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Passive Photonic Integrated Circuit Metrology

Todd Stievater[1], Steven Lipkowitz[1], Marcel Pruessner[1], Nathan Tyndall[1], Jacob Bouchard[1], Kyle Walsh[1,2], Scott Holmstrom[1,2,3]

[1]US Naval Research Laboratory, Washington DC

[2]Amentum Inc., Chantilly, VA

[3]University of Tulsa, Tulsa, OK

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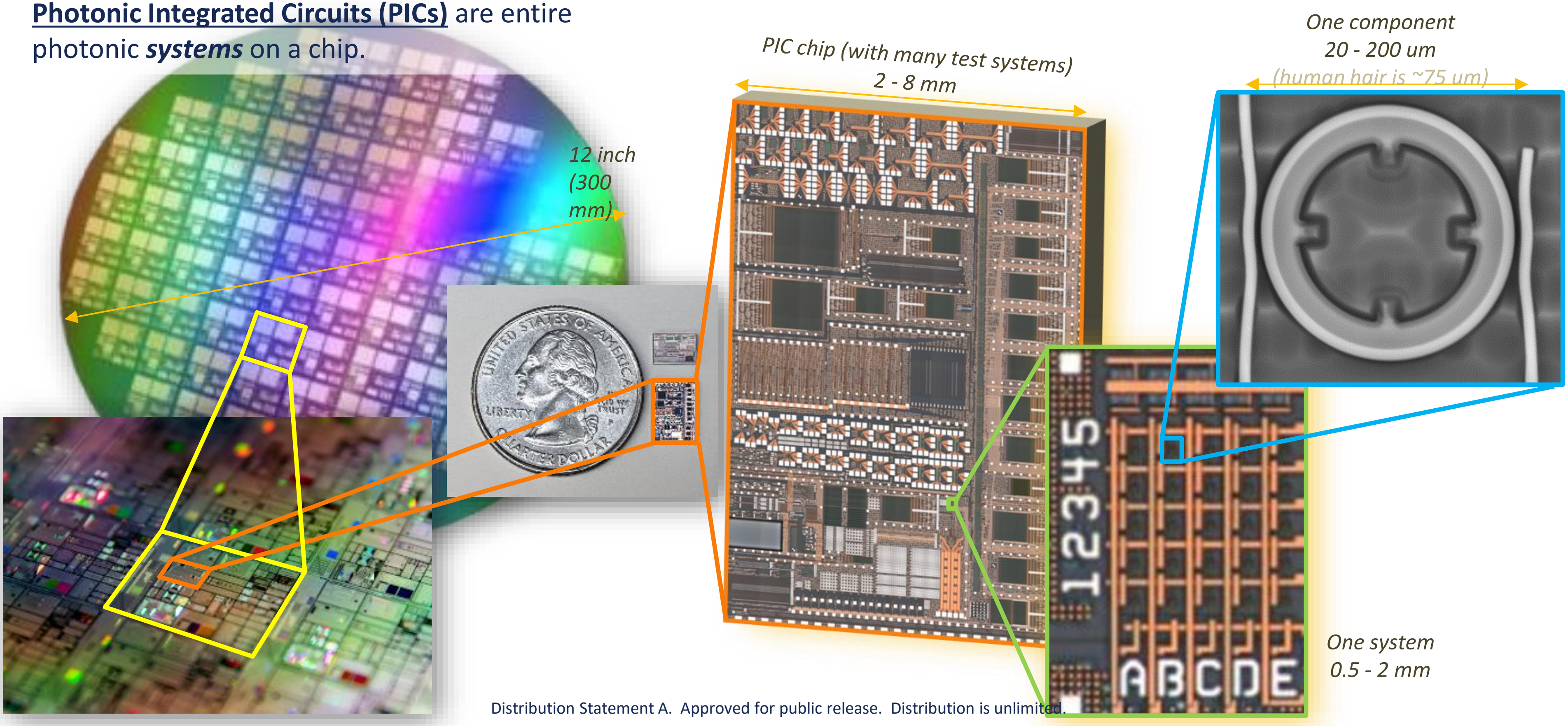
3/17/2026

Photonic Integrated Circuits

Photonic Integrated Circuits (PICs) are entire photonic ***systems*** on a chip.



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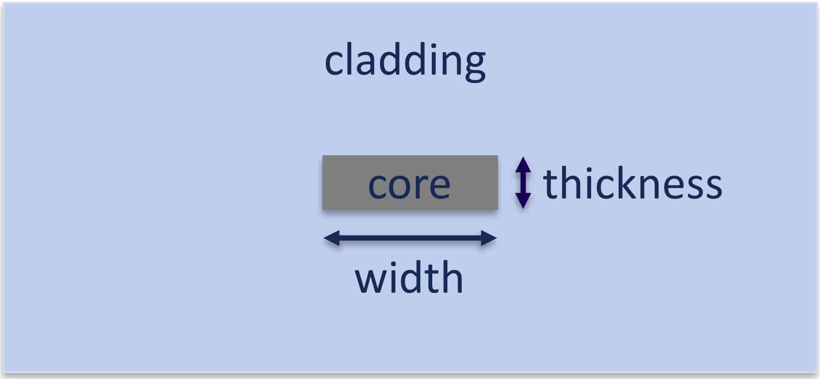
The passive PIC design problem

A PIC design is only as good as the parameters used to simulate it



How can key PIC parameters be measured and tracked accurately and simply?

Core geometry

- Core thickness (***t***)
- Core width (or width bias = Δw)
- Sidewall roughness (σ^2, L_c)

Core index

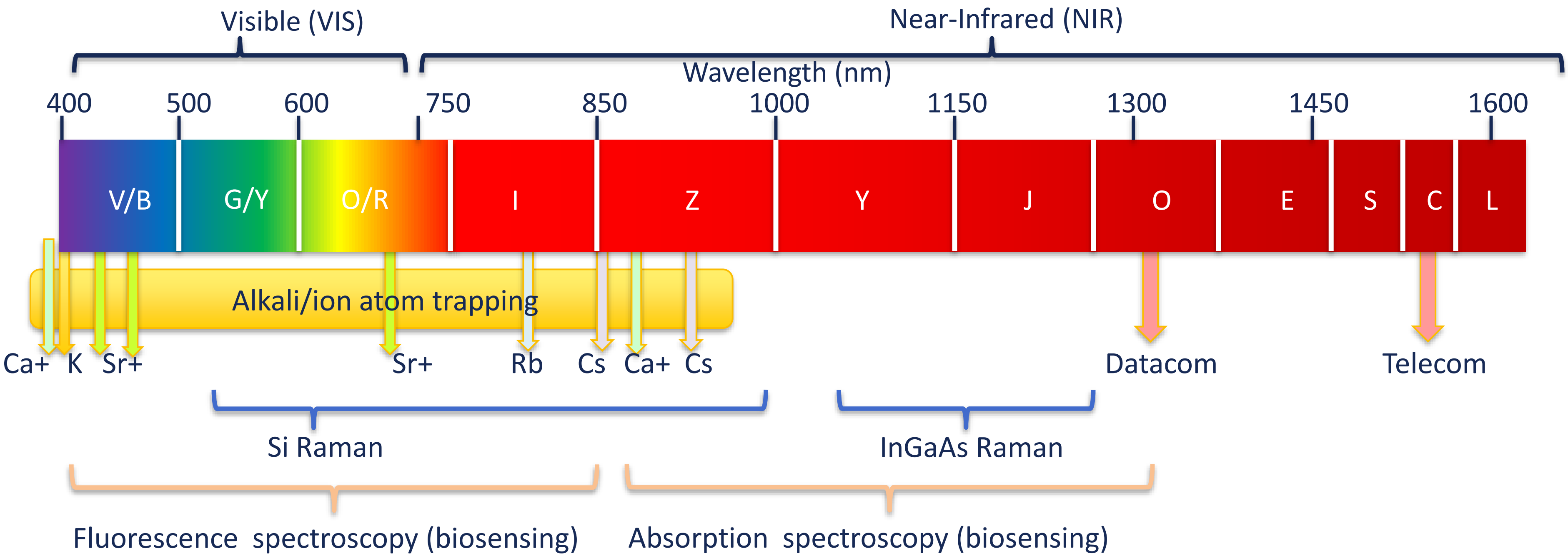
- refractive index ($n_{core\text{-}real}$) vs. λ
- absorption ($\alpha_{core} = 4\pi n_{core\text{-}imag}/\lambda$) vs. λ

Cladding index

- refractive index ($n_{clad\text{-}real}$) vs. λ
- absorption ($\alpha_{clad} = 4\pi n_{clad\text{-}imag}/\lambda$) vs. λ

Assumptions:
Core is rectangular, cladding is uniform …

Moving ~~silicon~~ integrated photonics to the visible



- Silicon nitride (SiN) is most mature material for integrated photonics for whole 400 nm → 1600 nm
- Short wavelengths are most sensitive to scattering and absorption losses
- Short wavelengths are most sensitive to core geometry (width and thickness)

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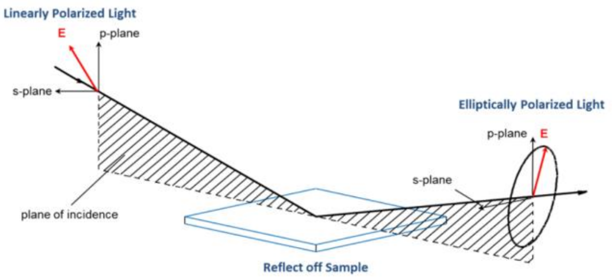
Current waveguide characterization methods

Refractive index and loss

Ellipsometry



(image courtesy Woollam)

Prism-coupling

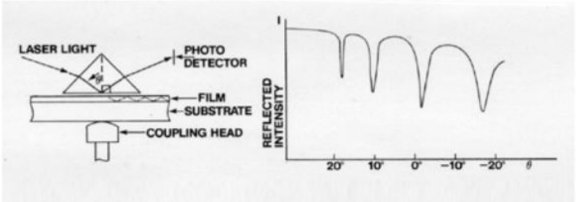


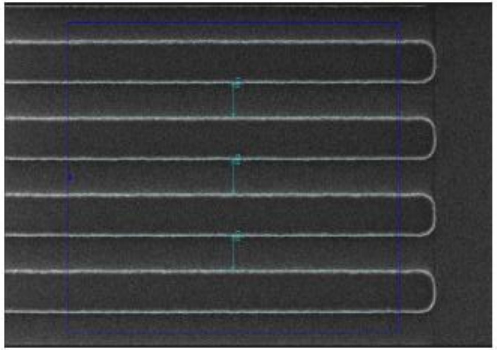
FIG. I. MEASUREMENT PRINCIPLE FOR THIN FILM

(image courtesy Metricon)

Core size and shape

SEM/TEM

(image courtesy AIM Photonics)



- Ellipsometry and prism coupling require pre-processed thin films or short-loops (may not capture full process
- Ellipsometry and prism coupling have limited sensitivity to loss (~ dB/cm)
- X-sectional SEM/TEM is destructive and time-consuming
- Top-down SEM requires direct access to waveguide core (no top cladding /other waveguides)

Can the characterization be done with high-accuracy and “in-situ”? (ie with full-flow waveguides?)

