DESIGNING LARGE-SCALE PHOTONIC INTEGRATED CIRCUITS (PICS)

Muhammad Umar Khan, Yufei Xing and Wim Bogaerts

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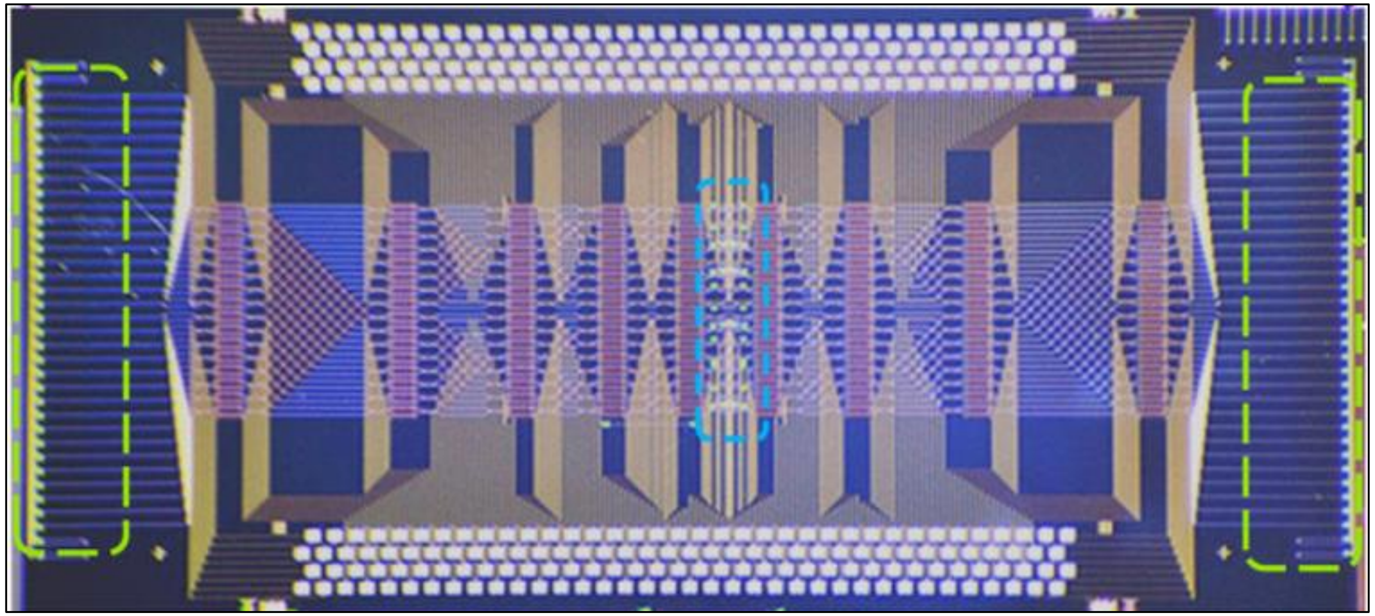
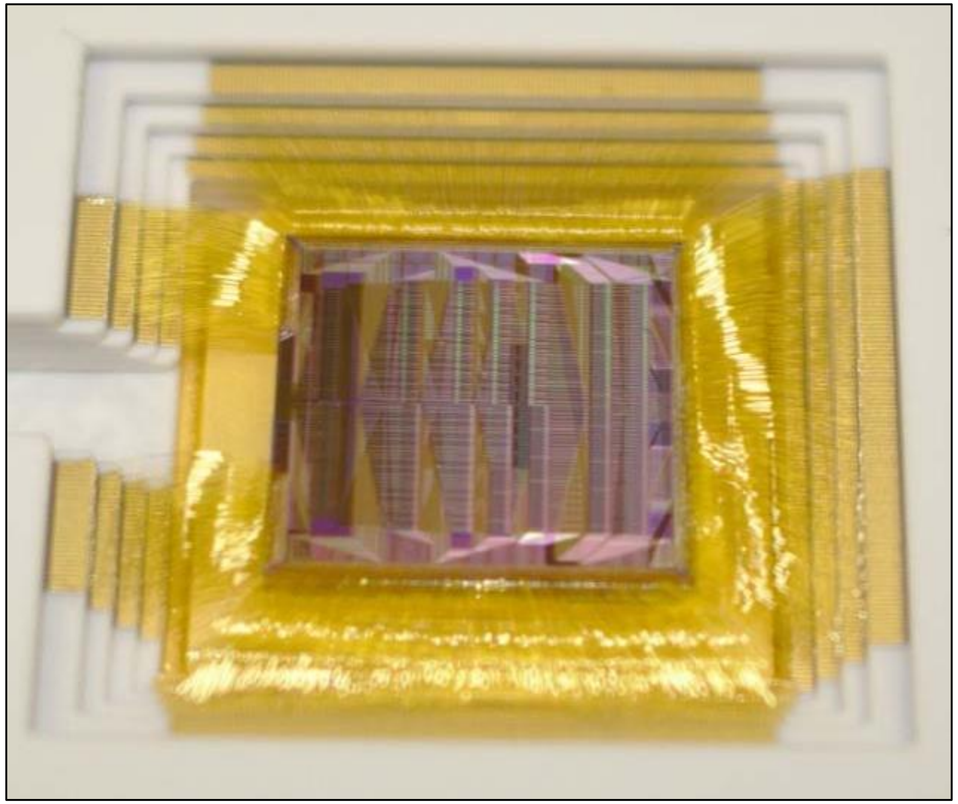
OUTLINE

- Large scale PICs
    - Fabrication imperfections/variability
        - *Silicon-on-insulator* (SOI) waveguide
- Design flow
    - Layout aware yield prediction
        - Parameter Extraction & spatial variability
- Summary

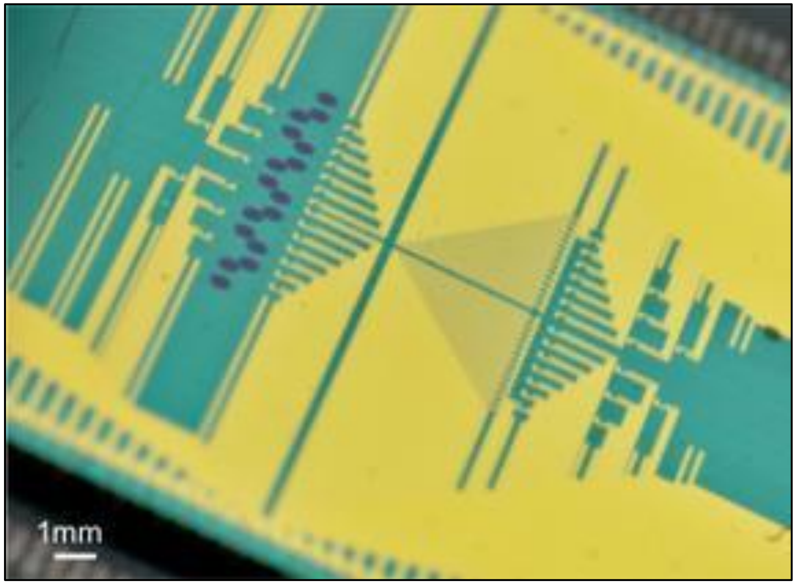
PHOTONIC LARGE-SCALE INTEGRATION IS HERE



Photonic switch
Cheng, et al., *Optics Express 2018*



32 × 32 SiPh switch matrix
D. Celo et al. 2016



Quantum silicon chip
J. Wang, et al. *Science 2018*

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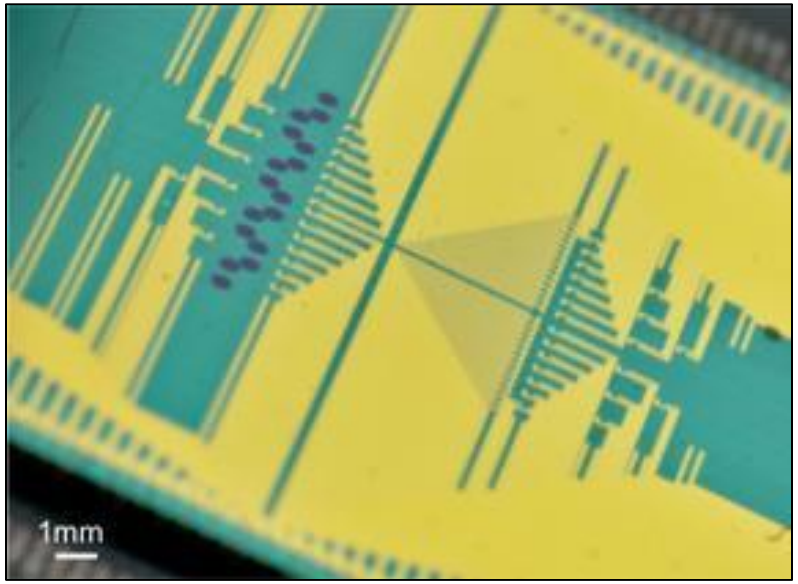
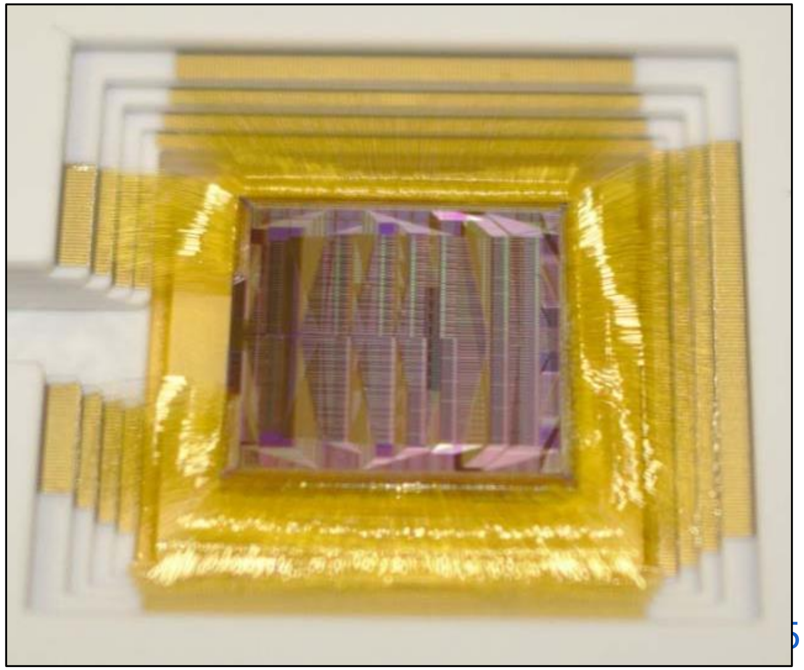
PHOTONIC LARGE-SCALE INTEGRATION IS HERE

- Large scale PICs
  - Complexity
  - Functionality ☺

- Fabrication imperfections
  - Linewidth and thickness
    - Not as desired ☹
  - Fabrication variations accumulate
    - Performance degradation ☹
  - Lower fabrication yield
    - Expensive ☹

