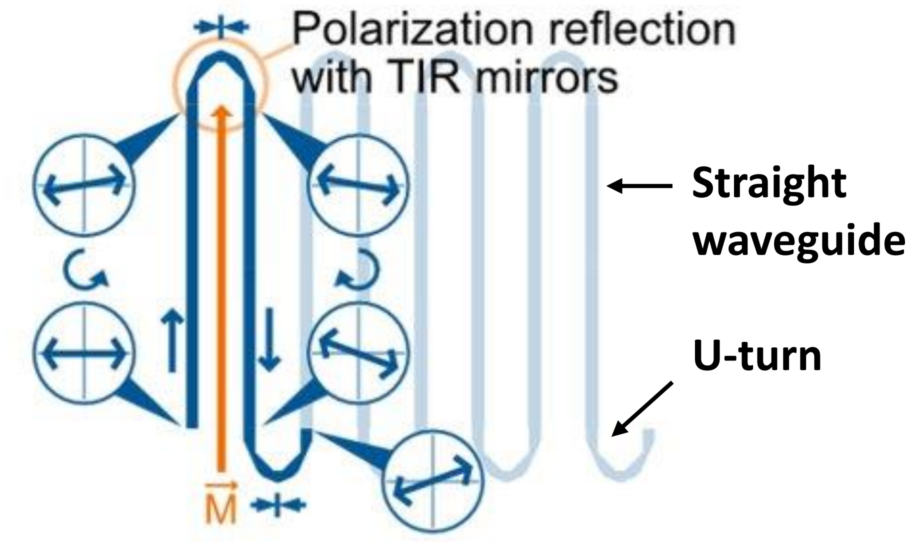
Multiple components needed for a sensor

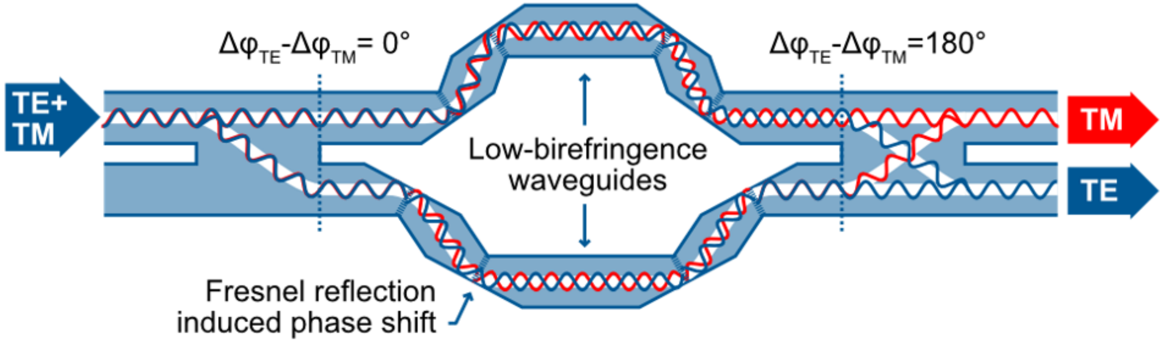
Faraday rotator based on

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

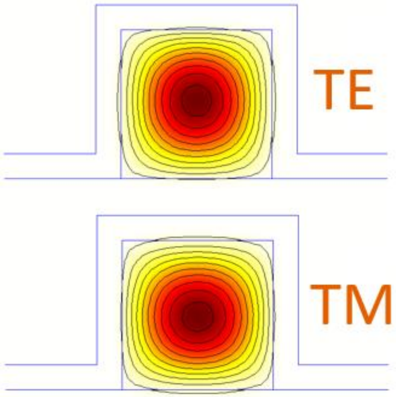
Polarisation splitter at the input and output of the Faraday rotator