Broadband waveguide characterization: PIC test structures

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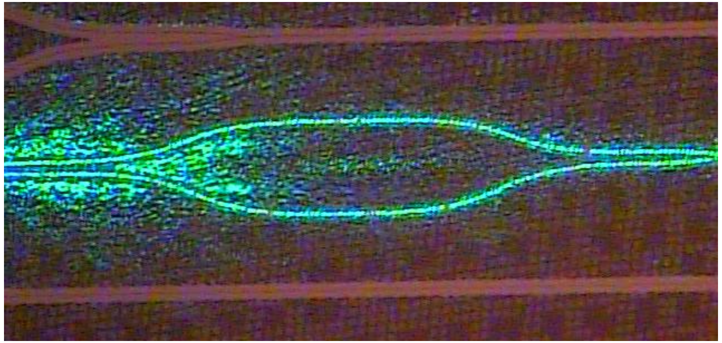
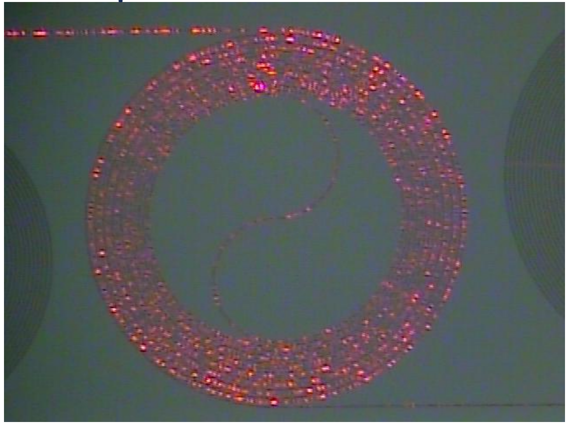
Mach-Zehnder Interferometers



Spirals for “cutback”



real(n_{eff})

imag(n_{eff})

t, Δw, $n_{core\text{-}real}$, $n_{clad\text{-}real}$, α_{core}, α_{clad}, σ^2, L_c

(and a temperature-controlled sample holder → dn/dT)

Broadband waveguide characterization: Test equipment

Sources

Propagation loss and broadband component (MZI) characterization:

- 450 nm – 700 nm (LED source)
- 700 nm – 1625 nm (blackbody source)

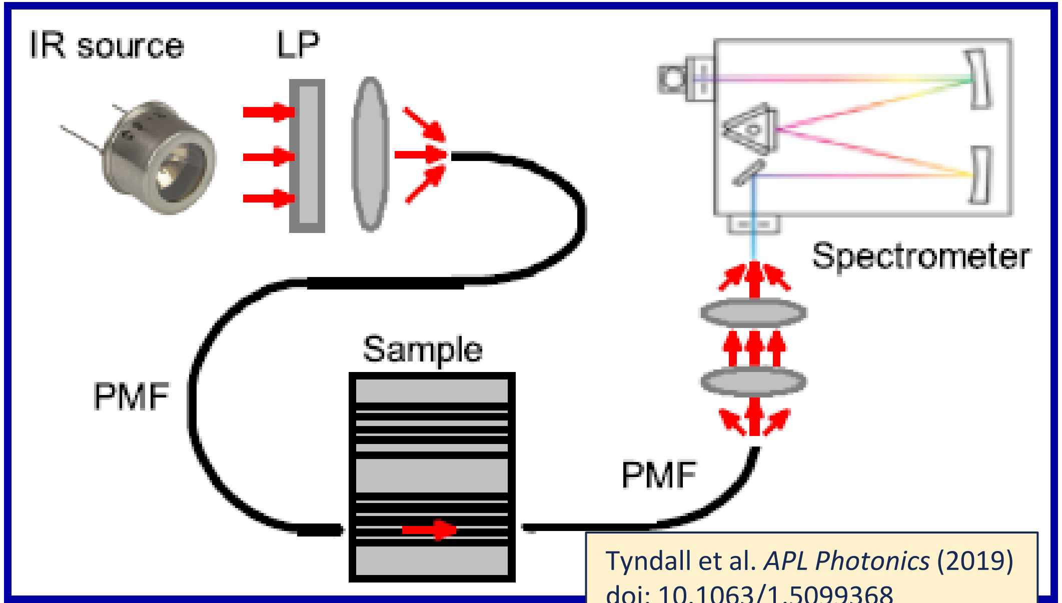
Raman scattering and fluorescence:

- 785 nm laser

Detectors

- Silicon spectrometer for 390 – 1025 nm Si (Wasatch / PI)
- InGaAs spectrometer for 900 nm – 1700 nm (Wasatch / PI)

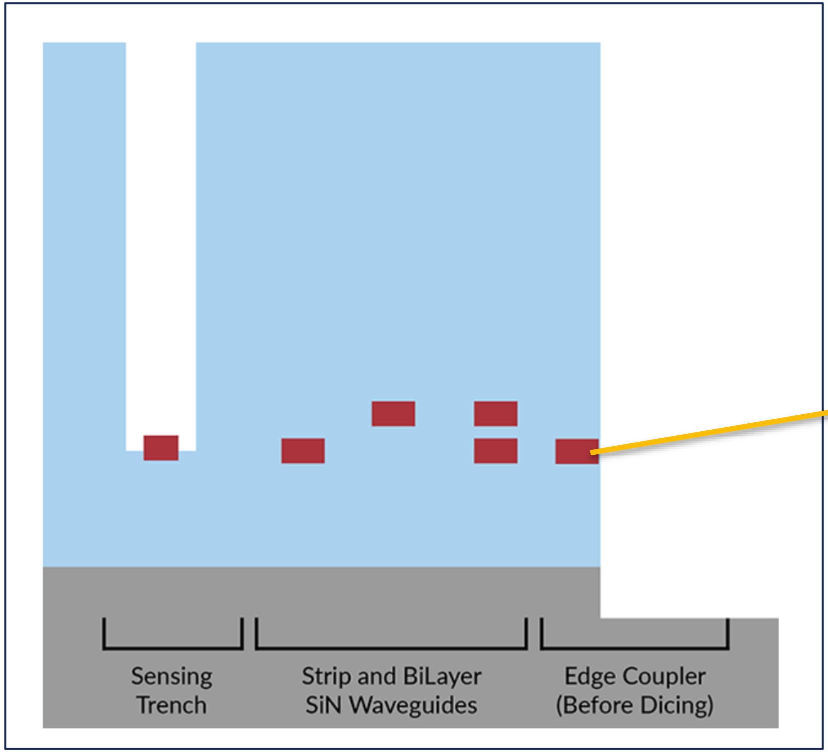
White-light PIC spectroscopy



Tyndall et al. *APL Photonics* (2019)
doi: 10.1063/1.5099368

We are working with AIM Photonics to implement this in-line at wafer scale

AIM SiN-Only Platform



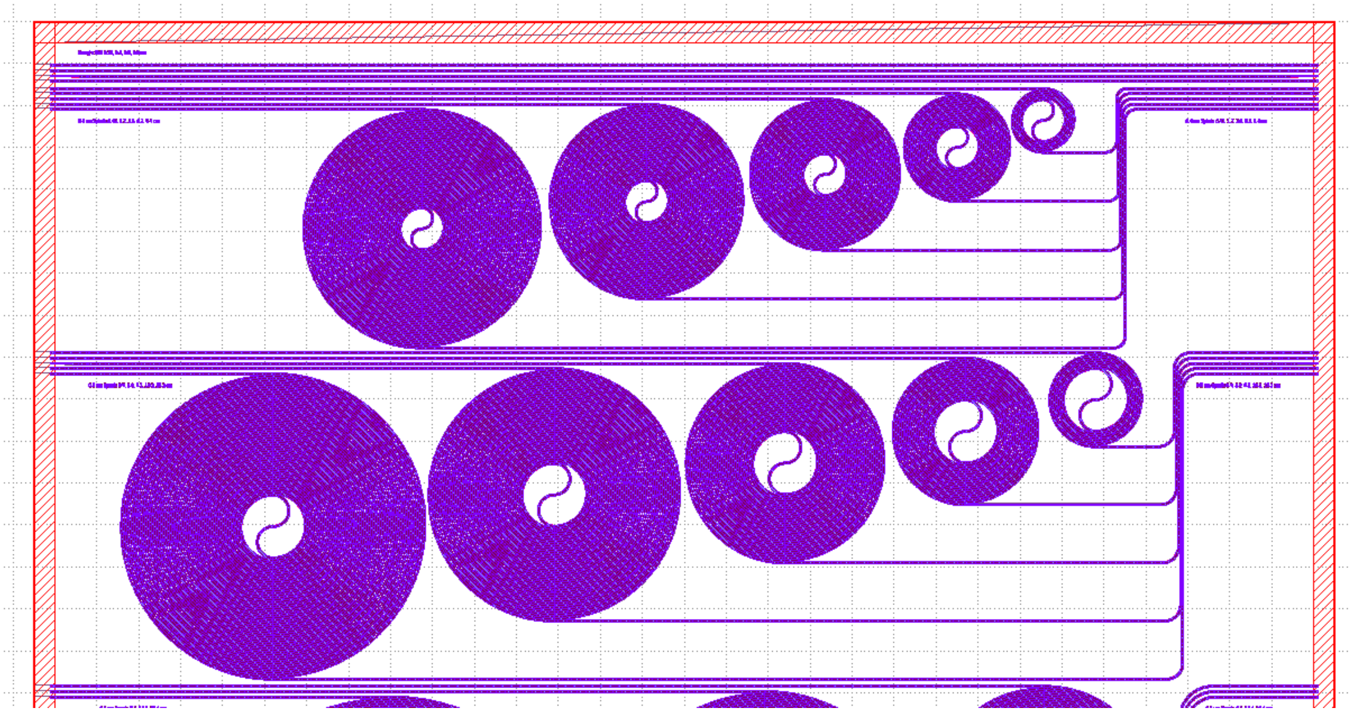
We focus on **SiN waveguides**:
220 nm thick (for NIR)
150 nm thick (for VIS)