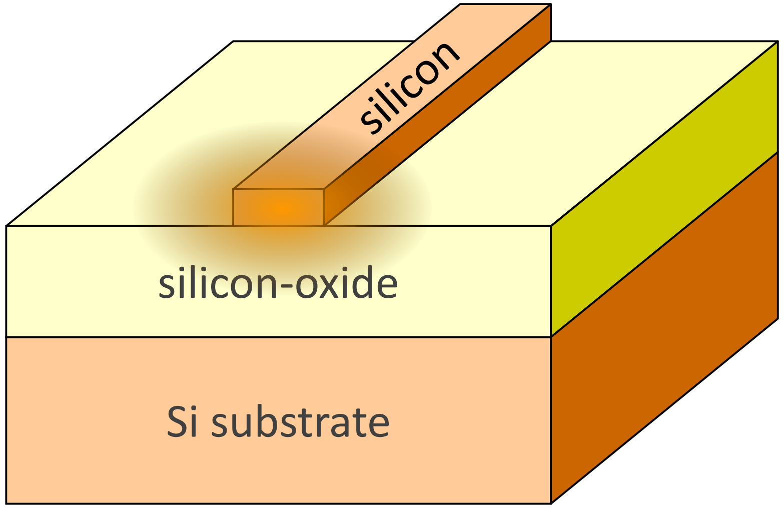


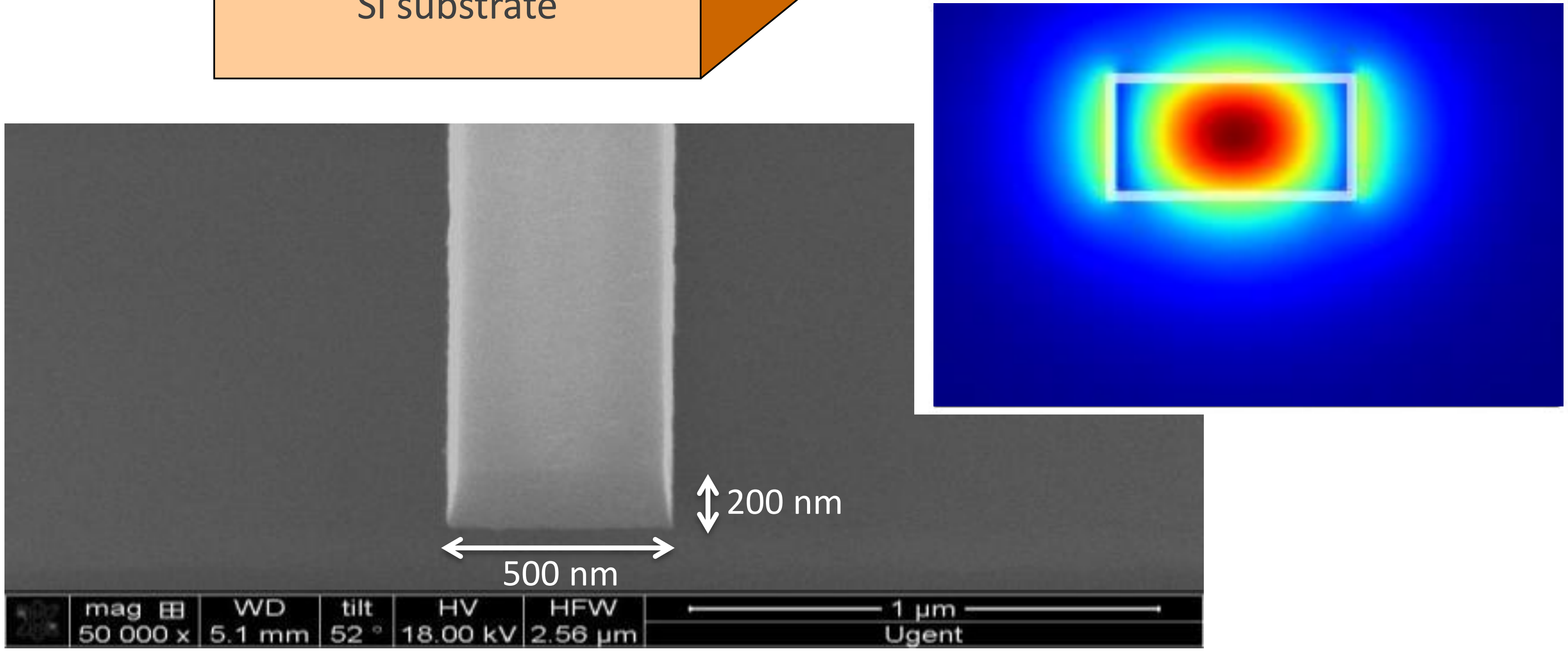


FABRICATION IMPERFECTIONS (VARIABILITY)

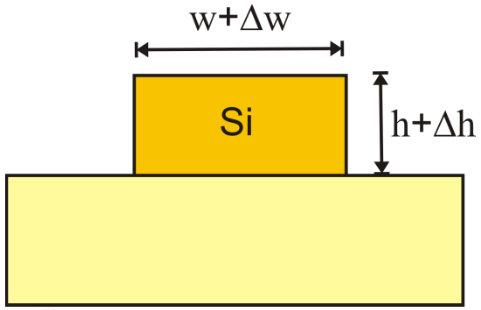
SILICON PHOTONIC WAVEGUIDE

$\mathbf{n_1}$(=3.5)>$\mathbf{n_2}$(=1.45)

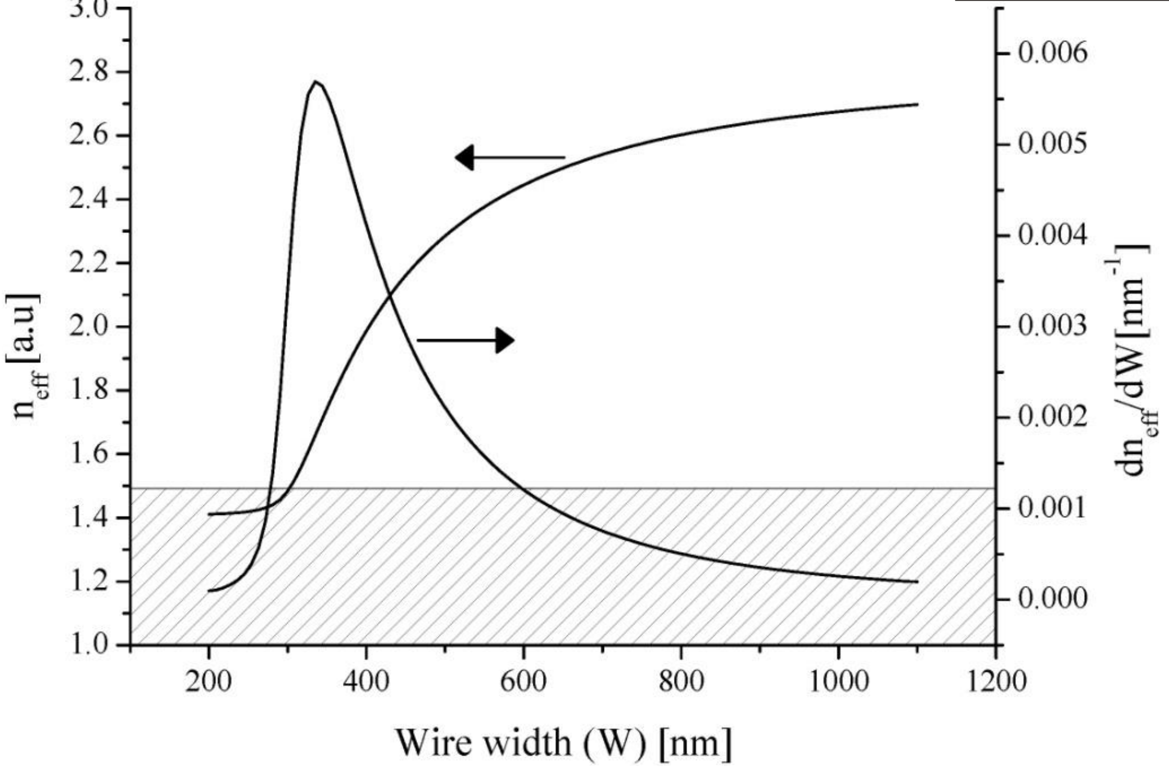




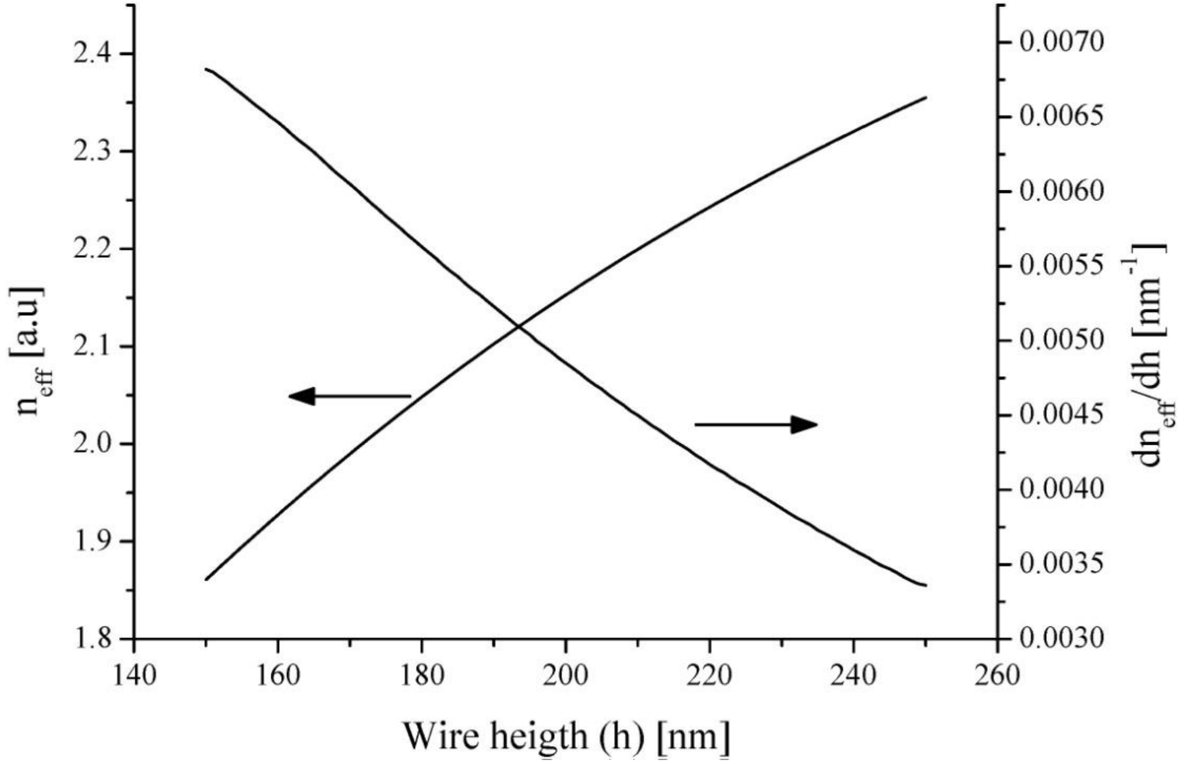
DIMENSIONAL DEPENDENCE OF A WAVEGUIDE



Effective index for different widths



Effective index for different heights



SENSITIVITY OF SILICON PHOTONICS

Silicon photonic waveguides are sensitive to

- geometry
- stress
- temperature
- …

wire width $$\frac{\partial\lambda}{\partial w} \approx 1\,{}^{nm}\!/_{nm}$$

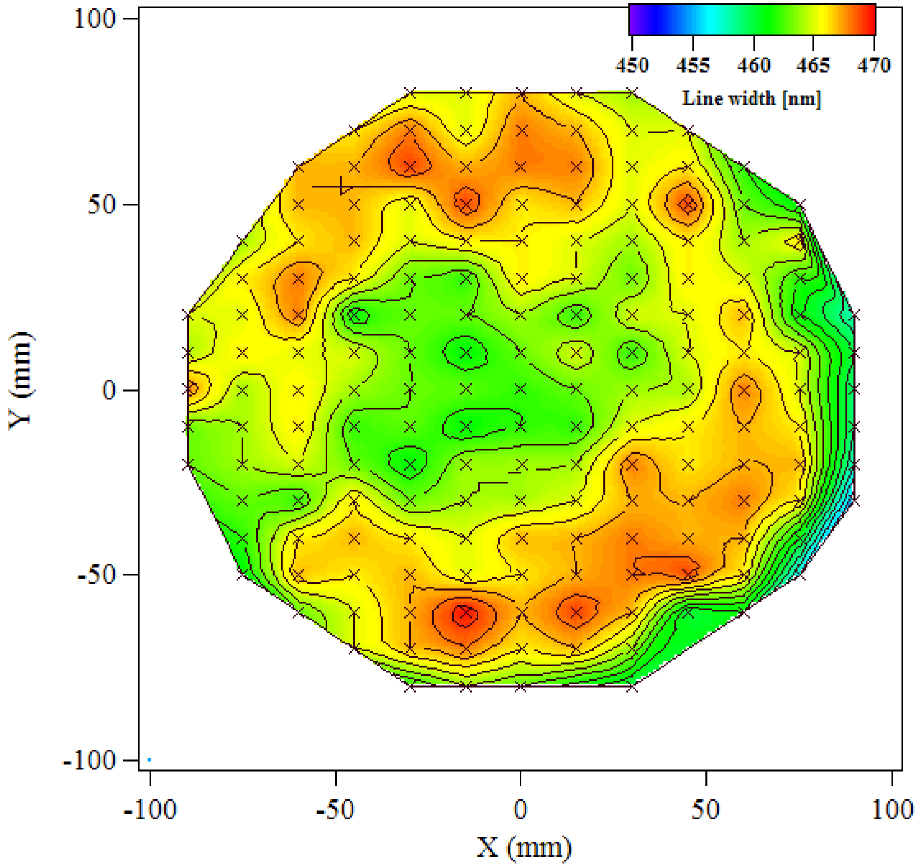
wire height $$\frac{\partial\lambda}{\partial h} \approx 2\,{}^{nm}\!/_{nm}$$

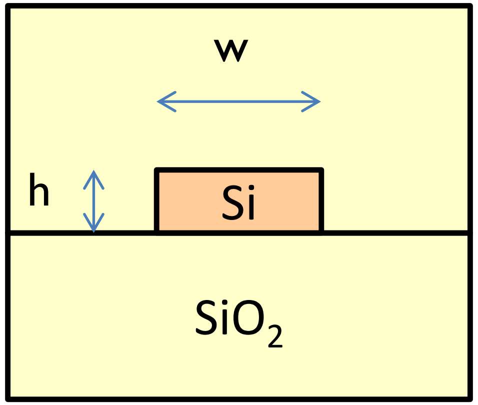
temperature $$\frac{\partial\lambda}{\partial T} \approx 0.08\,{}^{nm}\!/_{K}$$