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

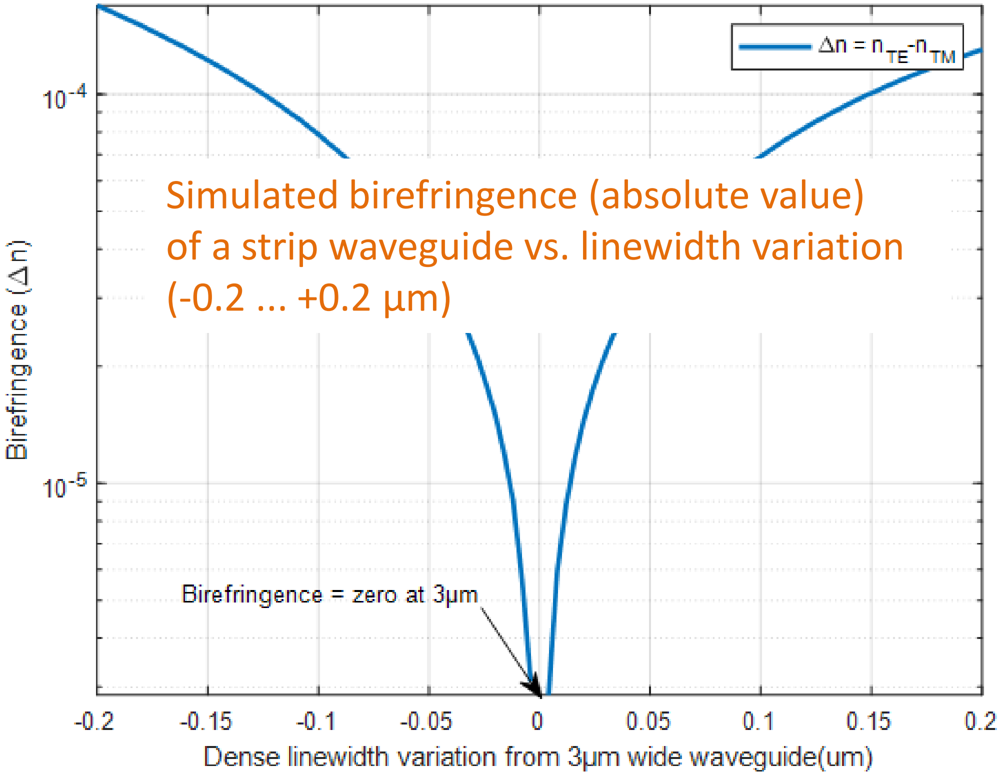




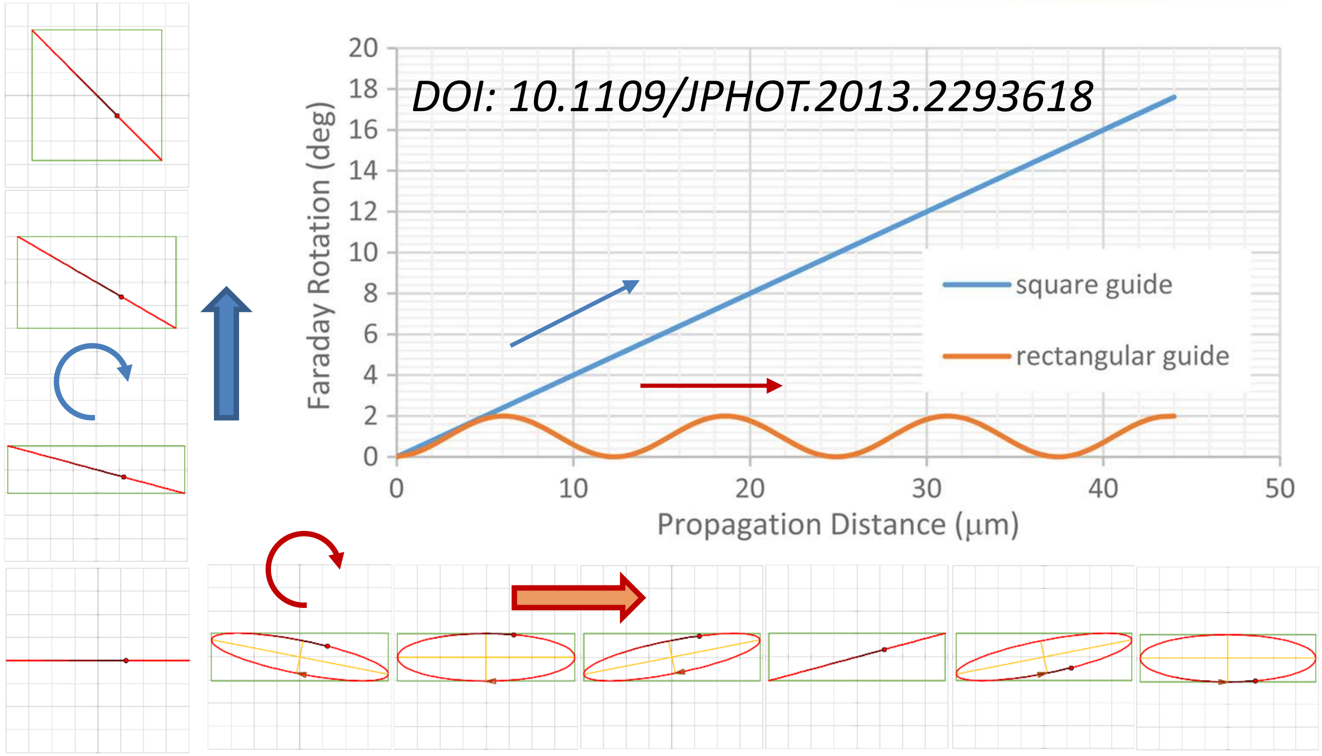
~Zero birefringence waveguides



- 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



Simulated birefringence (absolute value) of a strip waveguide vs. linewidth variation (-0.2 ... +0.2 µm)