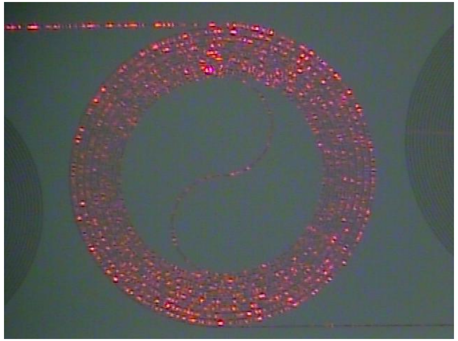
(but our methods can be used for any passive waveguide material)

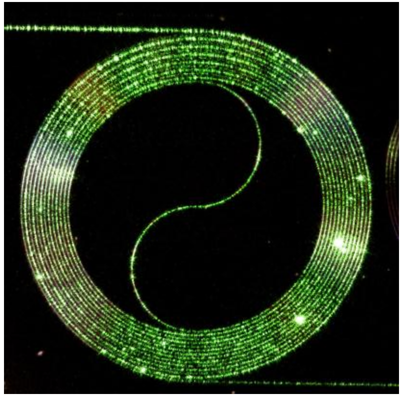
WAVEGUIDE PROPAGATION LOSS

Waveguide propagation loss: spirals for "cutback"

- Use sets of spirals ("cutback") with automated fitting to obtain loss spectrum







Waveguide loss

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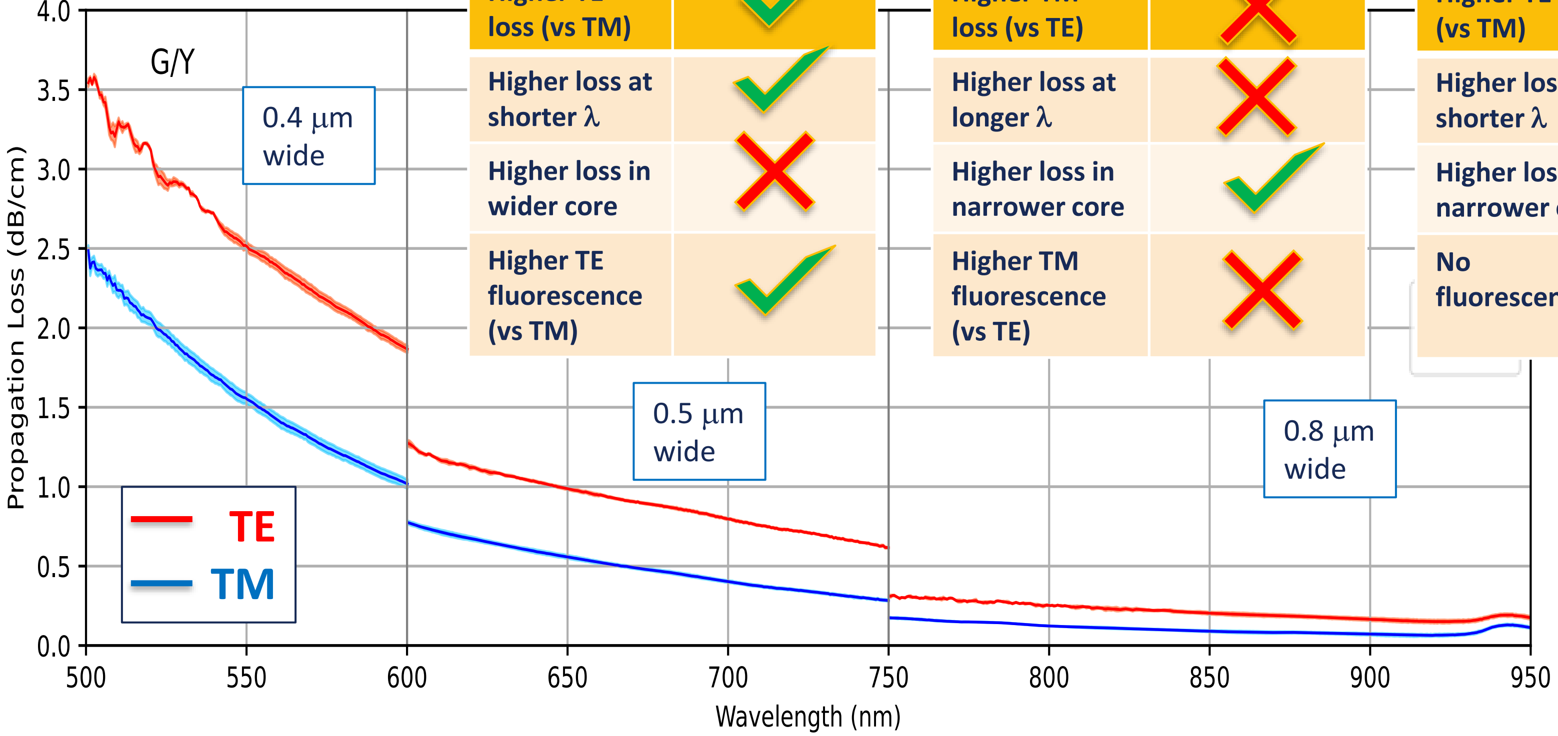
SiN (core) Absorption	
Higher TE loss (vs TM)	✓
Higher loss at shorter λ	✓
Higher loss in wider core	✗
Higher TE fluorescence (vs TM)	✓

SiO2 (cladding)Absorption	
Higher TM loss (vs TE)	✗
Higher loss at longer λ	✗
Higher loss in narrower core	✓
Higher TM fluorescence (vs TE)	✗

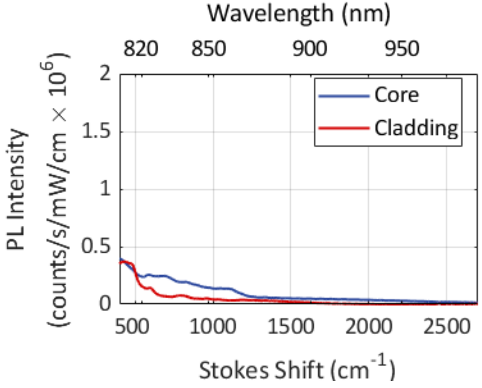
Sidewall scattering	
Higher TE loss (vs TM)	✓
Higher loss at shorter λ	✓
Higher loss in narrower core	✓
No fluorescence	✗



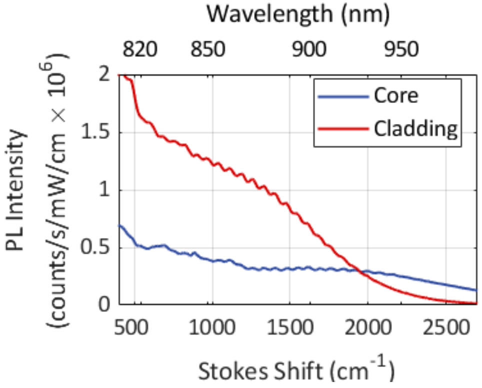
Photoluminescence and Loss (MIT Notaros Group)

Measured TE and TM emission, can be rearranged to give core and cladding contributions

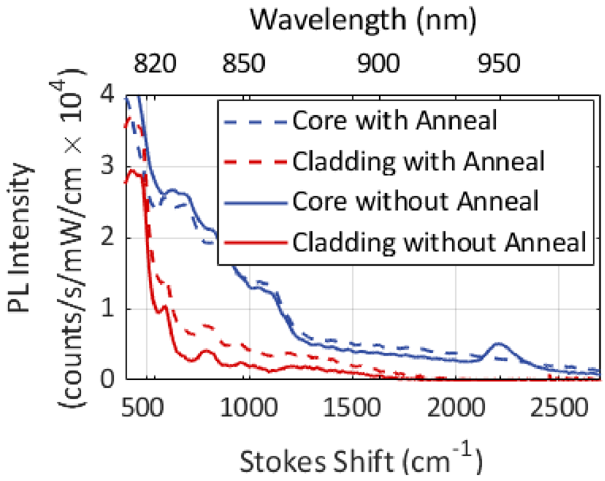
PL Intensity for Wafer A



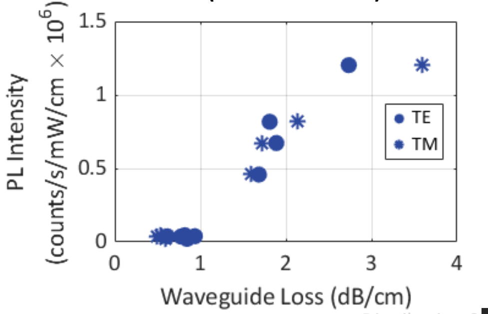
PL Intensity for Wafer B



PL Intensity for Anneal vs No-Anneal Wafer



Average Total PL Intensity vs Red Waveguide Losses (Across 9 Wafers)