1nm ~20K

1nm ~10K

Silicon wire linewidth





SOURCES OF NON-UNIFORMITY

Reticle/Mask
- CD uniformity
- Flatness
- Transmission

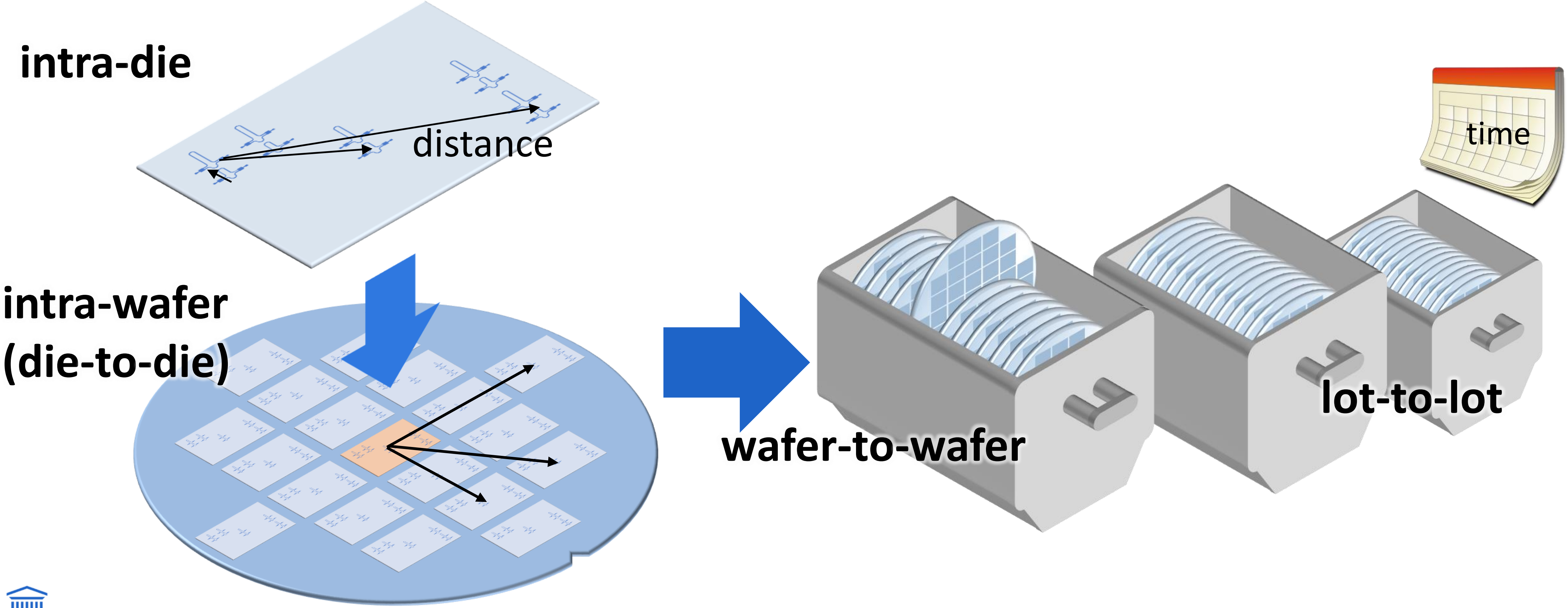
Litho tool
- Exposure dose
- Slit uniformity
- Chuck flatness
- Focus stability
- Scan direction
- Source spectrum

Resist process
- BARC uniformity
- Resist uniformity
- PEB °C Uniformity
- Developer
- Metrology

Wafer
- Wafer flatness
- Stack uniformity
- Topography

Etch process
- Plasma Chemistry
- Coil power stability
- Bias stability
- Resist coverage
- °C stability
- Metrology

VARIABILITY EFFECTS WORK ON DIFFERENT SCALES



intra-die

distance

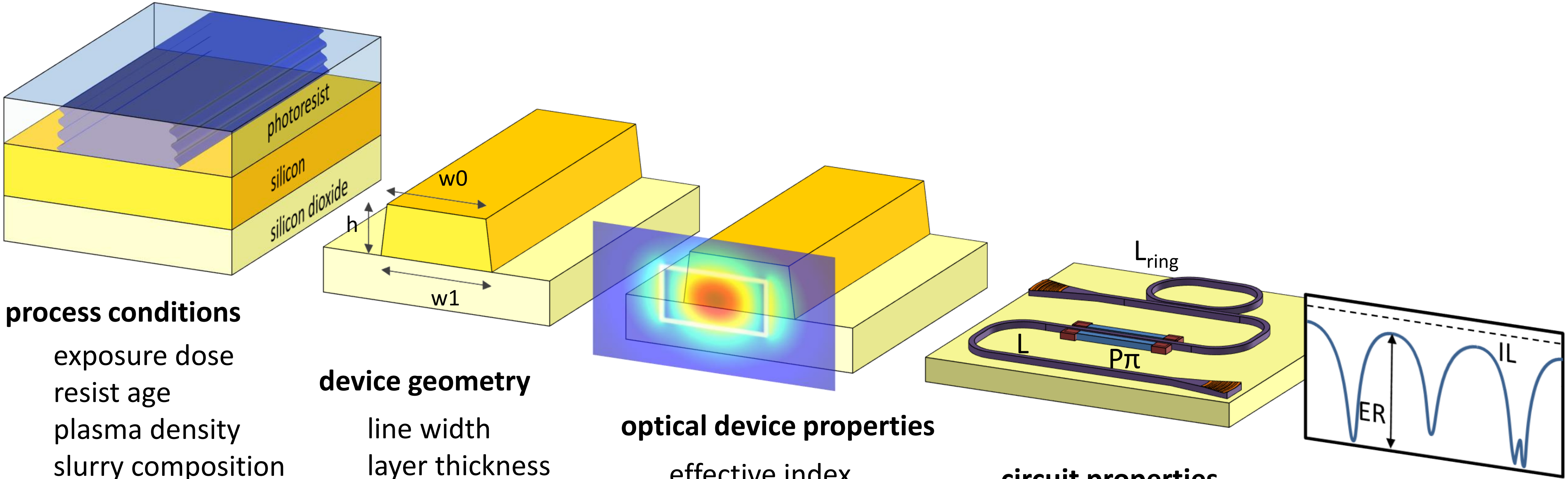
intra-wafer (die-to-die)

wafer-to-wafer

lot-to-lot

time

DESCRIBING VARIABILITY AT DIFFERENT LEVELS



process conditions

- exposure dose
- resist age
- plasma density
- slurry composition
- …

device geometry

- line width
- layer thickness
- sidewall angle
- doping profile
- …

optical device properties

- effective index
- group index
- coupling coefficients
- center wavelength
- …

circuit properties

- optical delay
- path imbalance
- tuning curve
- …

system performance

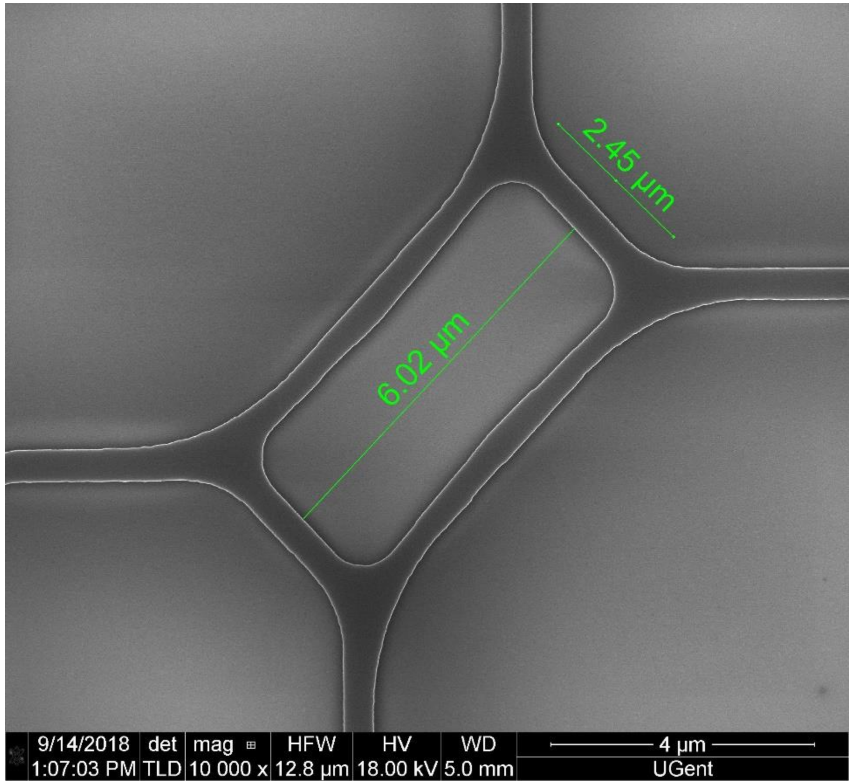
- insertion loss
- crosstalk
- noise figures
- power consumption
- …

DESIGN WORKFLOW

- Parameter Extraction & Spatial Variability
  - Geometrical parameters
    - Waveguide width
    - Waveguide thickness
      - Optical parameters
      - Mapping of optical parameters to geometrical parameters
- Layout-Aware Yield Prediction

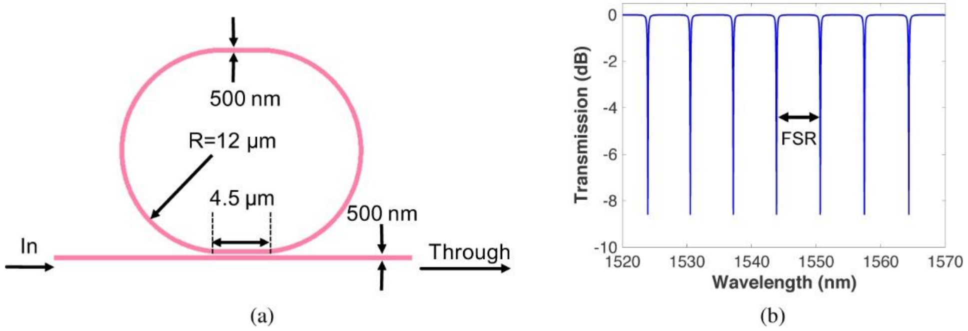
PARAMETER EXTRACTION & SPATIAL VARIABILITY

PARAMETER EXTRACTION



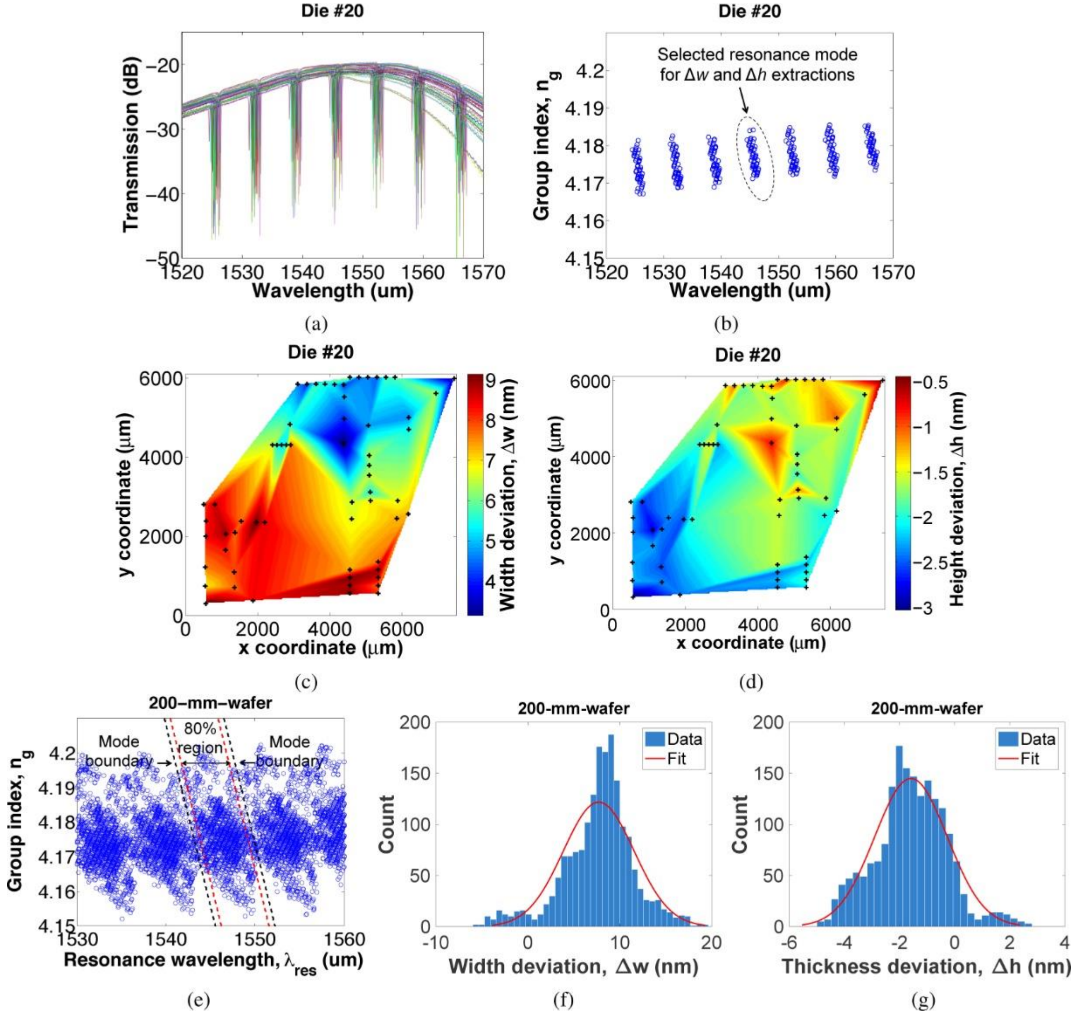
- Metrology measurements
  - Scanning electron microscope (SEM)
  - Atomic force microscope (AFM)
    - Time consuming ☹
    - Expensive ☹
    - Destructive ☹
    - Extraction error (~nm) ☹
    - Few places on the wafer/die ☹
- Optical Measurements
  - Fitting of measurements to simulations
  - Mapping of optical parameters to geometric parameters
    - Smaller extraction errors (sub-nanometer) ☺
    - Non-destructive ☺
    - Many places over the wafer/die ☺

Extrtaction - Optical Measurements of Rings



(a)

(b)



(a)

(b)

(c)

(d)

(e)

(f)

(g)

- Extract parameters (n_{eff}, n_g) using wafer scale measurements
- Link n_{eff}, n_g to width and thickness
- Cannot separate straight and bend waveguide