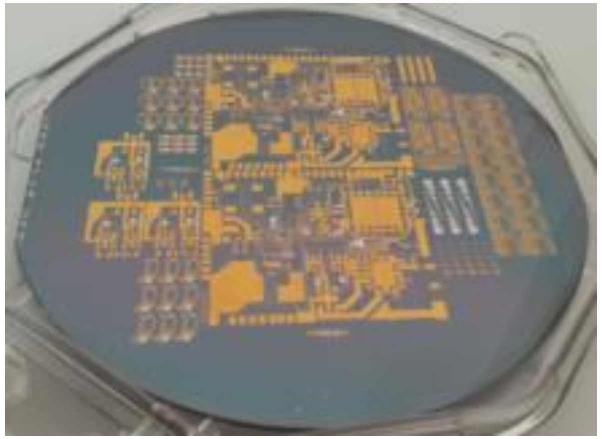


DOI: 10.1109/JPHOT.2013.2293618

A Salmi,Final review, 24th Oct 2024

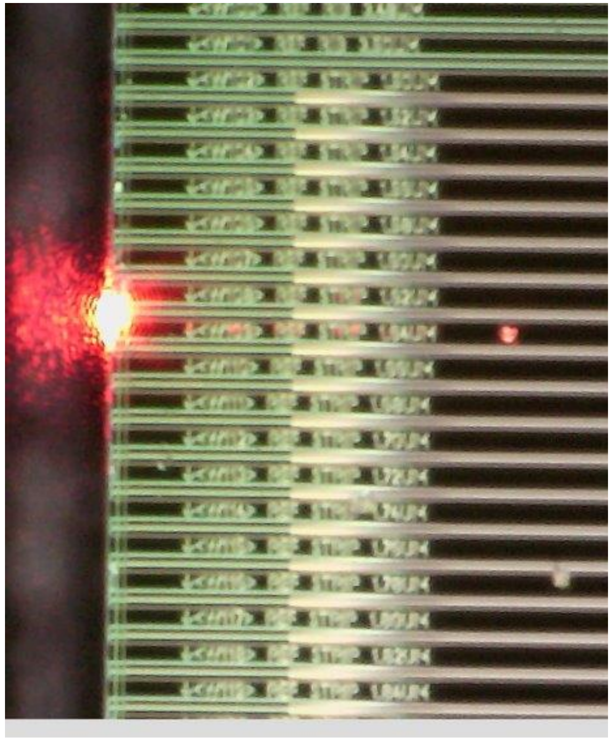
Manufacturing workflow

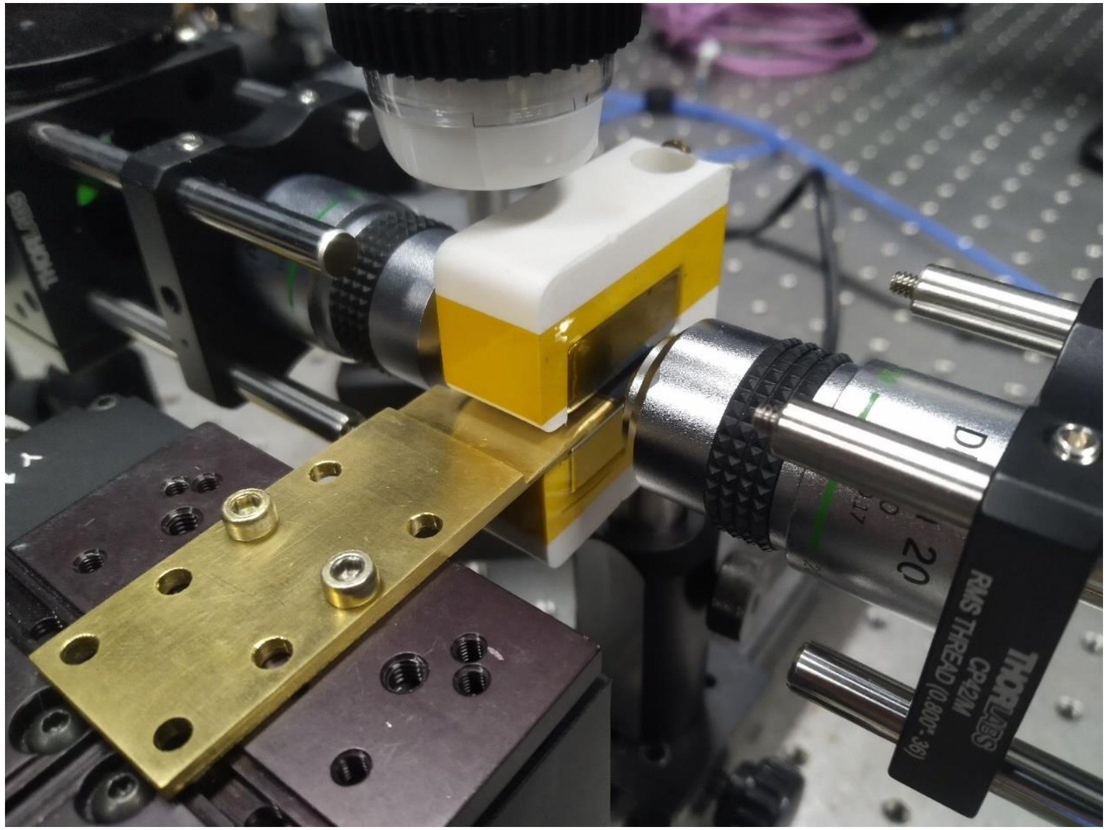
- Wafer processing involves ~30 separate steps from design, to masking, etching, polishing, cutting
  - Either expensive or slow
- Cost saving means Multi-Wafer-Process with wafer shared and processed with multiple projects on one go
- Multiple specialists needed
- This was initially thought to be the limiting factor
- However, even more problems rose from difficulties in finding the Faraday effect



Faraday rotation measurement setup

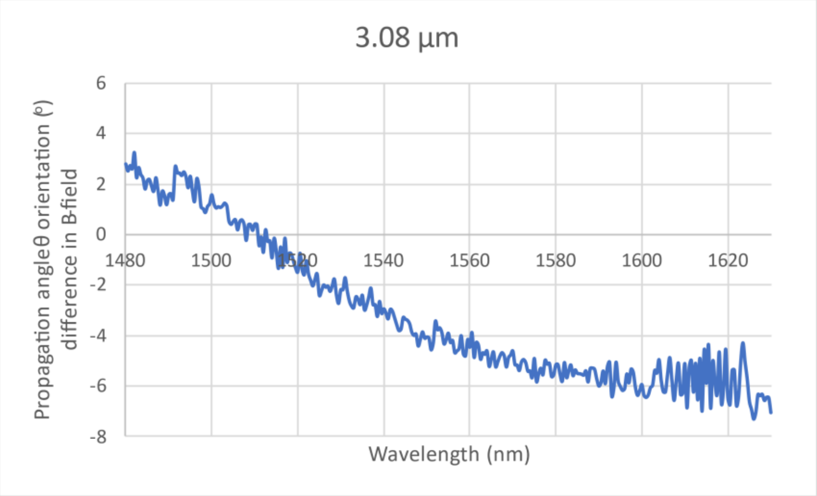
- Movable permanent magnet with 1 T allows clean measurement of with and without magnetic field
  - COMSOL calculations confirm magnetic field uniformity

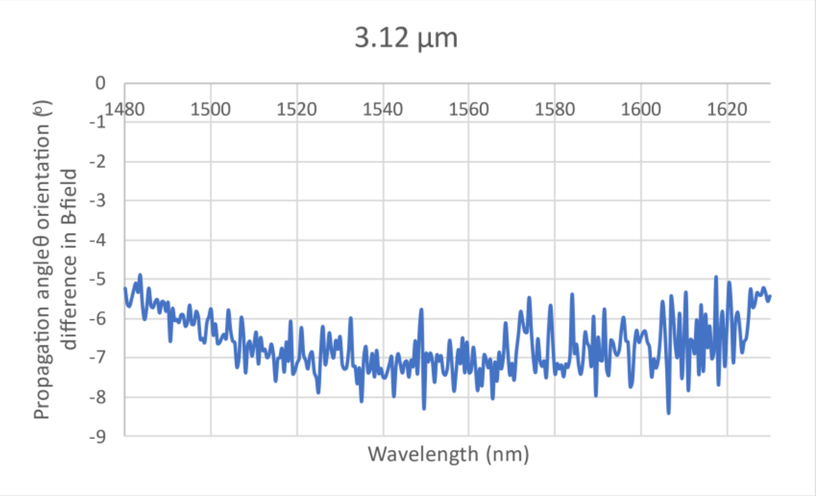


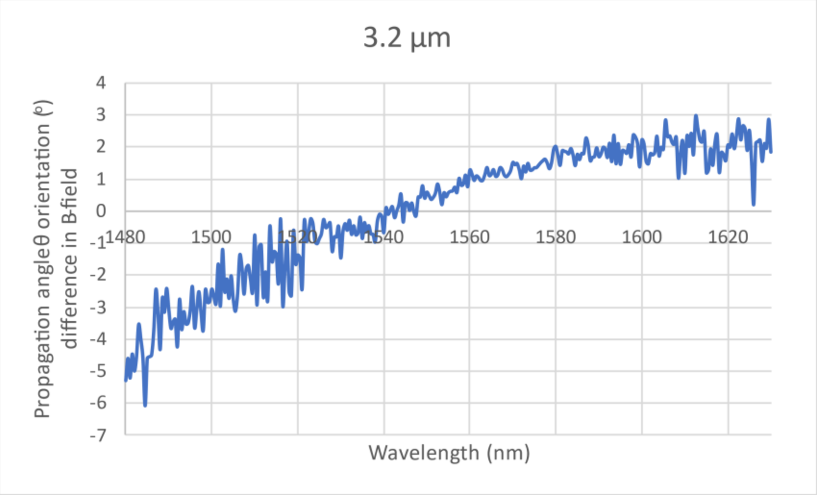


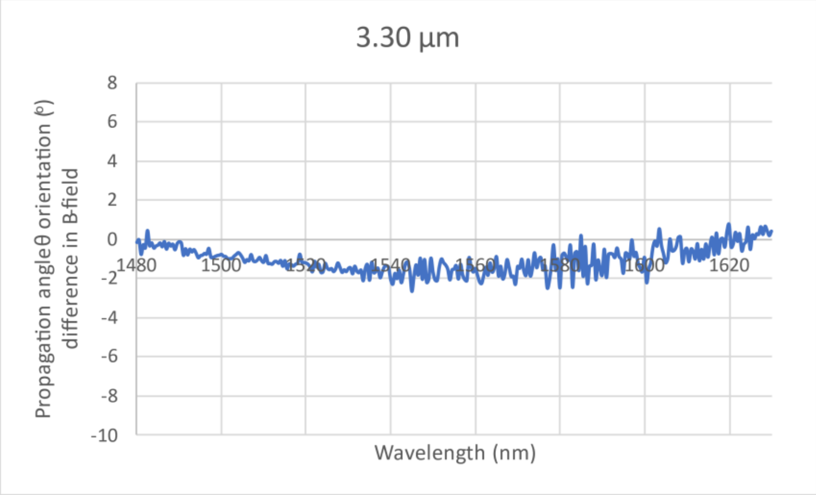
Rotation angle difference measurement @1T