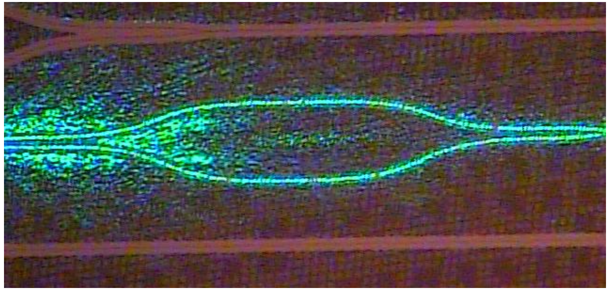


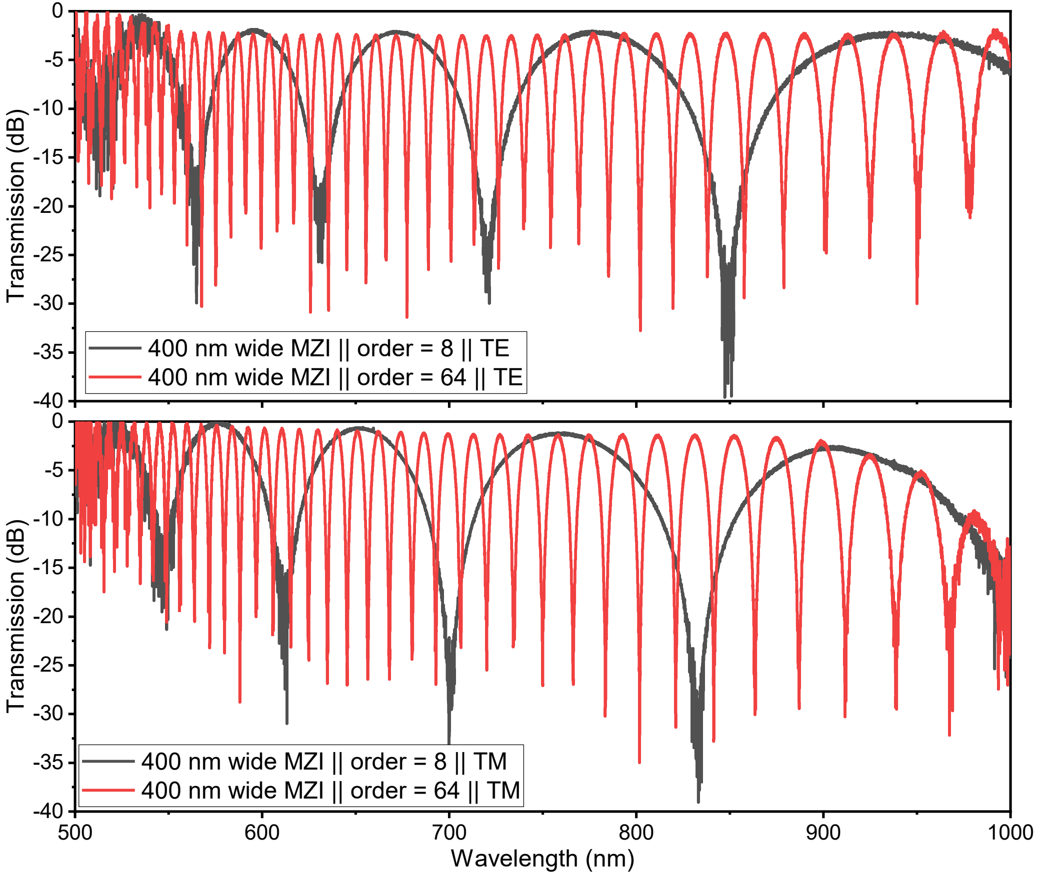
- Annealing reduces hydrogen-related defects in the core, can be detected at any wavelength (not just 1520 nm)
- Strong correlation between waveguide loss and PL
- PL shows source of loss (core vs. cladding)

[Garcia Coleto, et al., Opt. Exp. (2026) doi: 10.1364/OE.575183

REFRACTIVE INDEX AND GEOMETRY: GAUSS-NEWTON METHOD

MZIs for n_{eff} measurement in the visible



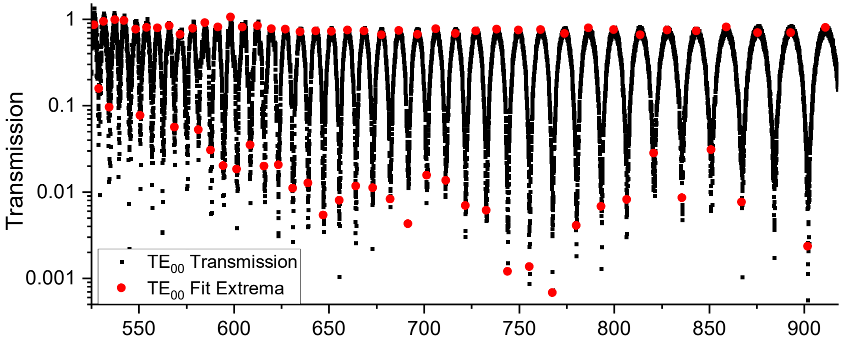


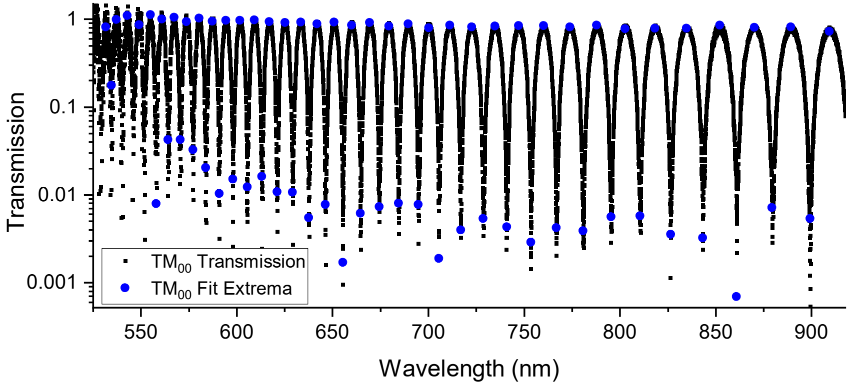
<u>White-light spectroscopy</u>

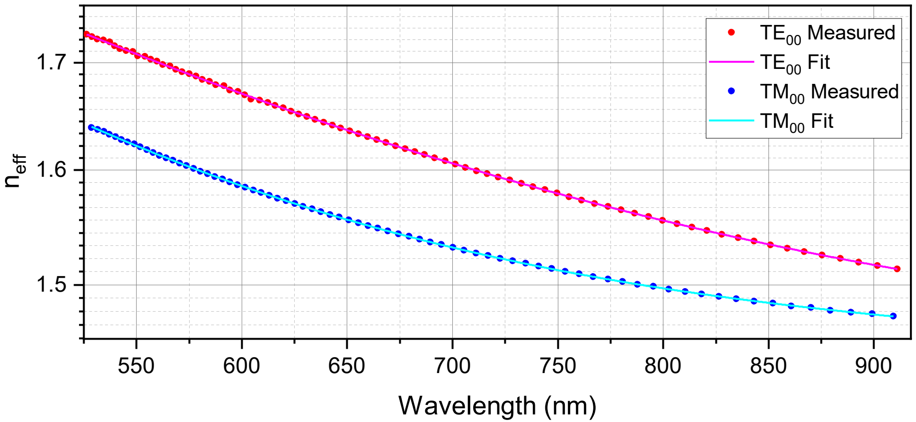
- Measurements span from 500 nm to 1000 nm in first measurement
- Measurements span from 900 nm to 1600 nm in second measurement

MZIs for n_{eff} measurement in the visible

500 nm wide waveguides







Measure similar spectra for

- 400 nm wide
- 800 nm wide

Refractive index and geometry

- Measure TE_{00} and TM_{00} n_{eff} of two different waveguide widths (at the same wavelength)
- Four known n_{effs}, four unknown waveguide parameters: t, Δw, $n_{core\text{-}real}$, $n_{clad\text{-}real}$

- Measured values in brown
- COMSOL values in blue
- Extracted parameters in red

Gauss-Newton method to solve this least-squares problem

measured — initial guesses — parameter dependencies — to be solved for

$$n_{\mathrm{eff}}^{\mathrm{TEw_1}} = n_{\mathrm{eff}(0)}^{\mathrm{TEw_1}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TEw_1}}}{\partial n_{\mathrm{core}}}\Delta n_{\mathrm{core}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TEw_1}}}{\partial n_{\mathrm{clad}}}\Delta n_{\mathrm{clad}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TEw_1}}}{\partial t}\Delta t + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TEw_1}}}{\partial w}\Delta w$$

$$n_{\mathrm{eff}}^{\mathrm{TMw_1}} = n_{\mathrm{eff}(0)}^{\mathrm{TMw_1}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TMw_1}}}{\partial n_{\mathrm{core}}}\Delta n_{\mathrm{core}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TMw_1}}}{\partial n_{\mathrm{clad}}}\Delta n_{\mathrm{clad}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TMw_1}}}{\partial t}\Delta t + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TMw_1}}}{\partial w}\Delta w$$