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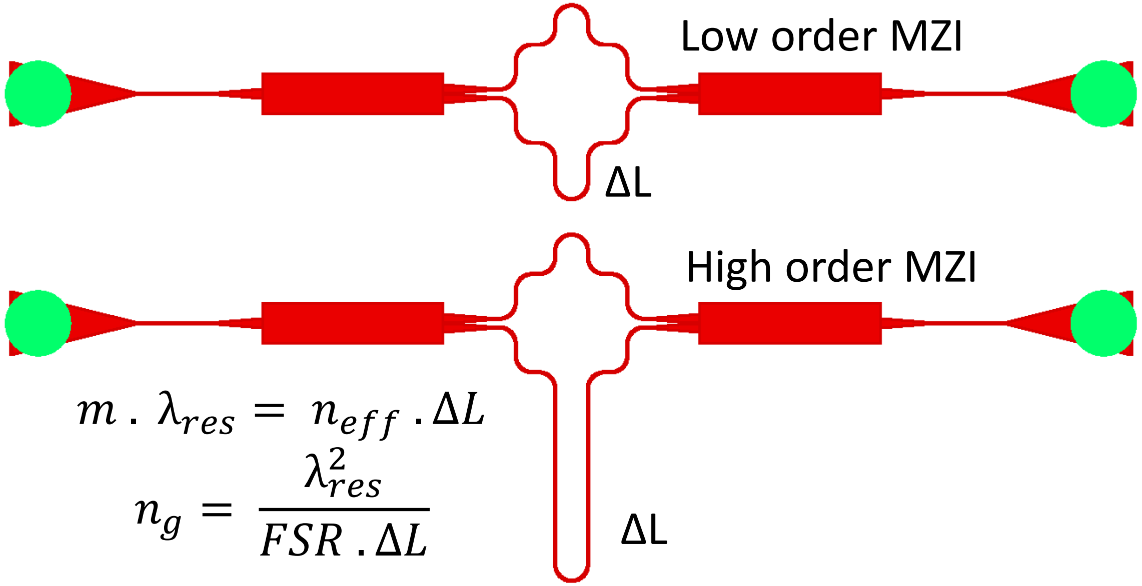
Lu, Optics Express 2017

EXTRACTION - OPTICAL MEASUREMENTS OF TWO MZIs



$$m \, . \, \lambda_{res} = n_{eff} \, . \, \Delta L$$

$$n_g = \frac{\lambda_{res}^2}{FSR \, . \, \Delta L}$$

Spectrum

- n_{eff}, n_g: Straight waveguide
- Length difference between two arms

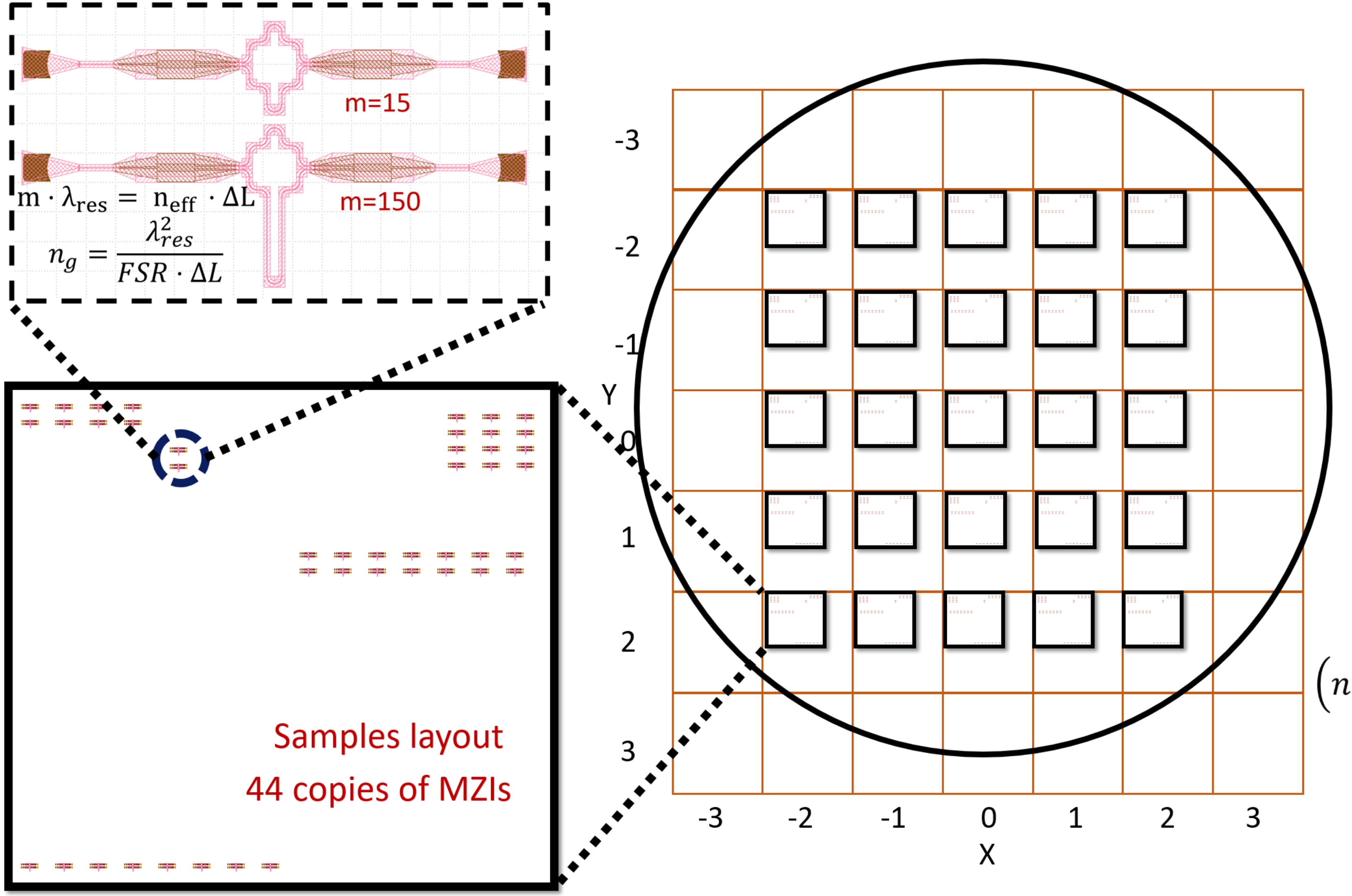
Low order

- Inaccurate extraction
- Tolerant to overall variation
- Set reference effective index

High order

- Accurate extraction of group index and effective index

MEASUREMENT SITES



$$m \cdot \lambda_{res} = n_{eff} \cdot \Delta L$$

$$n_g = \frac{\lambda_{res}^2}{FSR \cdot \Delta L}$$

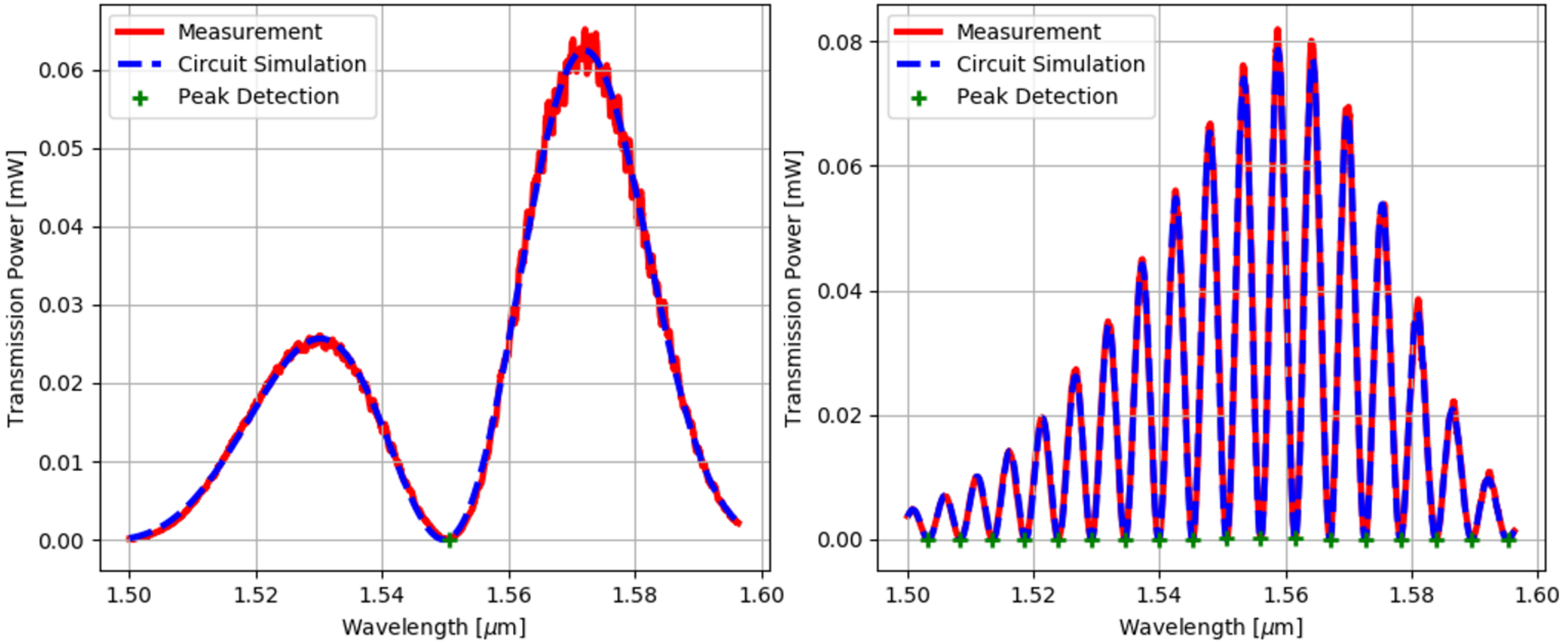
25 dies

44 copies of MZI pairs per die

Obtain geometry parameters

$$\left(n_{eff}(\lambda_0), n_g(\lambda_0)\right) \xRightarrow{(w,t)=f\left(n_{eff}(\lambda_0),n_g(\lambda_0)\right)} (w,t)$$

CURVE FITTING



$$\Rightarrow n_{eff}, n_g$$

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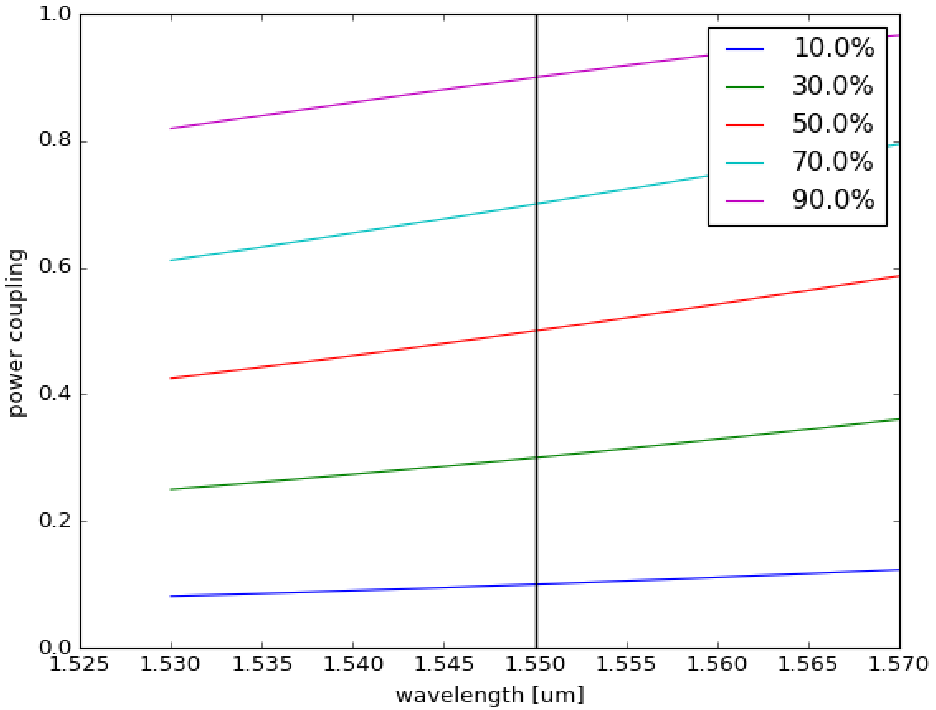
DIRECTIONAL COUPLERS

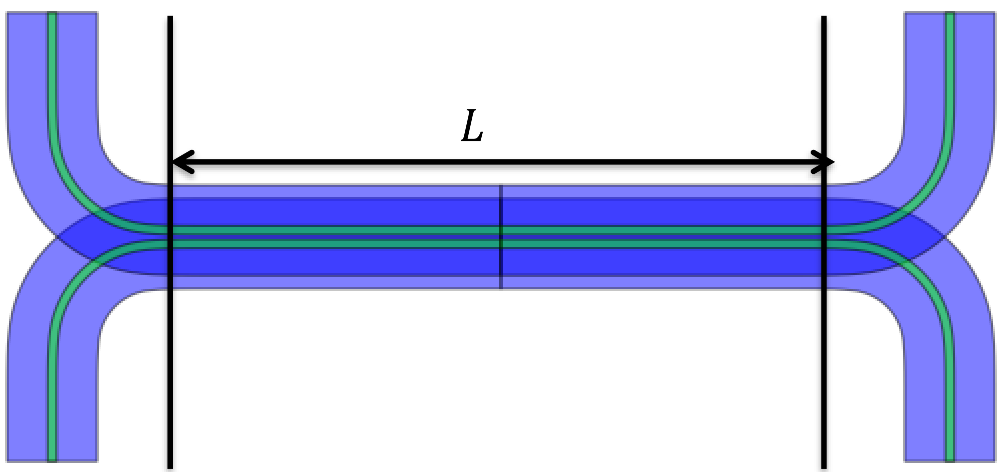
Treat coupler as circuit:

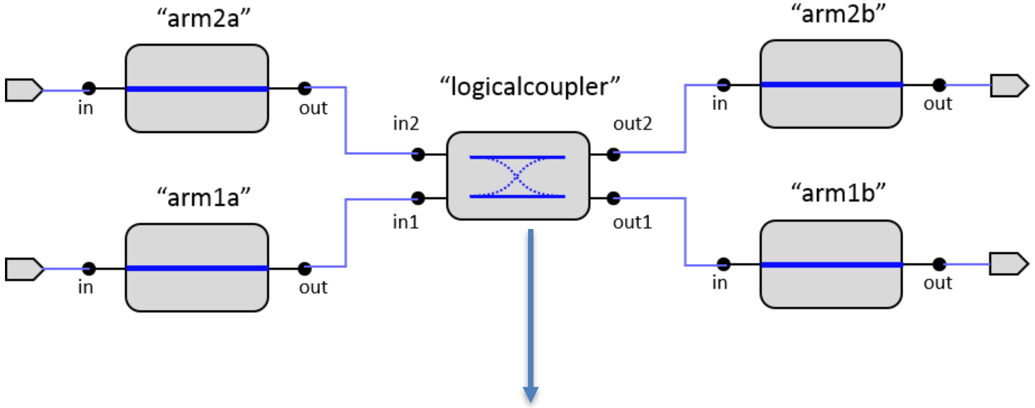
- 4 waveguides with their sensitivity to w, t
- 1 logical coupler with sensitivity to w, t

Coupling model = dispersive: straight + bends

Sensitivity calculated using mode solver + FDTD







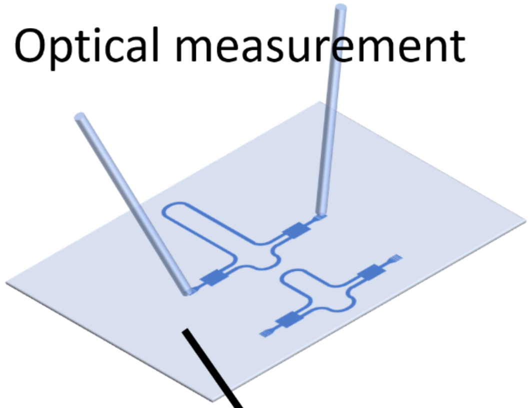
$$K = \cos^2(\kappa_0 + \kappa' L)$$

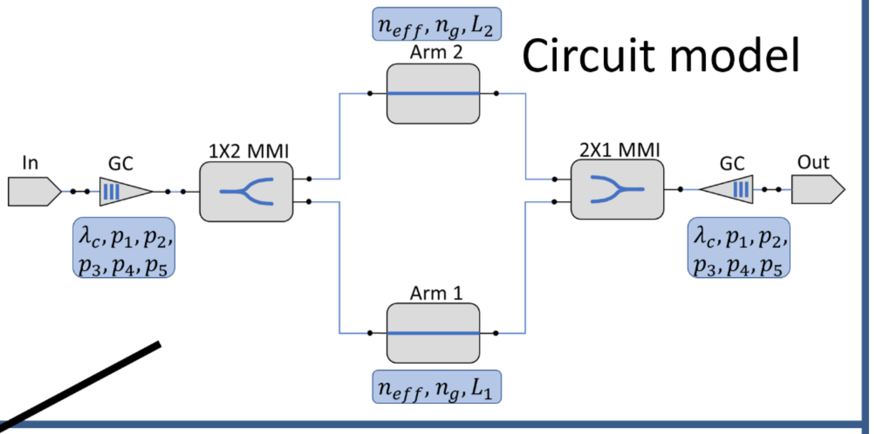
$$\kappa_0(\lambda) = \kappa_0(\lambda_0) + \frac{\partial \kappa_0}{\partial \lambda}(\lambda - \lambda_0) + \frac{1}{2}\frac{\partial^2 \kappa_0}{\partial \lambda^2}(\lambda - \lambda_0)$$

$$\kappa'(\lambda) = \kappa'(\lambda_0) + \frac{\partial \kappa'}{\partial \lambda}(\lambda - \lambda_0) + \frac{1}{2}\frac{\partial^2 \kappa'}{\partial \lambda^2}(\lambda - \lambda_0)$$

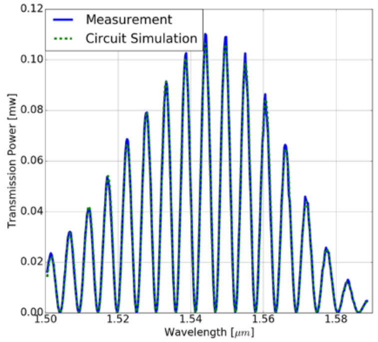
WORKFLOW TO EXTRACT GEOMETRY PARAMETERS

Optical measurement



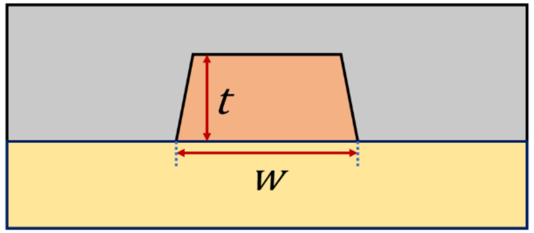


Circuit model



Match optical measurement with circuit simulation to extract behavior parameters

$$n_{eff}(\lambda_0), n_g(\lambda_0), \ldots$$



Obtain geometry parameters

$$\left(n_{eff}(\lambda_0), n_g(\lambda_0)\right) \xRightarrow{(w,t)=f\left(n_{eff}(\lambda_0),n_g(\lambda_0)\right)} (w,t)$$