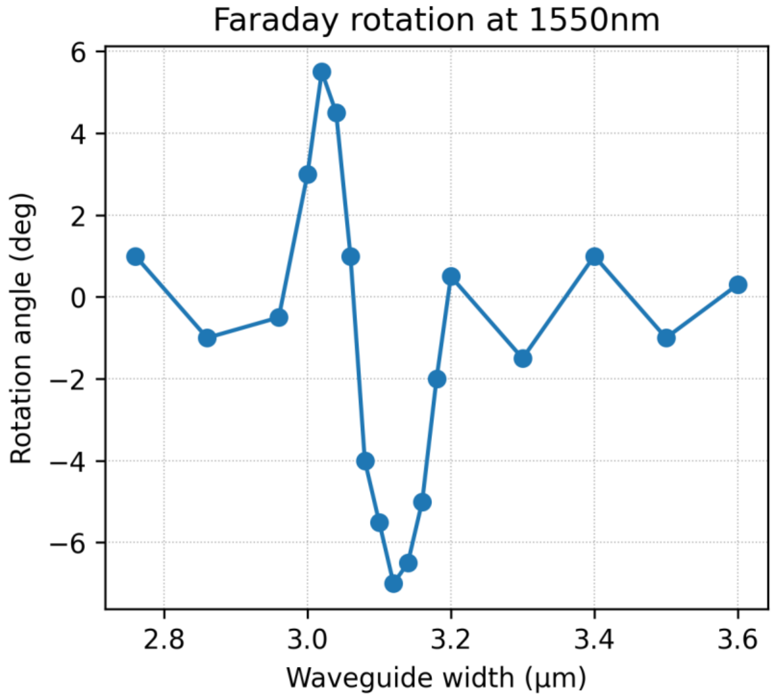
- Rotation angle should be ~22.5deg for *Verdet constant* 15 [deg/T/cm] at zero birefringence
- Is this Faraday rotation?