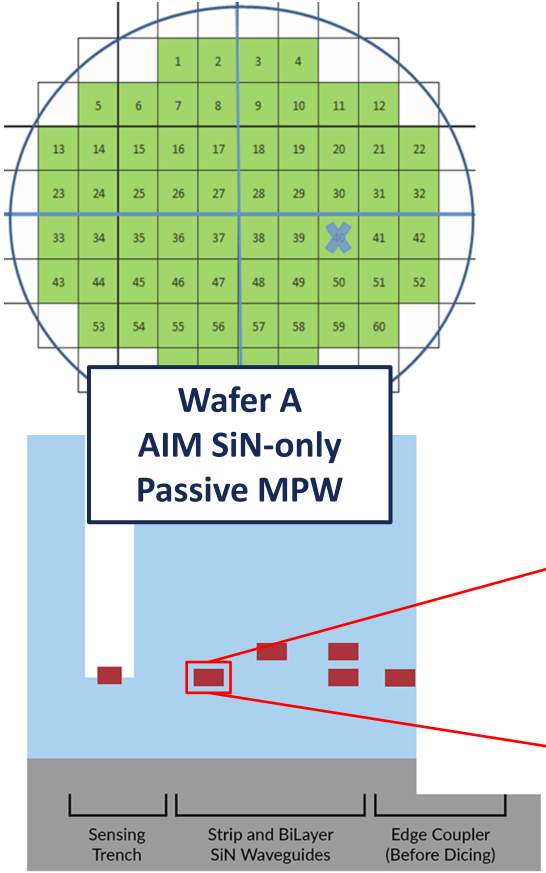
$$n_{\mathrm{eff}}^{\mathrm{TEw_2}} = n_{\mathrm{eff}(0)}^{\mathrm{TEw_2}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TEw_2}}}{\partial n_{\mathrm{core}}}\Delta n_{\mathrm{core}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TEw_2}}}{\partial n_{\mathrm{clad}}}\Delta n_{\mathrm{clad}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TEw_2}}}{\partial t}\Delta t + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TEw_2}}}{\partial w}\Delta w$$

$$n_{\mathrm{eff}}^{\mathrm{TMw_2}} = n_{\mathrm{eff}(0)}^{\mathrm{TMw_2}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TMw_2}}}{\partial n_{\mathrm{core}}}\Delta n_{\mathrm{core}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TMw_2}}}{\partial n_{\mathrm{clad}}}\Delta n_{\mathrm{clad}} + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TMw_2}}}{\partial t}\Delta t + \frac{\partial n_{\mathrm{eff}}^{\mathrm{TMw_2}}}{\partial w}\Delta w$$

Butt, *et al.*, *APL Photon.* **9**, 106104 (2024), doi 10.1063/5.0173914

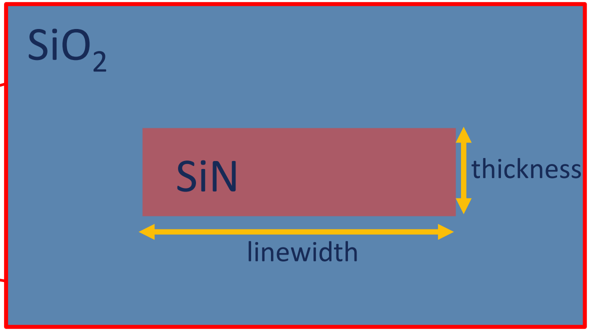
Stievater *et al.*, *Opt. Express* **30**, 14453 (2022), doi: 10.1364/OE.451719

Wafer A: an example



As a baseline, we extracted the waveguide parameters from the AIM SiN-only Passive MPW

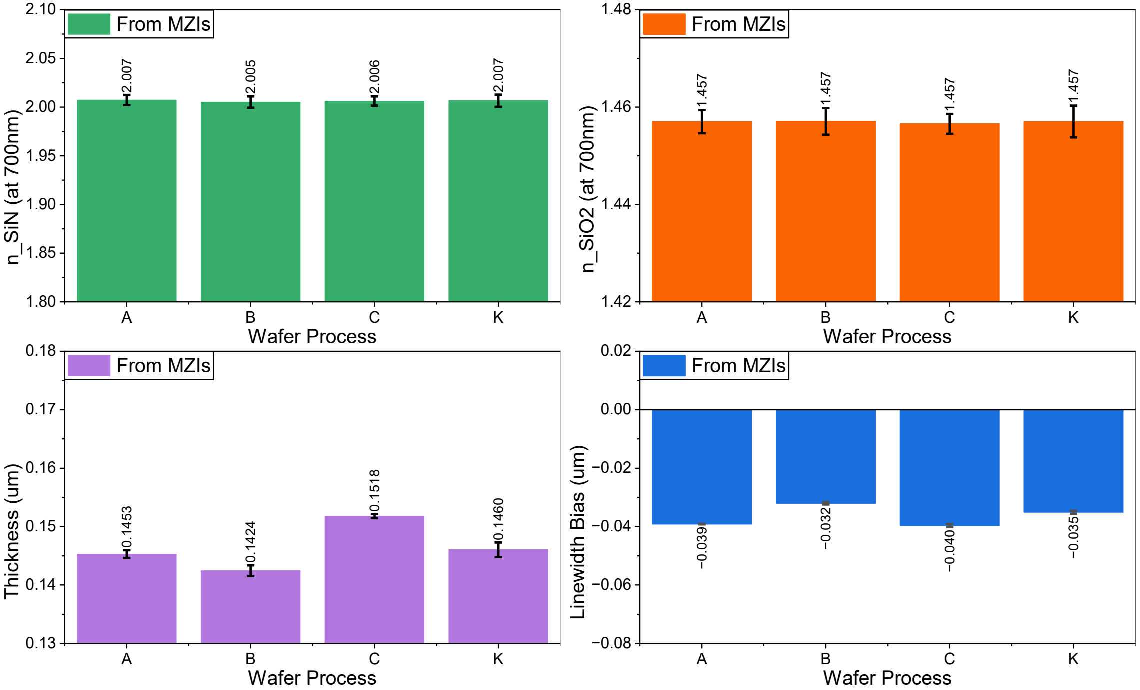
- Nominal SiN thickness of 150nm (bite-size custom offering)
- As shown below, we can extract the waveguide parameters with excellent precision



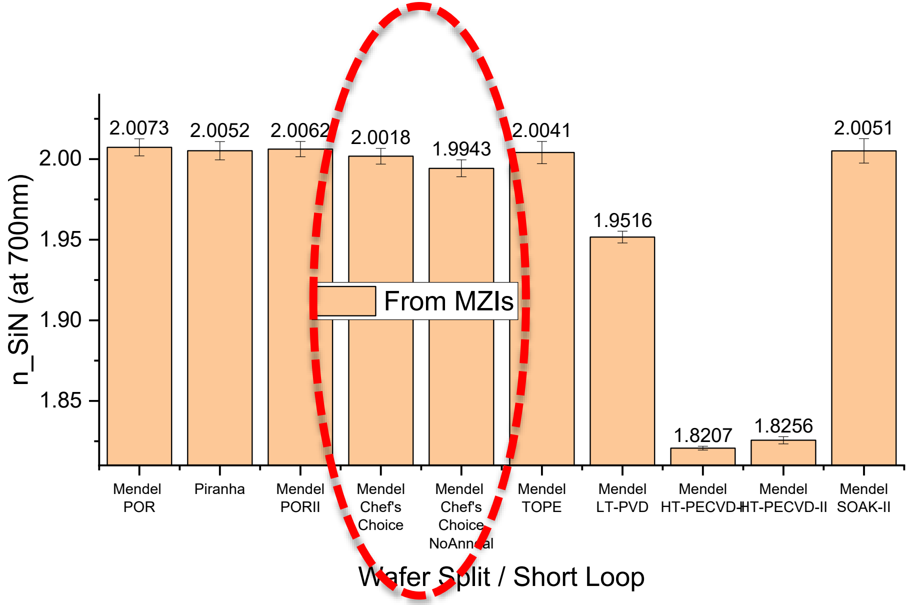
n_{SiN} @700nm	n_{SiO2} @700nm
2.007 ± 0.005	1.457 ± 0.002
Linewidth bias (nm)	Thickness (nm)
-39.1 ± 0.1	145.3 ± 0.6

Wafer-to-wafer variation for one process - POR

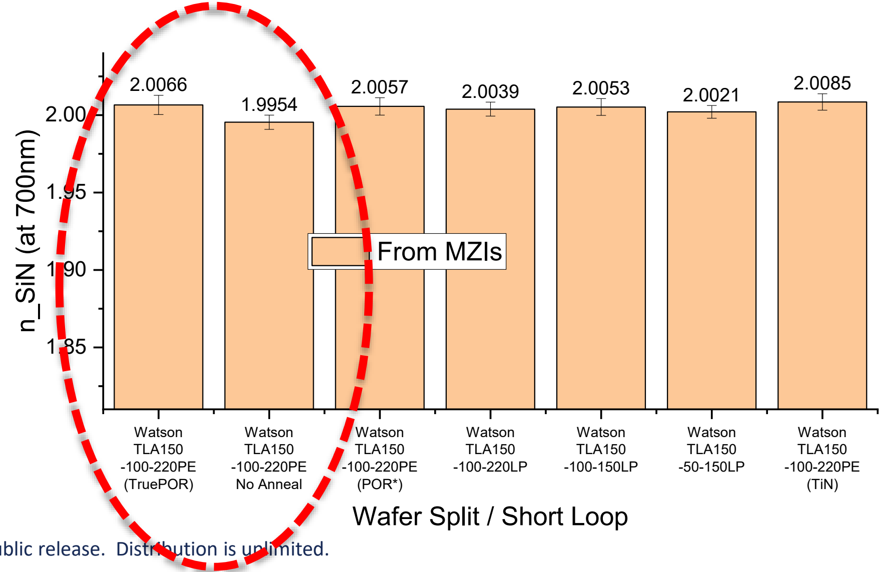
n_{SiN} @700nm	n_{SiO2} @700nm	Linewidth bias (nm)	Thickness (nm)
2.006 ± 0.001	1.4569 ± 0.0002	-36 ± 4	146 ± 4



SiN densification from anneal?