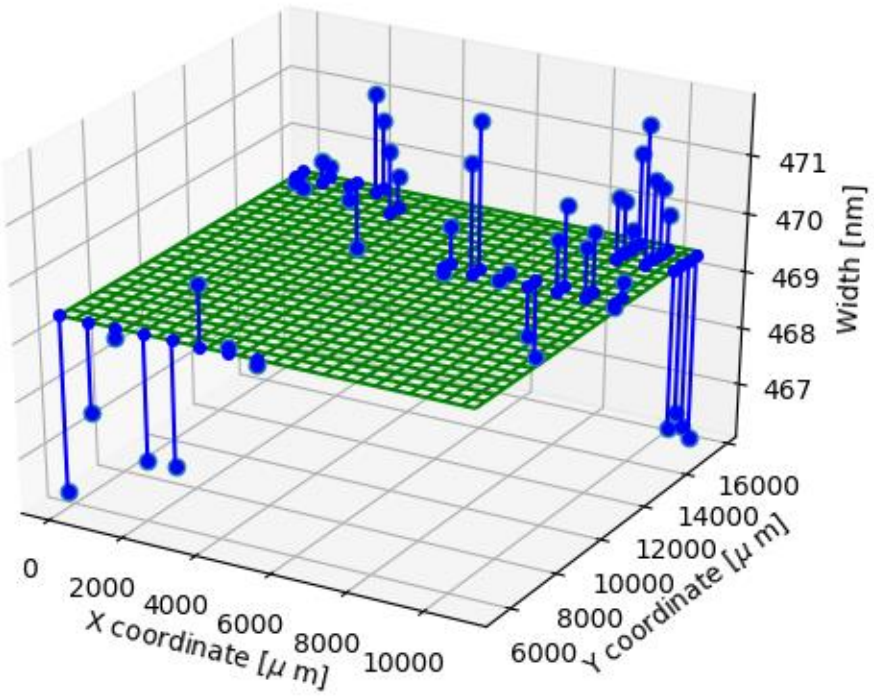
Extraction error of this experiment

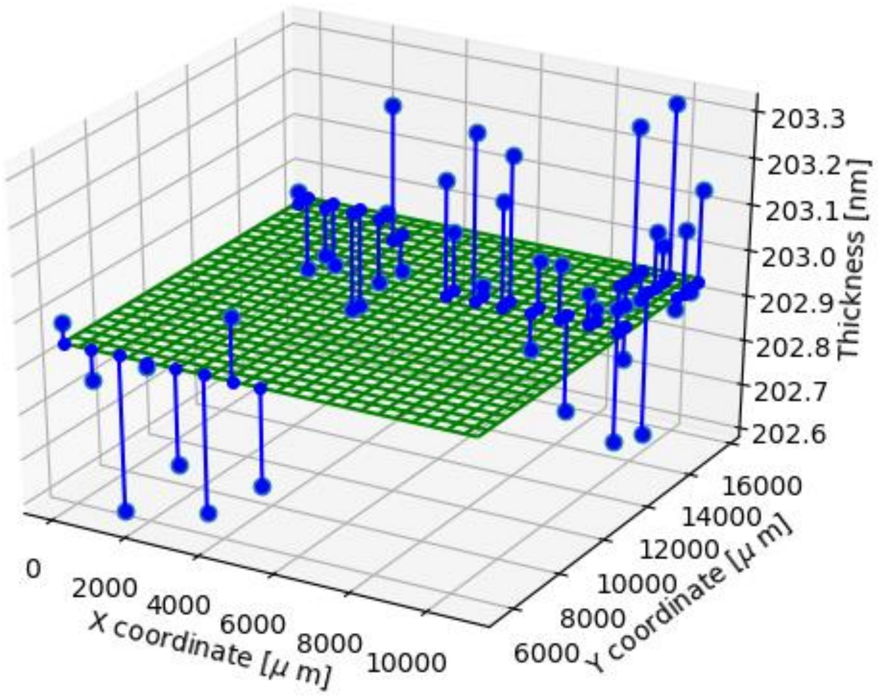
Width: 0.37 nm

Thickness: 0.26 nm

Xing et al., Photonics Research 2018

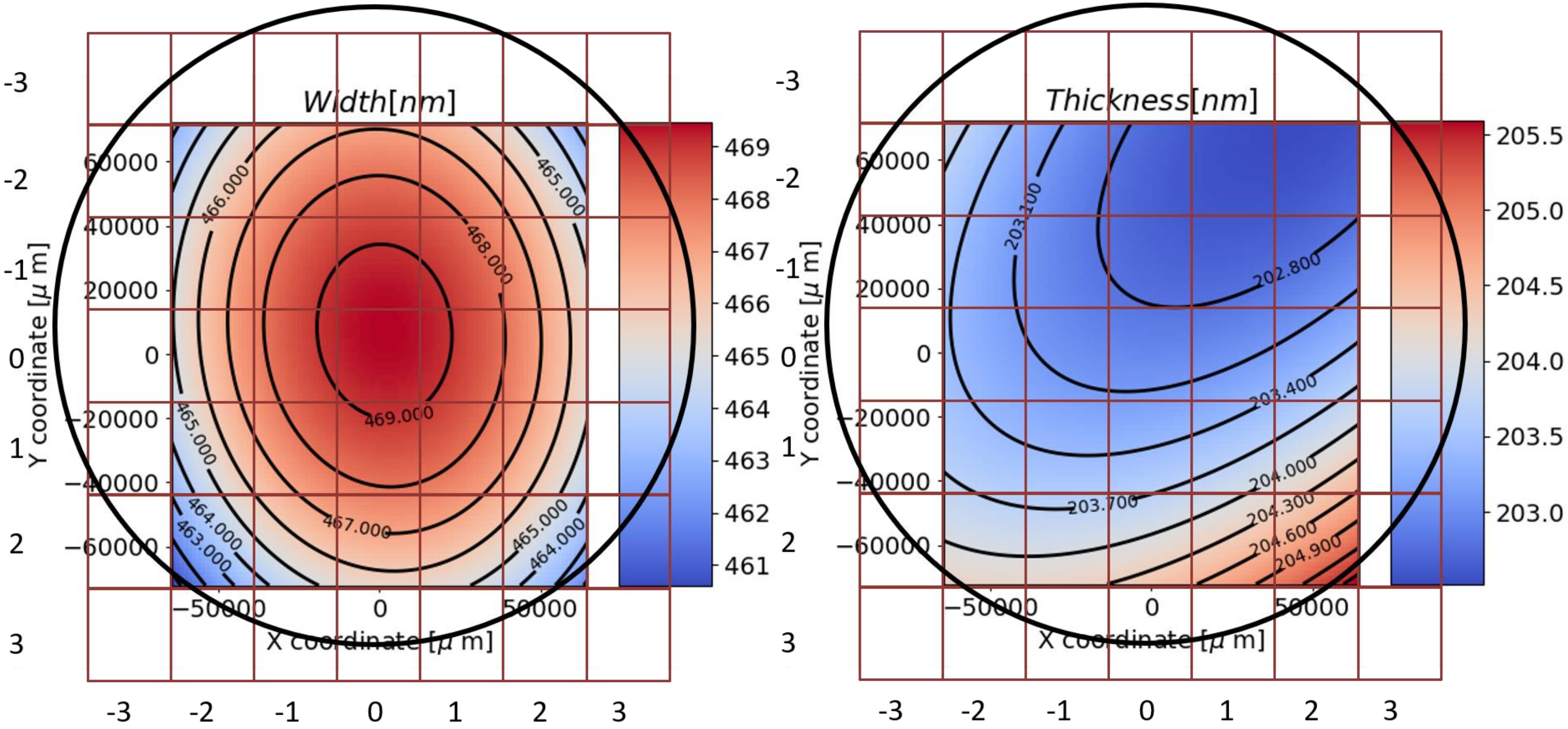
SYSTEMATIC INTRA-DIE VARIATION





Xing et al., GFP 2018

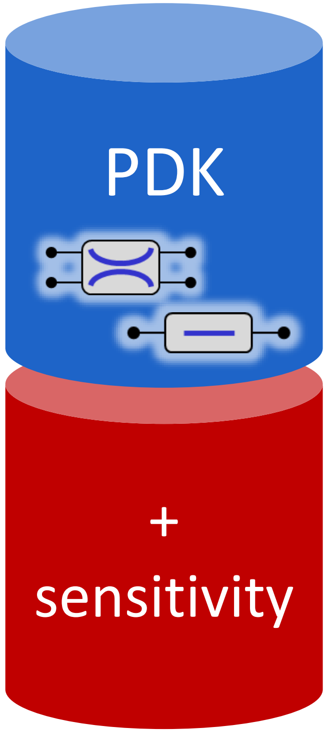
SYSTEMATIC INTRA-WAFER VARIATION



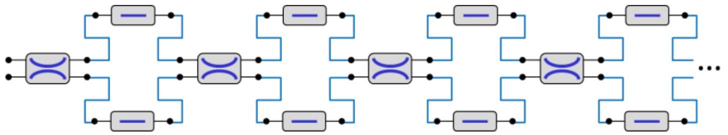
Xing et al., GFP 2018

LAYOUT-AWARE YIELD PREDICTION

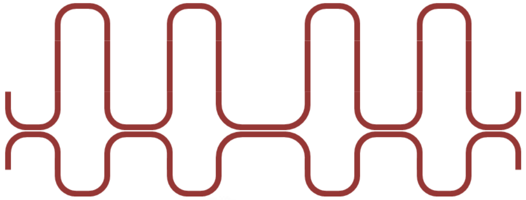
YIELD PREDICTION SCHEME



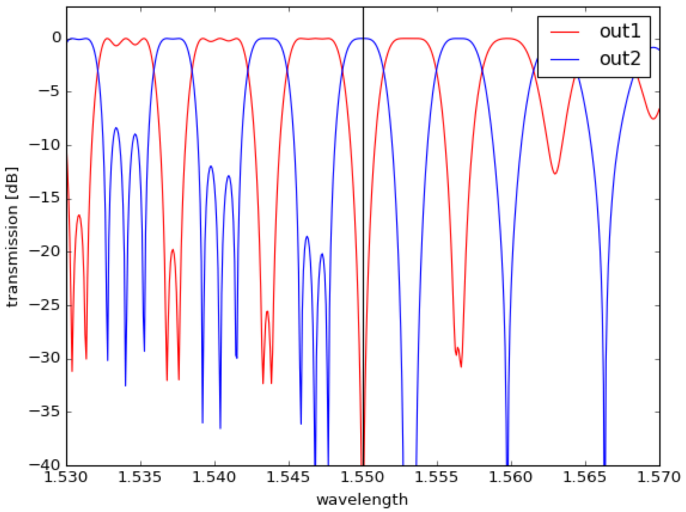
building blocks
+ models



circuit netlist + layout

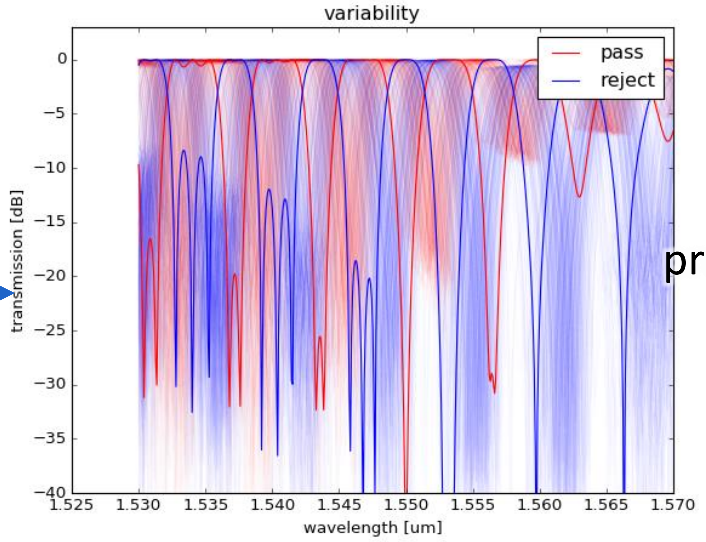


circuit simulation

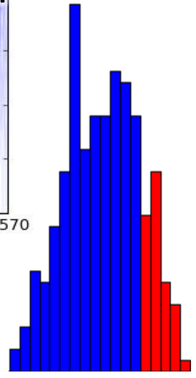


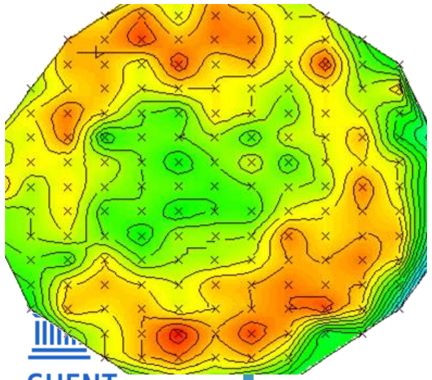
sensitivity of model
parameters
to fabrication
parameters

$\frac{\partial n_{eff}}{\partial w}$, …

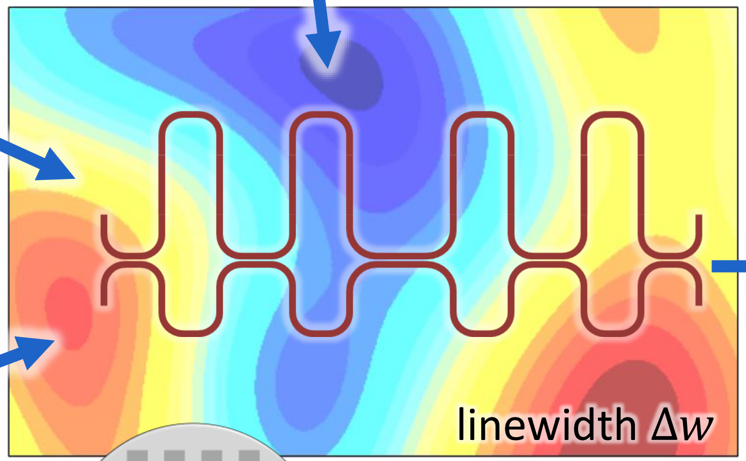


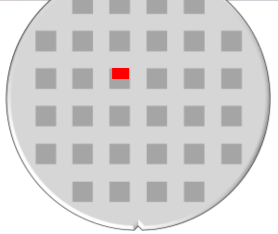
Yield
prediction





wafer maps
(or model)
for fabrication
parameters





place circuit on wafer
and adjust model
parameters

Monte-Carlo on
dies and wafers

EXAMPLE: MZI LATTICE FILTER

Simple (but sensitive) building blocks

- directional couplers
- waveguide delay lines

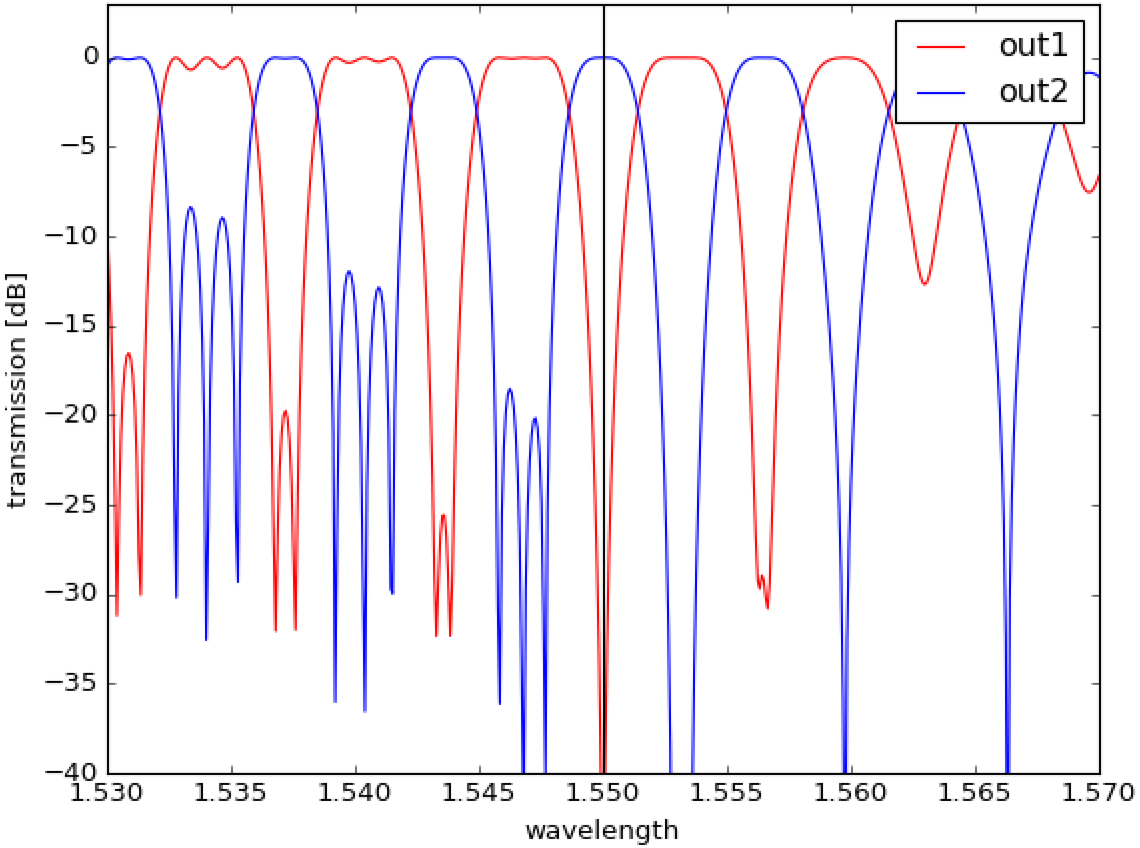
FSR = 800GHz (~6.4nm)