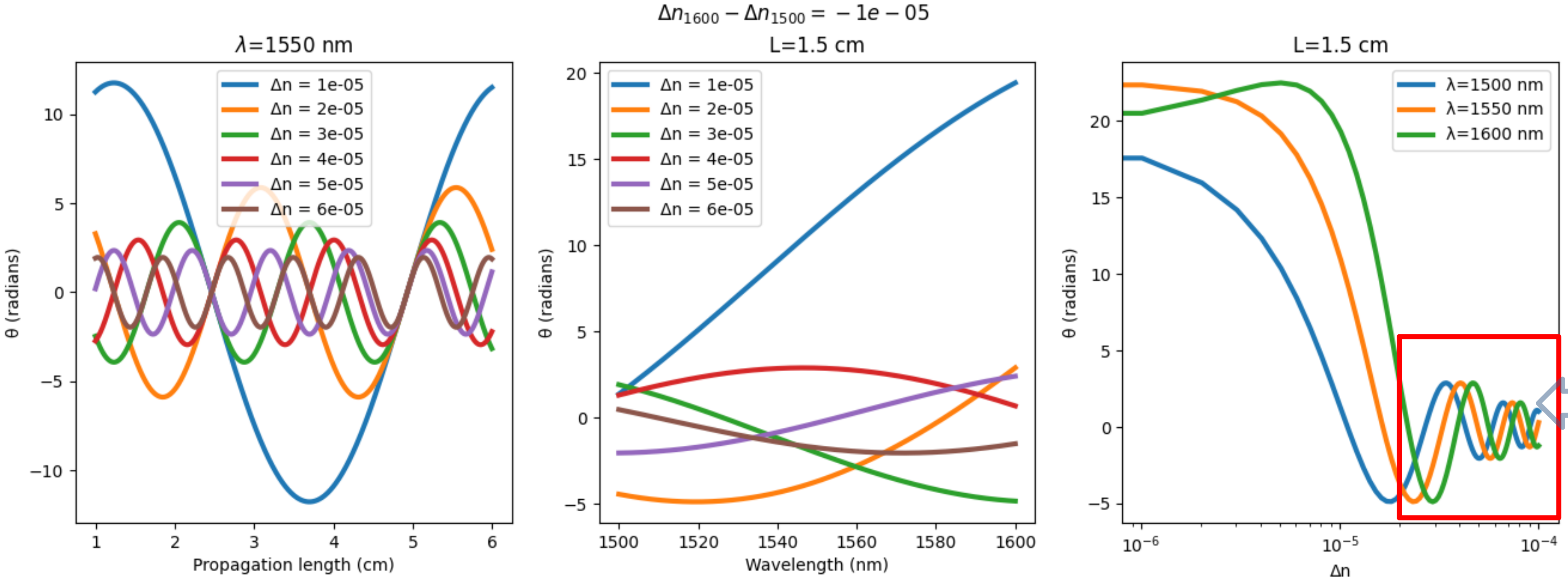


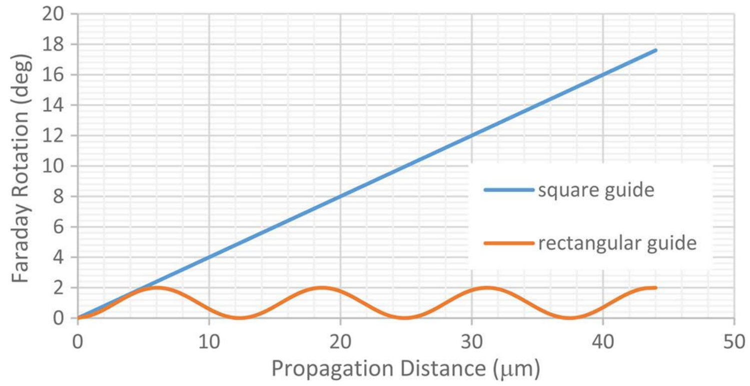


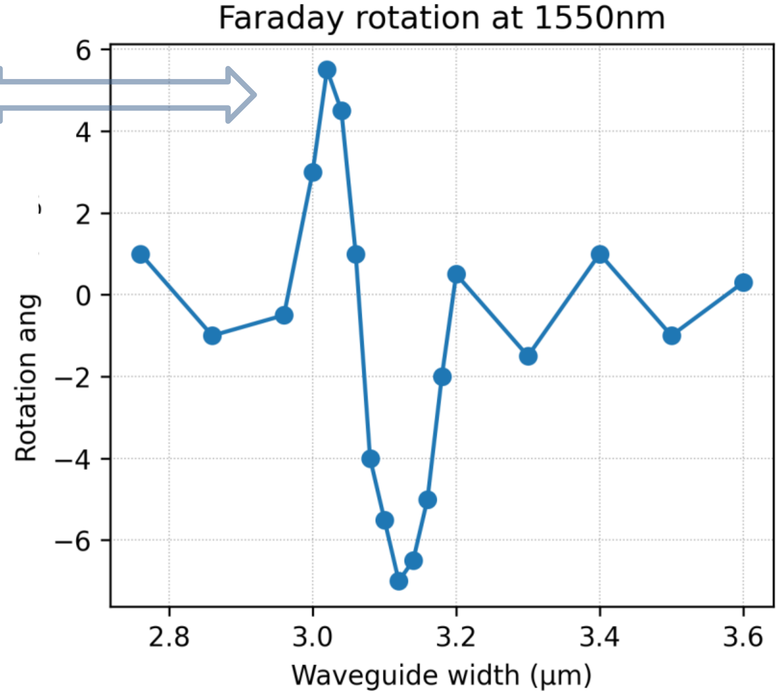


Faraday rotation

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



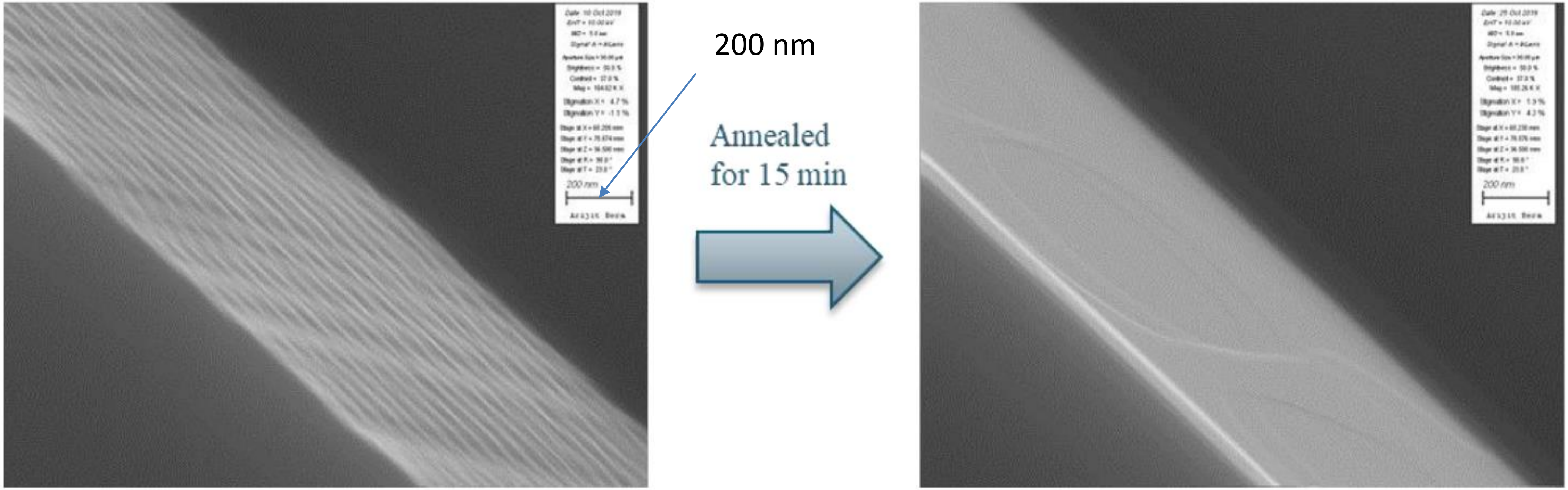




- Clear Faraday rotation measured 👍 but due to too high birefringence rotation does not accumulate but oscillates 👎
- High sensitivity not feasible by increasing waveguide length

Hydrogen annealing for smoother waveguides

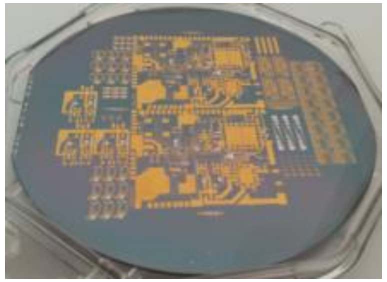
- SEM images of Hydrogen annealed waveguide surface after 15 min treatment
- Measurements show 75% improvement in polarisation extinction ratio and attenuation down to 4 dB/m

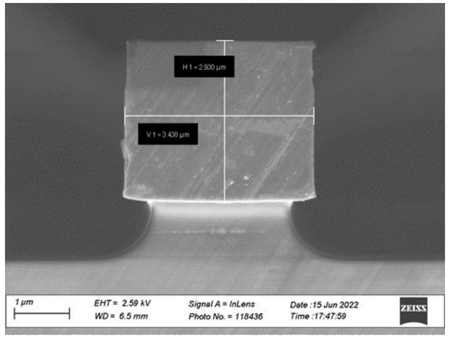


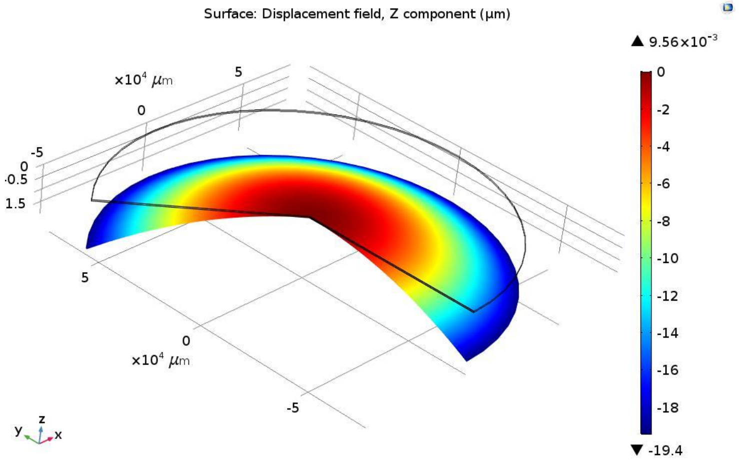
Experimentally inferred oxide stress values