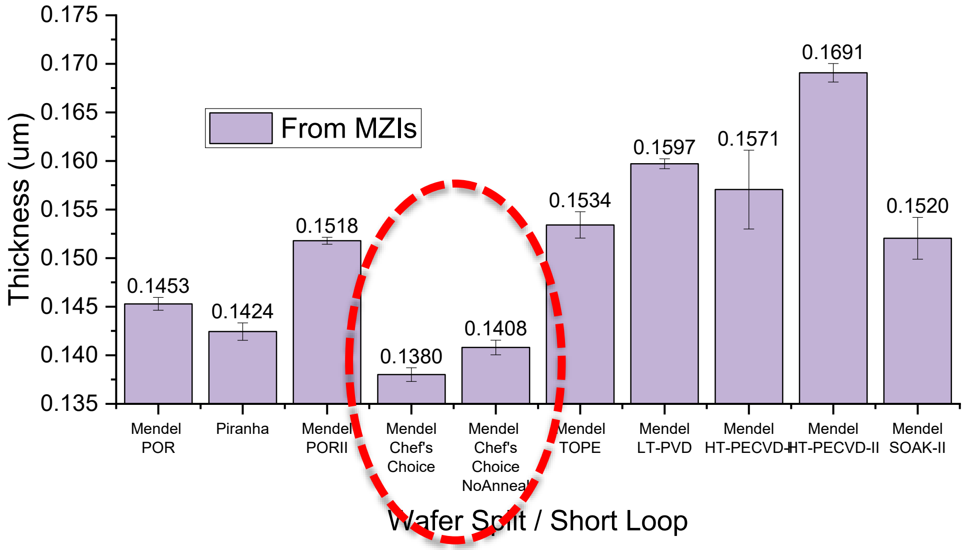


n_{SiN} increases from 1.9943 to 2.0018 due to anneal in Mendel Chef's Choice (0.38%)

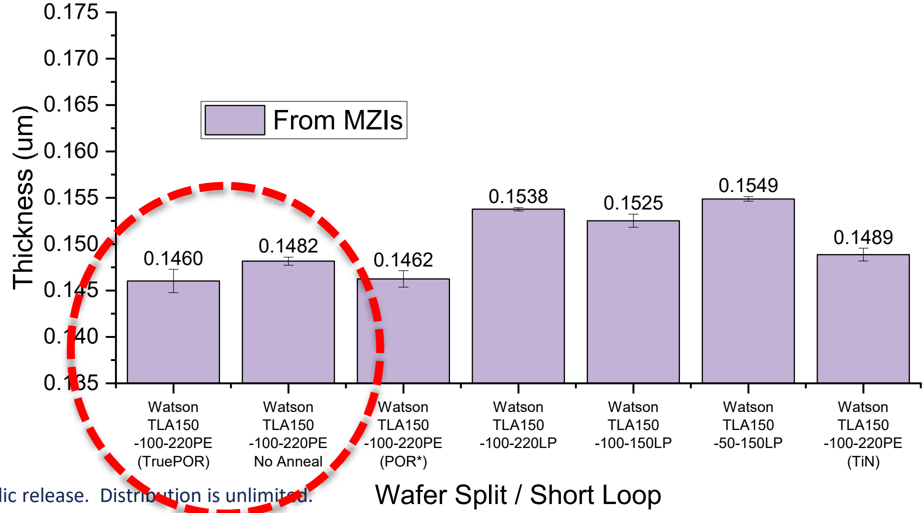


n_{SiN} increases from 1.9954 to 2.0066 due to anneal in Watson (0.56%)

SiN densification from anneal?



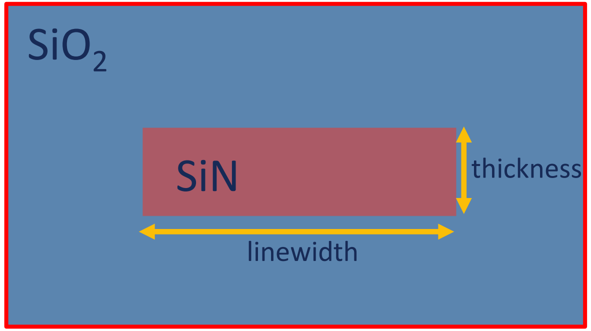
Thickness decreases from 140.8 nm to 138.0 nm due to anneal in Mendel Chef's Choice (2.0%)



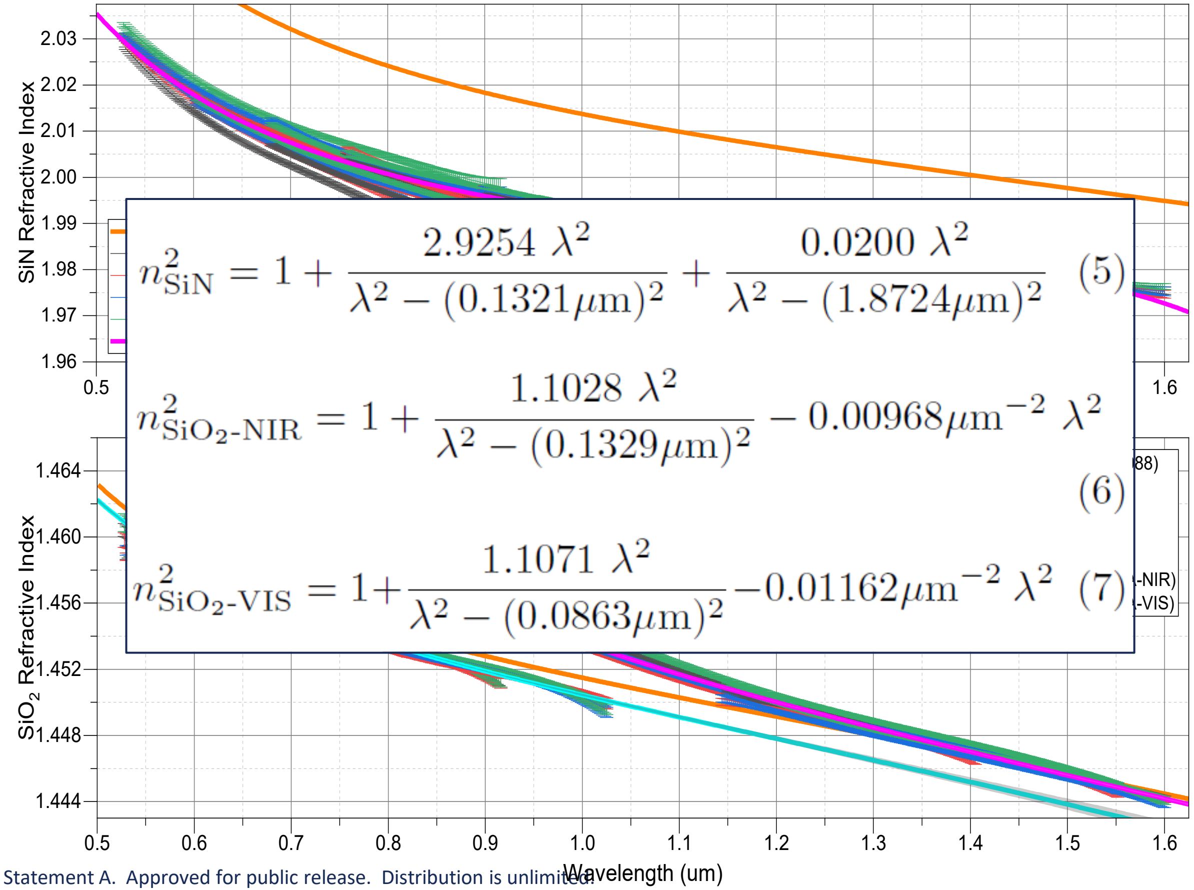
Thickness decreases from 148.2 nm to 146.0 nm due to anneal in Watson POR (1.5%)

LPCVD SiN refractive index from 500 nm to 1600 nm

Fix core geometry, solve for n_{SiN}, n_{SiO2} at every wavelength



n_{SiN} @1550nm	n_{SiO2} @1550nm
1.976± 0.003	1.4453± 0.0004
n_{SiN} @700nm	n_{SiO2} @700nm
2.007 ± 0.005	1.457 ± 0.002
Linewidth bias (nm)	Thickness (nm)
-39.1 ± 0.1	145.3 ± 0.6



$$n^2_{\mathrm{SiN}} = 1 + \frac{2.9254\ \lambda^2}{\lambda^2 - (0.1321\mu\mathrm{m})^2} + \frac{0.0200\ \lambda^2}{\lambda^2 - (1.8724\mu\mathrm{m})^2} \quad (5)$$

$$n^2_{\mathrm{SiO_2\text{-}NIR}} = 1 + \frac{1.1028\ \lambda^2}{\lambda^2 - (0.1329\mu\mathrm{m})^2} - 0.00968\mu\mathrm{m}^{-2}\ \lambda^2 \quad (6)$$

$$n^2_{\mathrm{SiO_2\text{-}VIS}} = 1 + \frac{1.1071\ \lambda^2}{\lambda^2 - (0.0863\mu\mathrm{m})^2} - 0.01162\mu\mathrm{m}^{-2}\ \lambda^2 \quad (7)$$

REFRACTIVE INDEX AND GEOMETRY: LEVENBERG-MARQUARDT METHOD

Gauss-Newton → Levenberg-Marquardt

<u>Old Gauss-Newton</u>

- Assumes waveguide bias is independent of linewidth
- Assumes fixed core shape
- Assume same cladding material for top cladding and bottom cladding
- Only extracts parameters at a single wavelength at a time
- Cumbersome to perform multiple iterations, and/or at multiple wavelengths

<u>New Levenberg-Marquardt Method</u>

- Builds mode-solver directly into each iteration
- Can process all data at all wavelengths simultaneously
- Can accommodate any refractive index model for core and cladding
- Can have independent width bias for different waveguide widths
- Can have different refractive index for top cladding vs. bottom cladding
- Can add other parameters as needed: sidewall angle, stress, etc.