Pass-band = 80GHz

Guard band = 80GHz

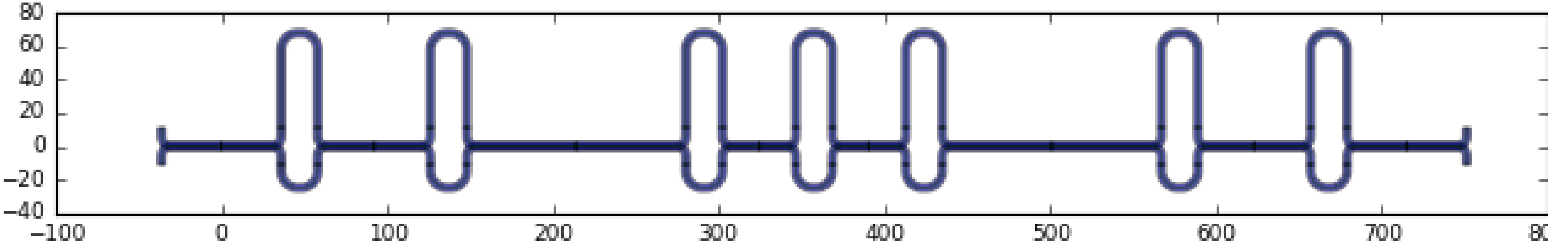
Crosstalk (rejection) = -15dB

Center wavelength = 1.55um



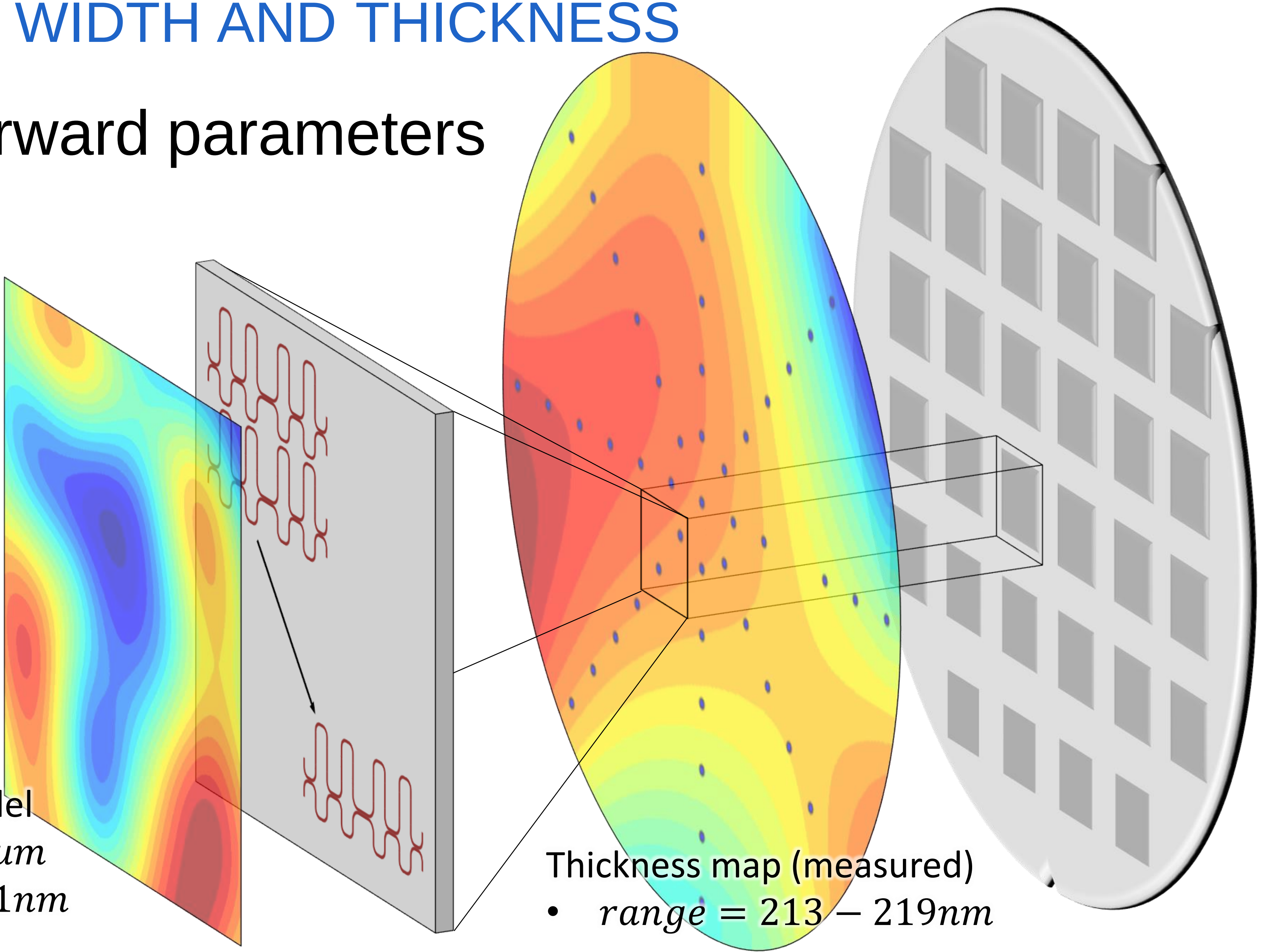
Long directional couplers

- dispersive
- very sensitive



WAFER MAPS: WIDTH AND THICKNESS

Most straightforward parameters



linewidth map

Simplex noise model

- $radius = 200\mu m$
- $amplitude = 1nm$

Thickness map (measured)

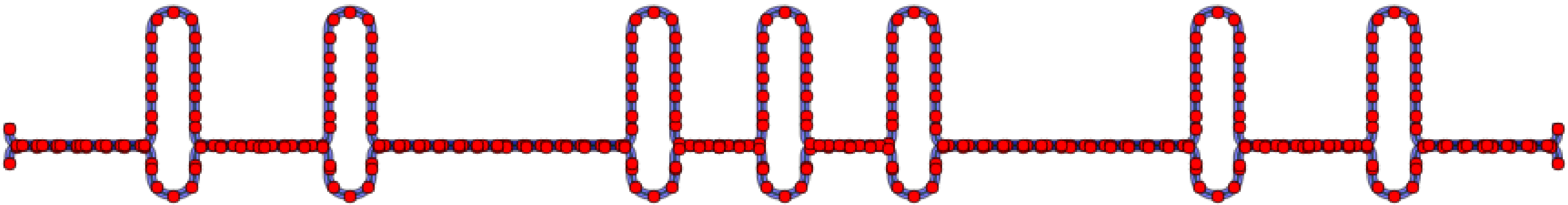
- $range = 213 - 219nm$

Bogaerts et al., JSTQE 2019

SAMPLING POINTS IN THE LAYOUT

All building blocks with a model will sample all variables (w, t)

- waveguides: n_{eff}, n_g
- logical couplers: $\kappa', \frac{\partial\kappa'}{\partial\lambda}, \frac{\partial^2\kappa\prime}{\partial\lambda^2}, \kappa_0, \frac{\partial\kappa_0}{\partial\lambda}, \frac{\partial^2\kappa_0}{\partial\lambda^2}$



- Sampling points are aggregated over the component: results in averaging, same as in fabricated devices

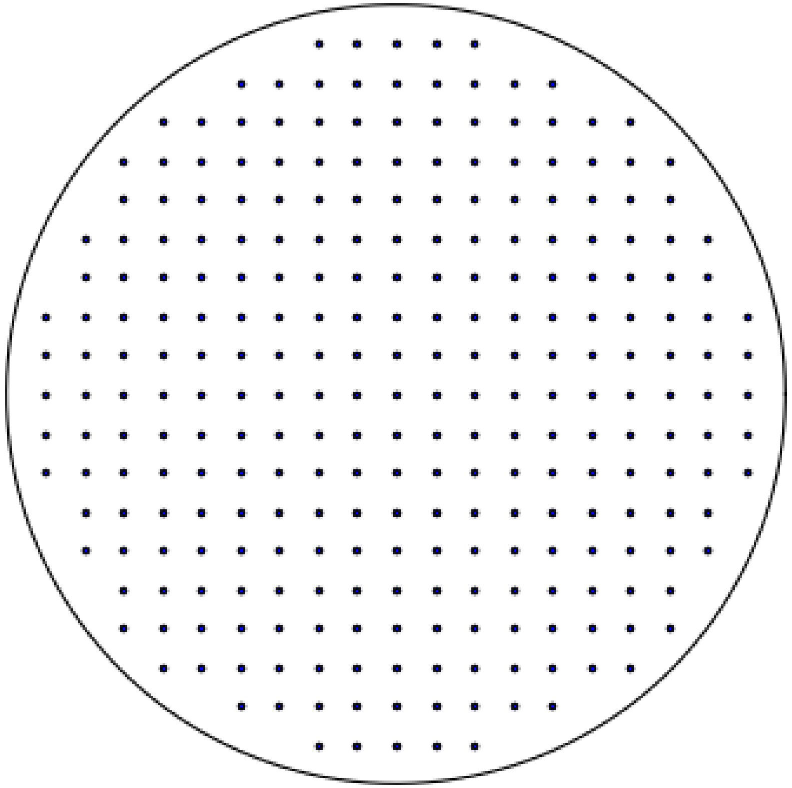
MONTE-CARLO SIMULATIONS OVER A WAFER

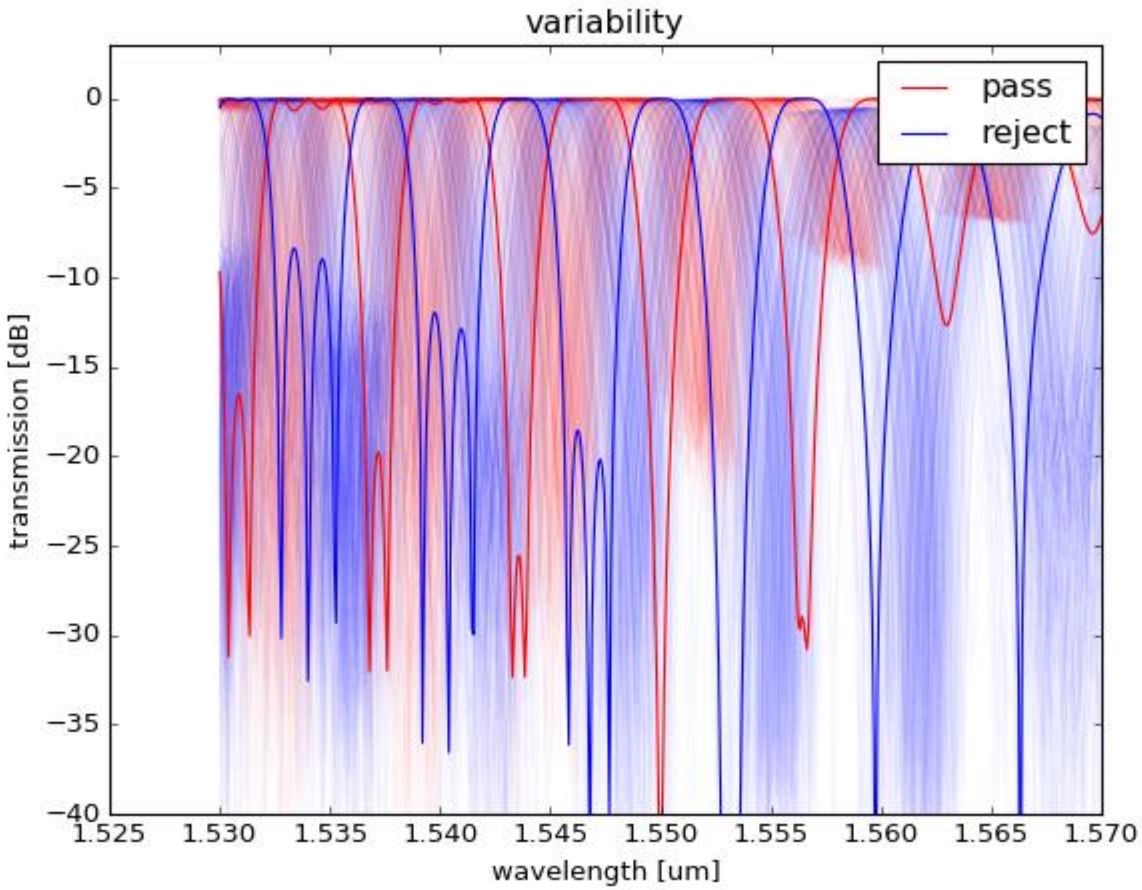
10mm spacing

277 dies on a wafer

Using CAPHE circuit simulator (Luceda)