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

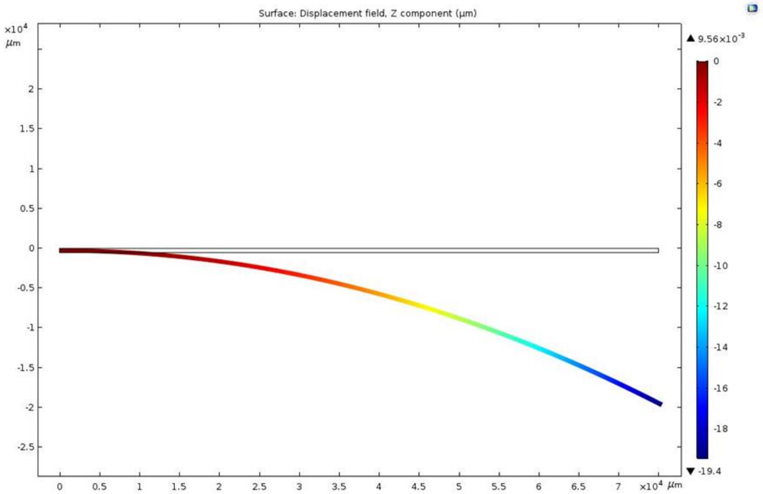
  $\Rightarrow$ Experimentally defined stress value