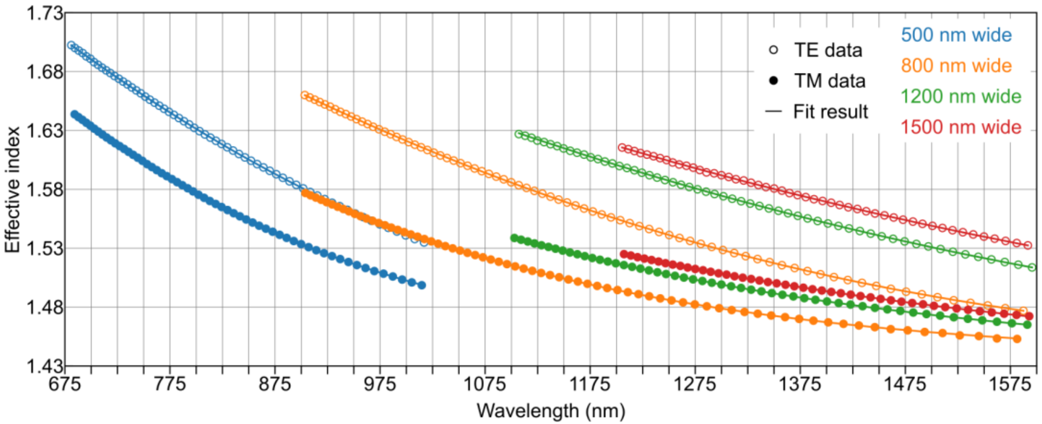
Procedure and Parameters of Interest

Parameters of interest:

- Waveguide Δw (varies with design width)
- Waveguide Δt (common across design width)
- Core Sellmeier coefficients
- Cladding Sellmeier coefficients

Function to minimize:

$$F = \Sigma_i \left(n_{eff,sim_i} - n_{eff,meas_i}\right)^2$$



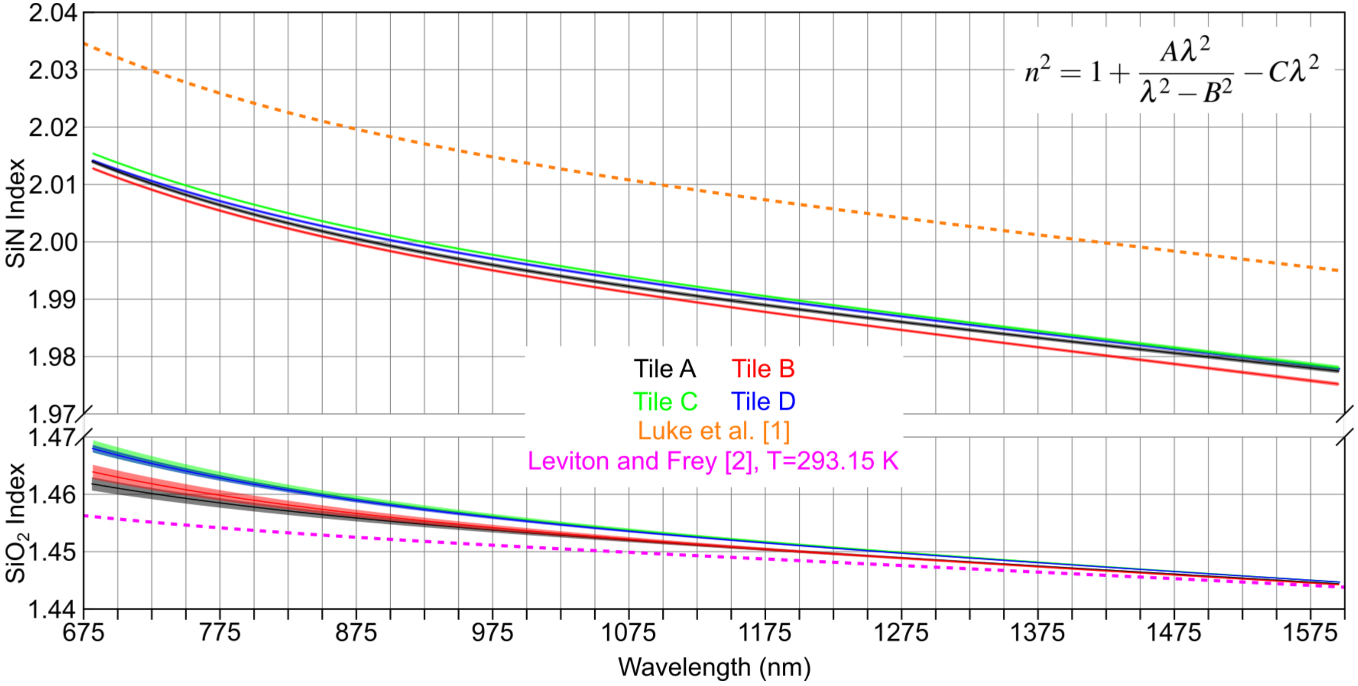
Procedure:

1. Using initial parameter guesses, we simulate the effective index at every wavelength where we have a data point.
2. The Jacobian matrix is calculated at each point using simulated fields and a perturbative approach.
3. Parameter values are updated via Levenberg-Marquardt algorithm
4. Return to step 1.

Result after 13 iterations (~7.3 hours)
(newer code is ~4x faster, ~ 2 hours)

Extraction Results (220 nm thick SiN) (4 tile locations)

	dW_{500} (nm)	dW_{800} (nm)	dW_{1200} (nm)	dW_{1500} (nm)	dT (nm)	A_{SiN}	B_{SiN} (µm)	C_{SiN} (µm^{-2})	A_{SiO_2}	B_{SiO_2} (µm)	C_{SiO_2} (µm^{-2})
Initial Guess	0	0	0	0	0	2.9254	0.1321	0.0057	1.1028	0.1329	0.0097
Tile A	-64.7 ± 0.3	-58.8 ± 1.7	-58.9 ± 5.0	-73.3 ± 8.4	-3.0 ± 0.5	2.9514 ± 0.0027	0.1325 ± 0.0009	0.0242 ± 0.0011	1.1062 ± 0.0009	0.1201 ± 0.0068	0.0103 ± 0.0002
Tile B	-55.4 ± 0.3	-47.4 ± 1.6	-35.6 ± 5.1	-36.9 ± 8.7	-4.1 ± 0.5	2.9543 ± 0.0022	0.1293 ± 0.0008	0.0284 ± 0.0010	1.1020 ± 0.0008	0.1356 ± 0.0062	0.0095 ± 0.0002
Tile C	-55.3 ± 0.3	-47.3 ± 1.8	-30.4 ± 5.1	-35.3 ± 8.6	-6.4 ± 0.4	2.9649 ± 0.0021	0.1290 ± 0.0009	0.0281 ± 0.0011	1.1019 ± 0.0009	0.1533 ± 0.0049	0.0098 ± 0.0002
Tile D	-55.9 ± 0.2	-49.9 ± 1.1	-36.0 ± 2.8	-43.1 ± 4.9	-5.0 ± 0.3	2.9639 ± 0.0018	0.1268 ± 0.0007	0.0028 ± 0.0007	1.1009 ± 0.0006	0.1530 ± 0.0029	0.0094 ± 0.0002



Geometry Means

dW_{500} (nm) = -57.8 ± 0.1

dW_{800} (nm) = -50.9 ± 0.8

dW_{1200} (nm) = -40.2 ± 2.3

dW_{1500} (nm) = -47.2 ± 3.9

dT (nm) = -4.6 ± 0.2

[1]: Luke, et al., Optics Letters (2015), DOI: 10.1364/OL.40.004823

[2]: Leviton and Frey, SPIE Optomechanical Technologies for Astronomy (2006), DOI: 10.1117/12.672853

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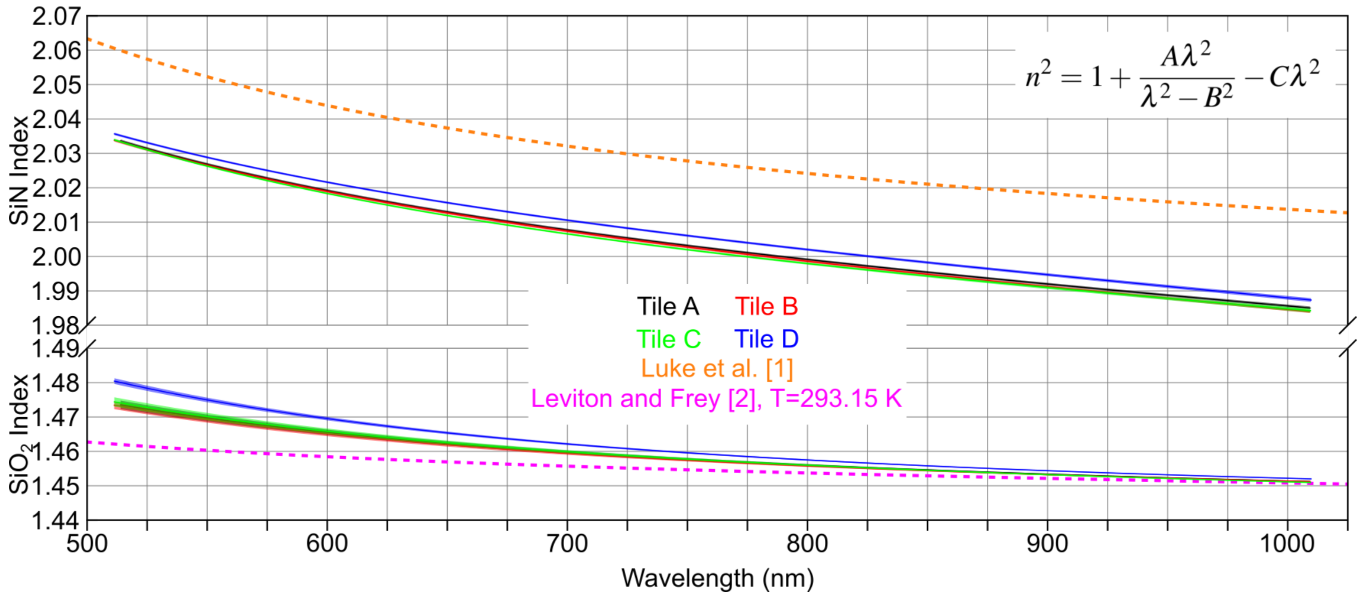
Extraction Results (150 nm Thick) (4 tile locations)