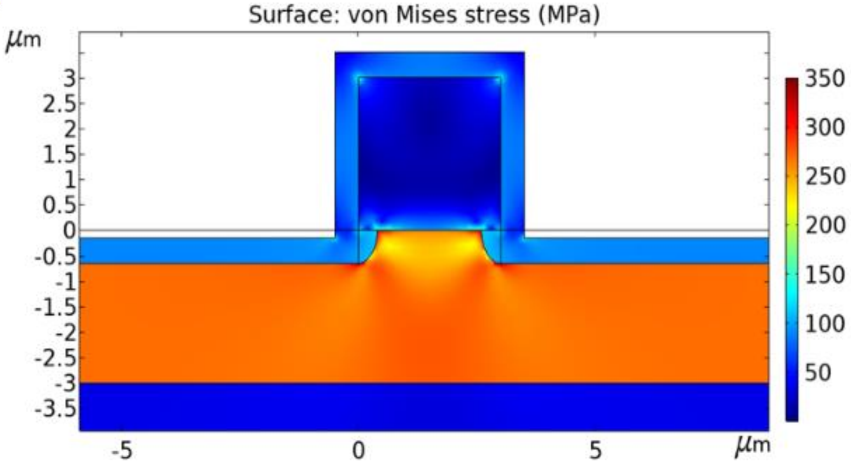






3D axisymmetric model

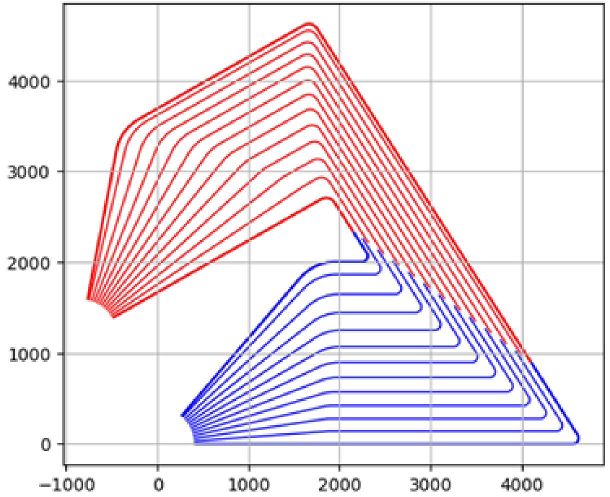




A Salmi,Final review, 24th Oct 2024

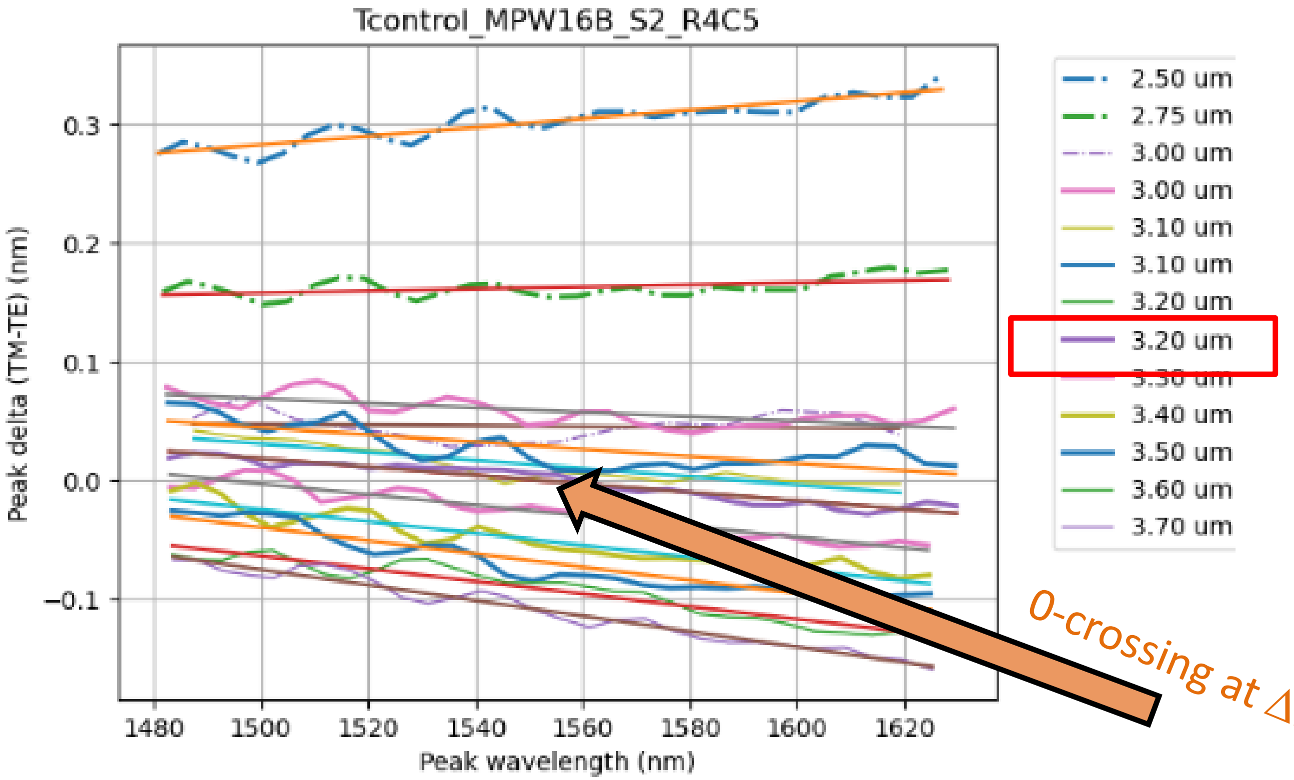
Birefringence measurements

- 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



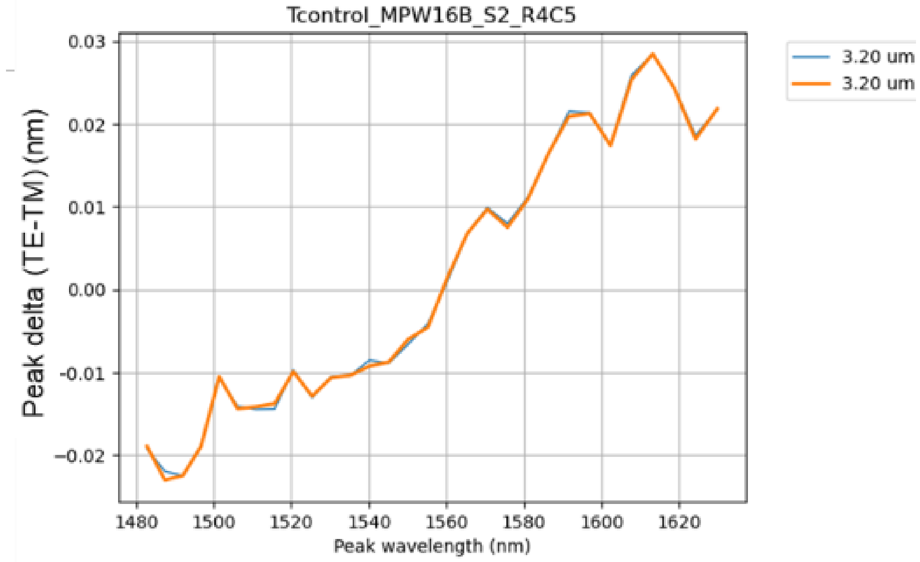
AWG measurements

- 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



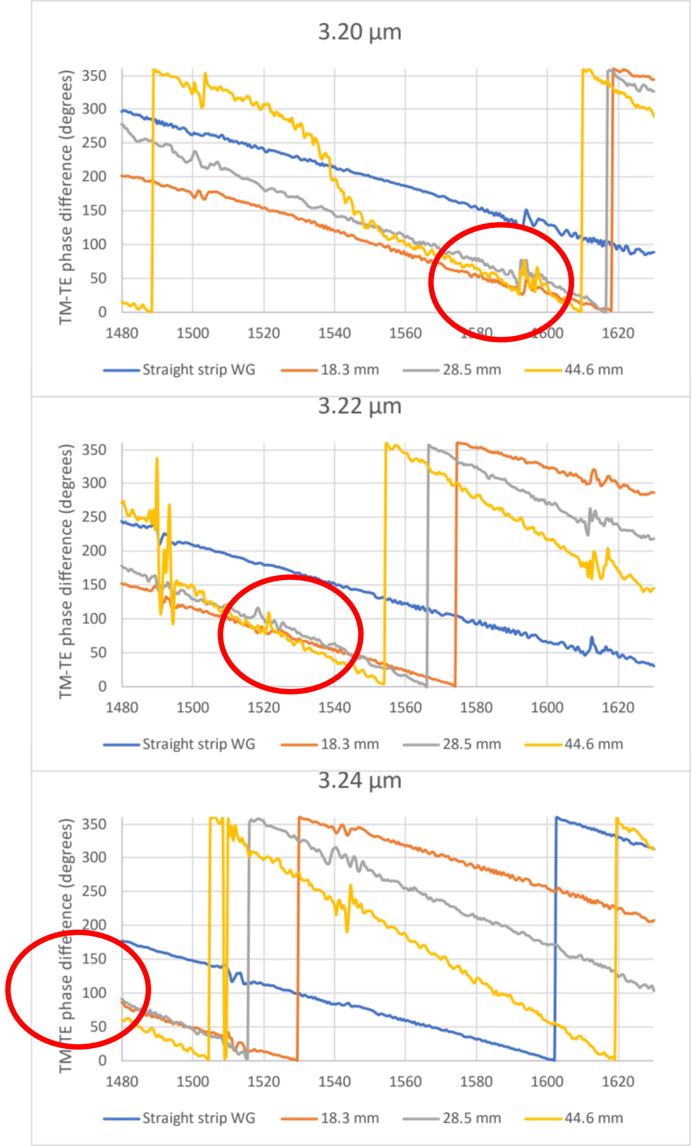
0-crossing at Δn=0

Repeat measurement



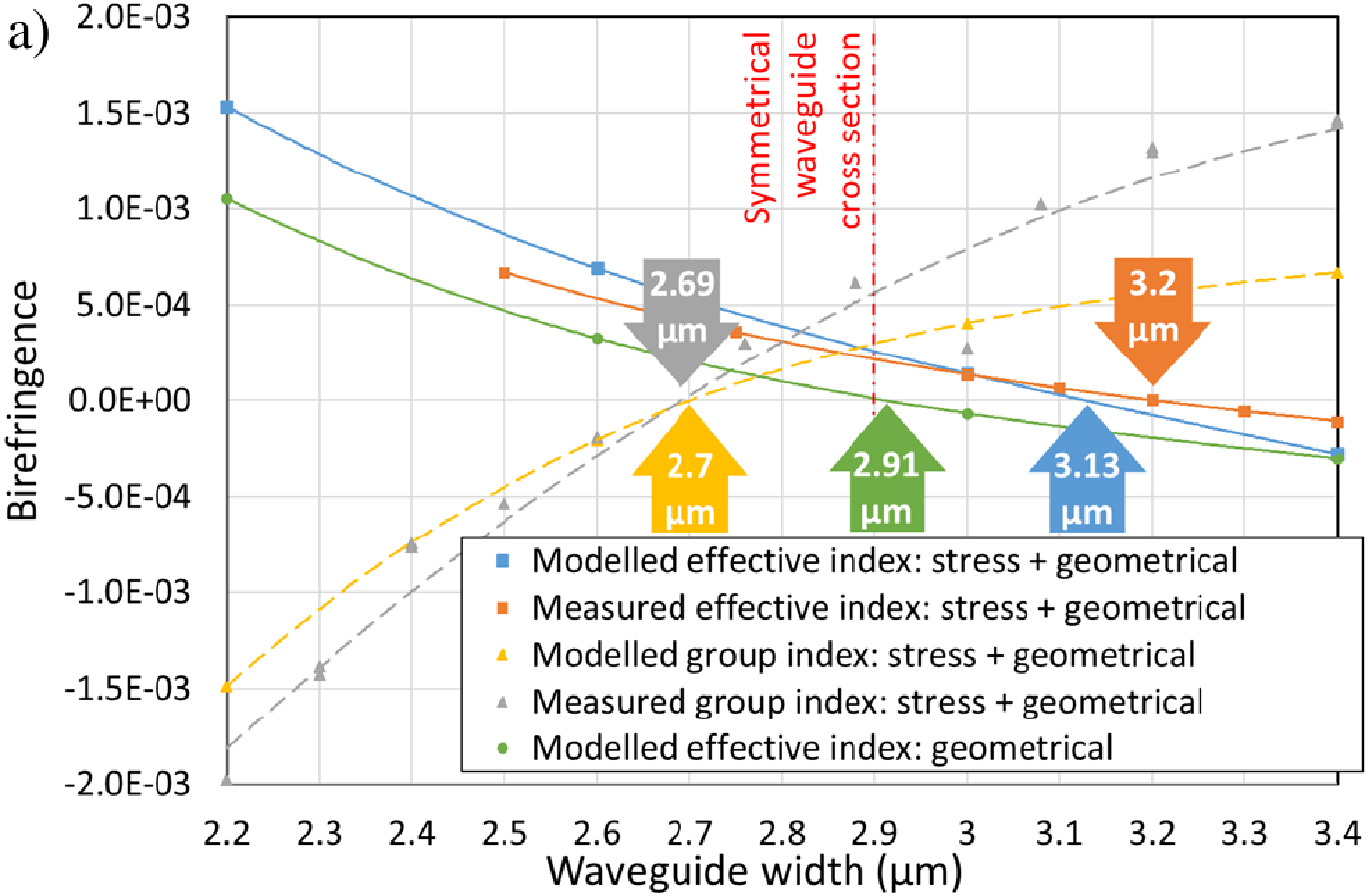
Folded waveguide

- 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’

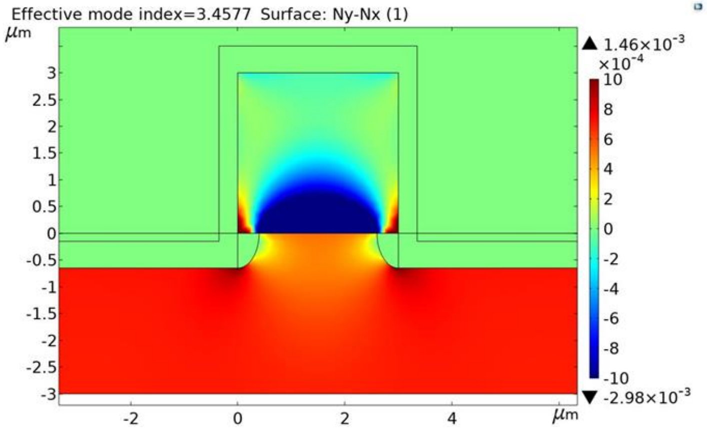


Simulated birefringence

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



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



Accepted: IEEE Journal of Lightwave Technology

- Comprehensive experimental and numerical research conducted to gain insights in birefringence properties of 1.5µm IR light in 3µm waveguides
- Good agreement found between multiple measurement techniques and modelling confirming the sensitivity on both the geometry and the wavelength
    - Explains why Faraday rotation is less than initially hoped for a sensor application

Zero Birefringence and Zero Birefringence Dispersion in 3 µm-thick Silicon-on-Insulator Waveguides

Katherine Bryant[1], Ari Hokkanen[1], Dura Shahwar[1,2], Mikko Harjanne[1], Antti Salmi[1], and Timo Aalto[1]

COMSOL

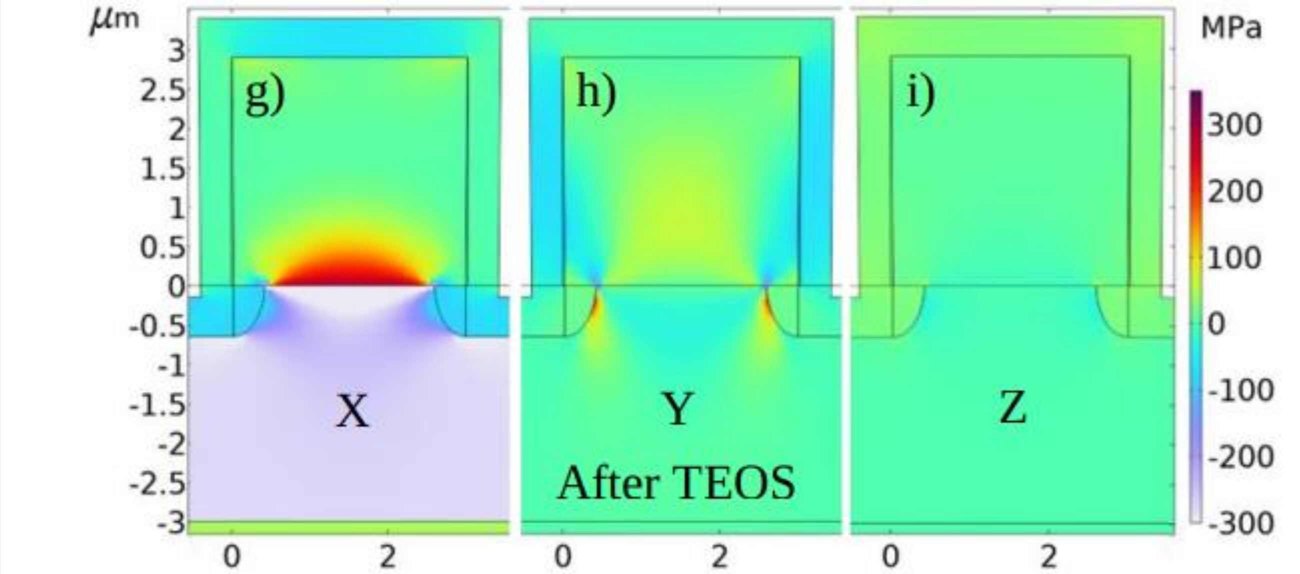


Fig. 18. a-c) Stress tensor components after SOI waveguide etching, d-f) stress tensor components after SOI wafer heating to 670°C for TEOS deposition and g-i) stress tensor components after TEOS deposition. The x direction is horizontal, y is vertical, and z is along the waveguide.

Conclusions

- COMSOL modelling in fair agreement with measurements
- Faraday effect demonstrated but found to be in the non-ideal ‘oscillating’ regime
- The inherently high birefringence 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 poorer polarization control than needed likely due to wall roughness
- Not recommended for further development until manufacturing tolerances are improved and birefringence / dispersion are made significantly smaller

Zero Birefringence and Zero Birefringence Dispersion in 3 µm-thick Silicon-on-Insulator Waveguides

Katherine Bryant[1], Ari Hokkanen[1], Dura Shahwar[1,2], Mikko Harjanne[1], Antti Salmi[1], and Timo Aalto[1]

Accepted

journal of LIGHTWAVE TECHNOLOGY
An IEEE / OPTICA PUBLISHING GROUP Publication