	dW_{400} (nm)	dW_{500} (nm)	dW_{800} (nm)	dT (nm)	A_{SiN}	B_{SiN} (μm)	C_{SiN} ($μm^{-2}$)	A_{SiO_2}	B_{SiO_2} (μm)	C_{SiO_2} ($μm^{-2}$)
Initial Guess	-25	-25	-25	-5	2.9254	0.1321	0.0057	1.1028	0.1329	0.0097
Tile A	-39.3 ± 0.5	-23.9 ± 1.2	$+8.8 \pm 5.0$	-8.5 ± 0.5	2.9711 ± 0.0050	0.1242 ± 0.0014	0.0750 ± 0.0047	1.0905 ± 0.0020	0.1359 ± 0.0040	0.0045 ± 0.0013
Tile B	-35.6 ± 0.5	-20.9 ± 1.2	$+13.1 \pm 4.9$	-8.5 ± 0.4	2.9744 ± 0.0045	0.1232 ± 0.0013	0.0816 ± 0.0042	1.0878 ± 0.0018	0.1367 ± 0.0036	0.0020 ± 0.0012
Tile C	-33.0 ± 0.6	-16.2 ± 1.6	$+21.1 \pm 6.1$	-8.6 ± 0.4	2.9564 ± 0.0049	0.1280 ± 0.0014	0.0661 ± 0.0054	1.0901 ± 0.0022	0.1376 ± 0.0043	0.0054 ± 0.0016
Tile D	-32.6 ± 0.6	-14.3 ± 1.2	$+26.0 \pm 4.4$	-10.5 ± 0.3	2.9967 ± 0.0044	0.1185 ± 0.0014	0.0873 ± 0.0046	1.0817 ± 0.0016	0.1553 ± 0.0023	-0.0004 ± 0.0013



Geometry Means

dW_{400} (nm) =-35.1 ± 0.3

dW_{500} (nm) = -18.8 ± 0.7

dW_{800} (nm) = 17.3 ± 2.3

dT (nm) = -9.0 ± 0.2

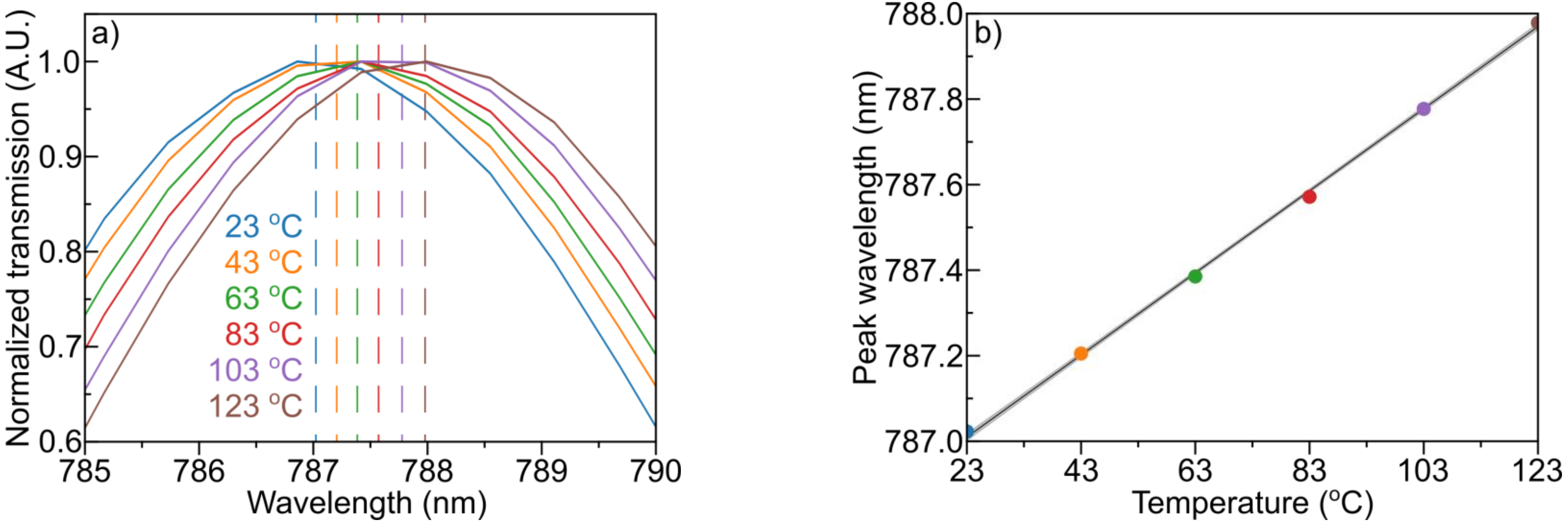
[1]: Luke, et al., Optics Letters (2015), DOI: 10.1364/OL.40.004823

[2]: Leviton and Frey, SPIE Optomechanical Technologies for Astronomy (2006), DOI: 10.1117/12.672853

SIN THERMO-OPTIC COEFFICIENT

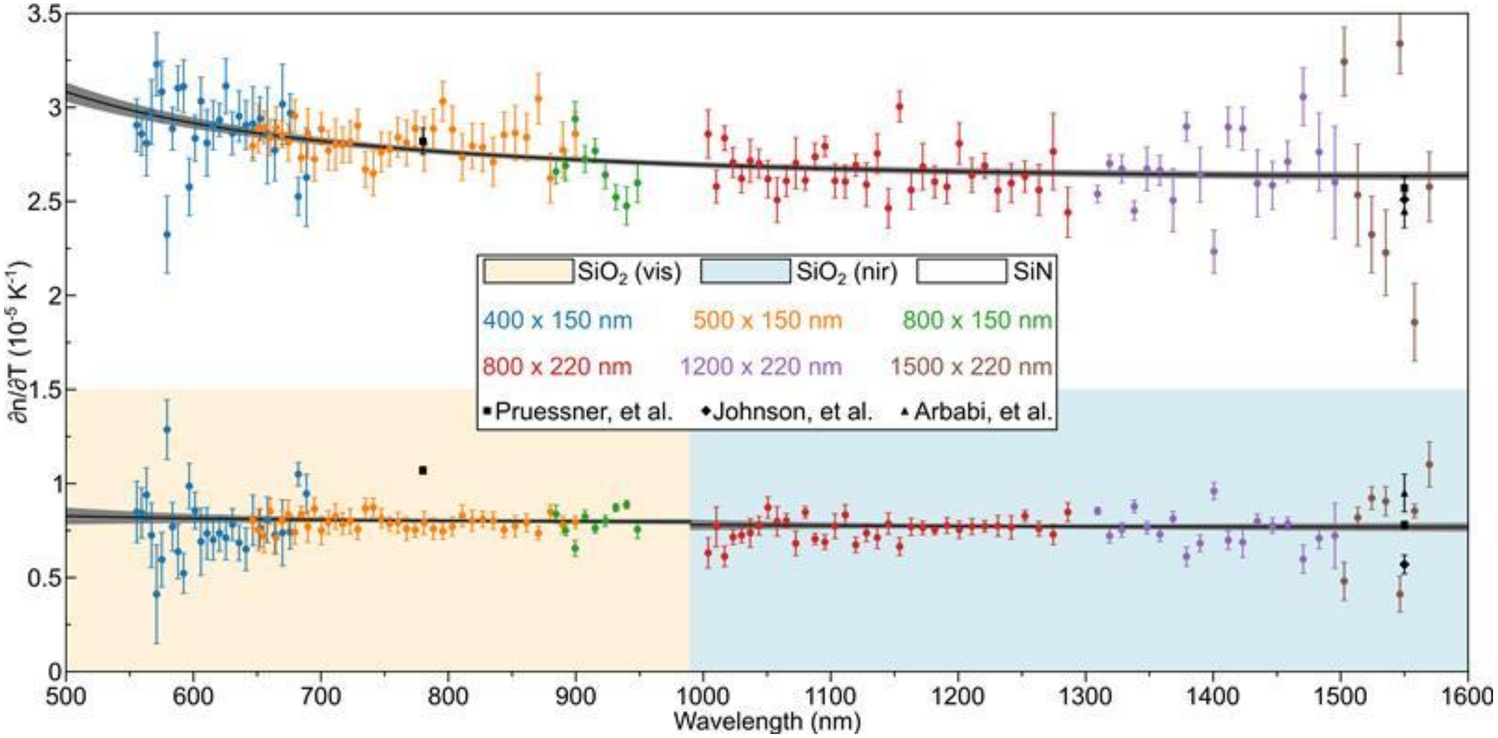
MZI measurements vs. temperature

- Use a heated sample chuck with broadband MZI measurements



- All MZI maxima and minima can be tracked with temperature
- Use modal overlaps to convert dn_{eff}^{TE} and dn_{eff}^{TM}/dT to dn_{core}/dT and dn_{clad}/dT

dn/dT for SiN and SiO2 vs wavelength



- SiO2 dn/dT agrees with previous measurements
- First measurement of SiN dn/dT in the visible

Summary

- Loss in AIM SiN waveguides measured accurately from 500 nm to 1620 nm
  - Loss is a combination of SiN absorption and sidewall scattering
  - Ongoing work to separate out their relative contributions

- SiN and SiO2 refractive index and core width and thickness measured accurately from waveguide MZIs
  - Measured from 500 nm to 1600 nm
  - Important for accurate component design
  - Post-fabrication measurements capture all processing steps
  - Can be used for wafer-scale statistics and process monitoring

- SiN thermo-optic coefficient measured from 550 nm to 1600 nm
  - First measurement of SiN TO coefficient in the visible
  - TO coefficient at 550 nm 18% higher than value at 1550 nm

- These techniques can be used with any waveguide material (AlO, TiO2, AlN, etc.)

- Current work is implementing fully automated Levenberg-Marquadt algorithm for integration with foundry test data

THANK YOU