1000 wavelength points

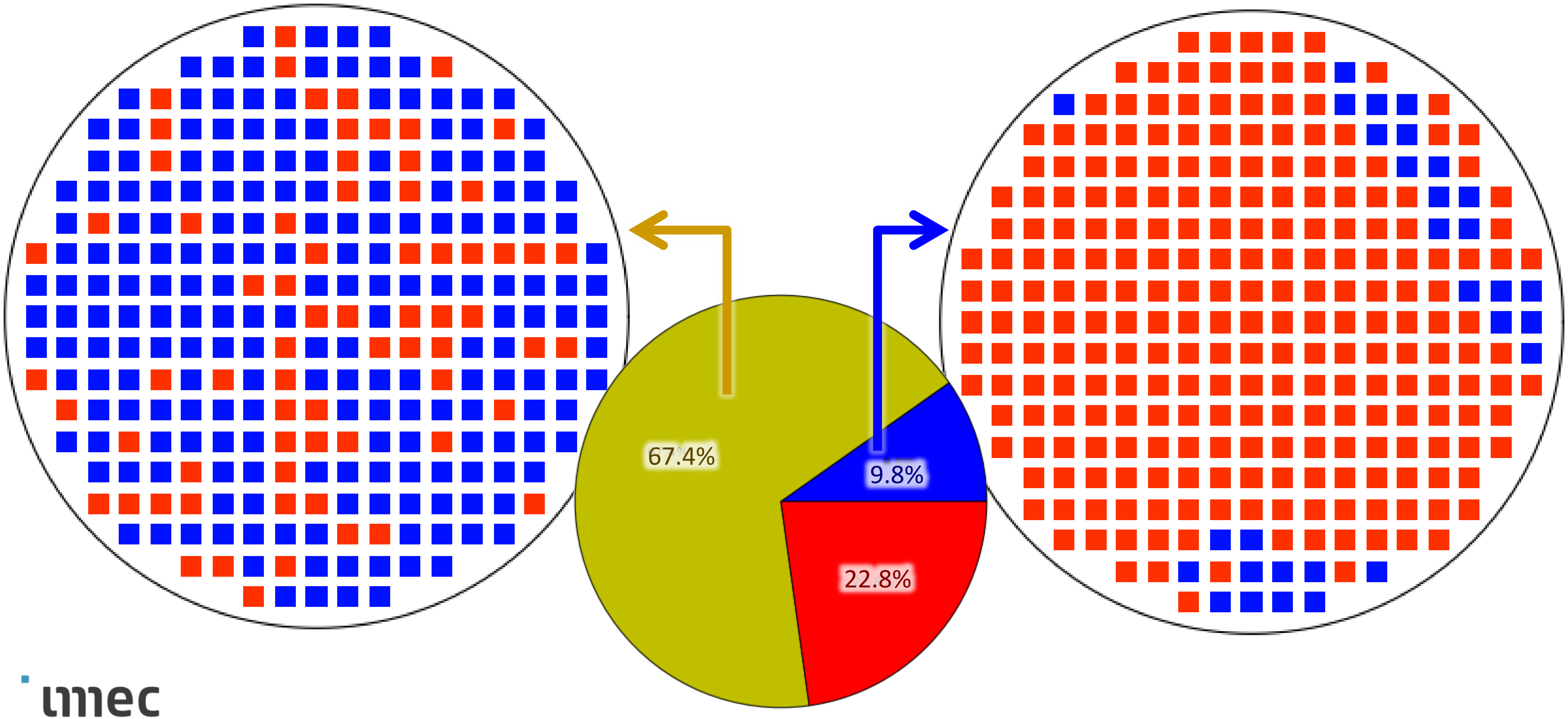




YIELD MAPS

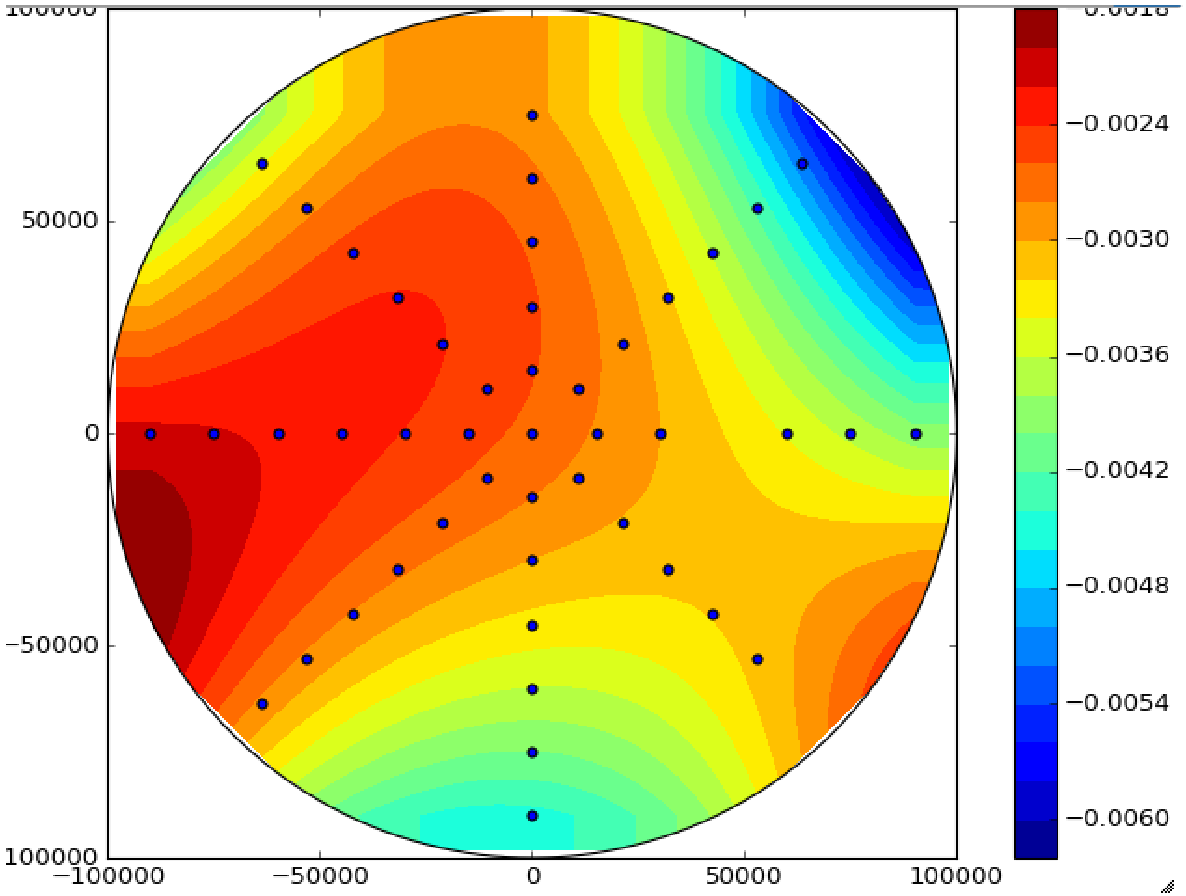
Without absolute wavelength spec

With absolute wavelength spec: peak = 1.55μm ± 80 GHz

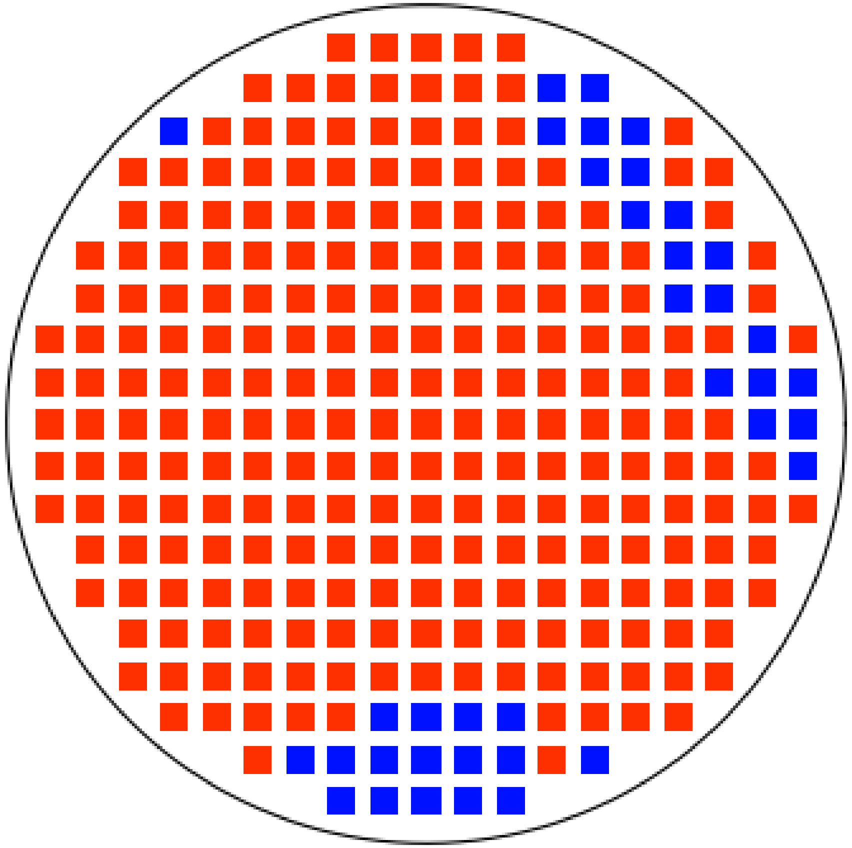


PEAK WAVELENGTH: LARGELY AFFECTED BY THICKNESS

Wafer thickness map



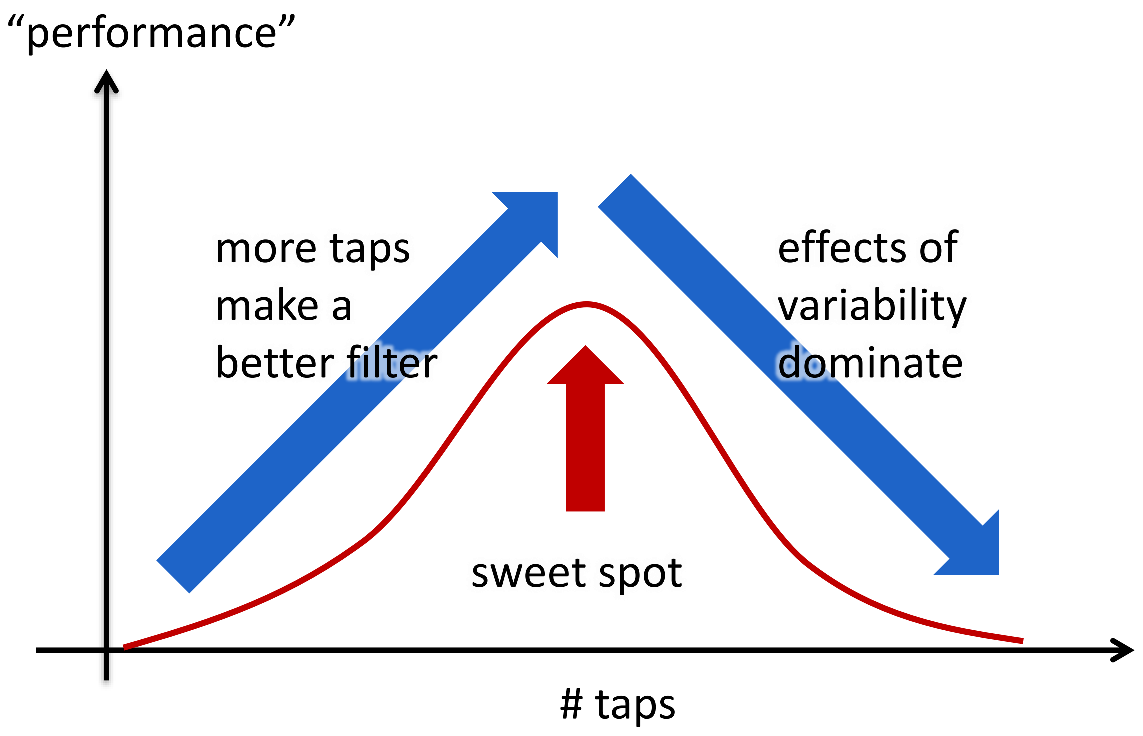
yield on wavelength spec



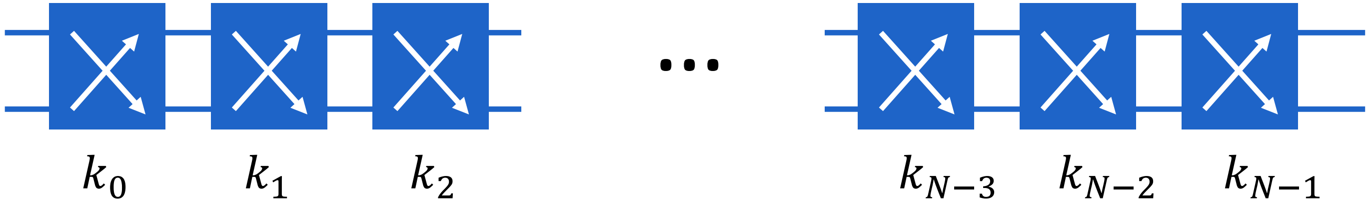
IMPROVE FILTER ?

Sweep number of taps

- More taps: better (box-like) filter
  - higher rejection ratio
  - sharper edges
- With variability
  - phase errors add up
  - coupler errors add up



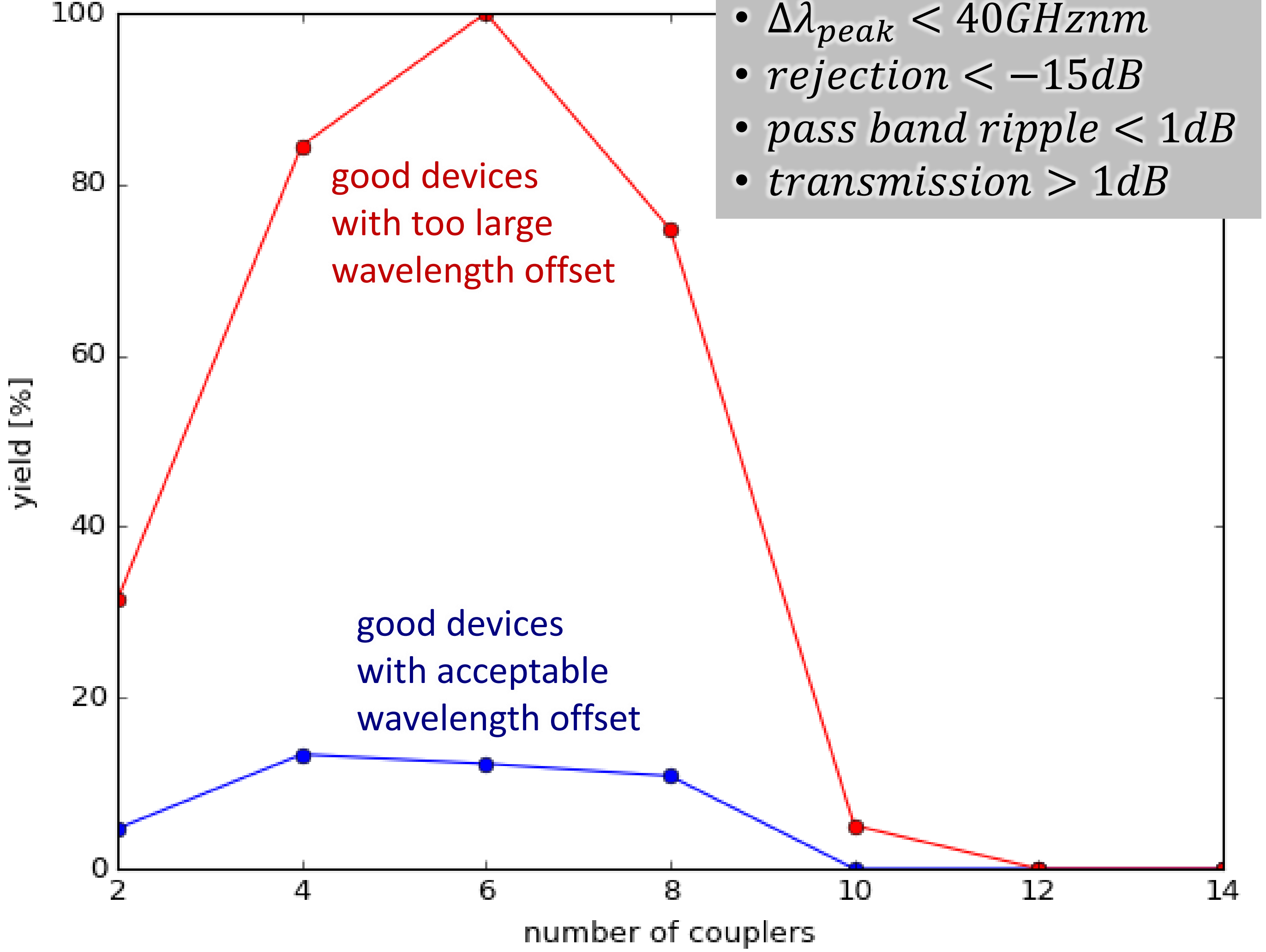
YIELD ANALYSIS



Increase number of taps:

- 2: not enough taps to reacl rejection ratio
- 4-8: good quality
- 10-14: variability kills performance

Best: 6 taps

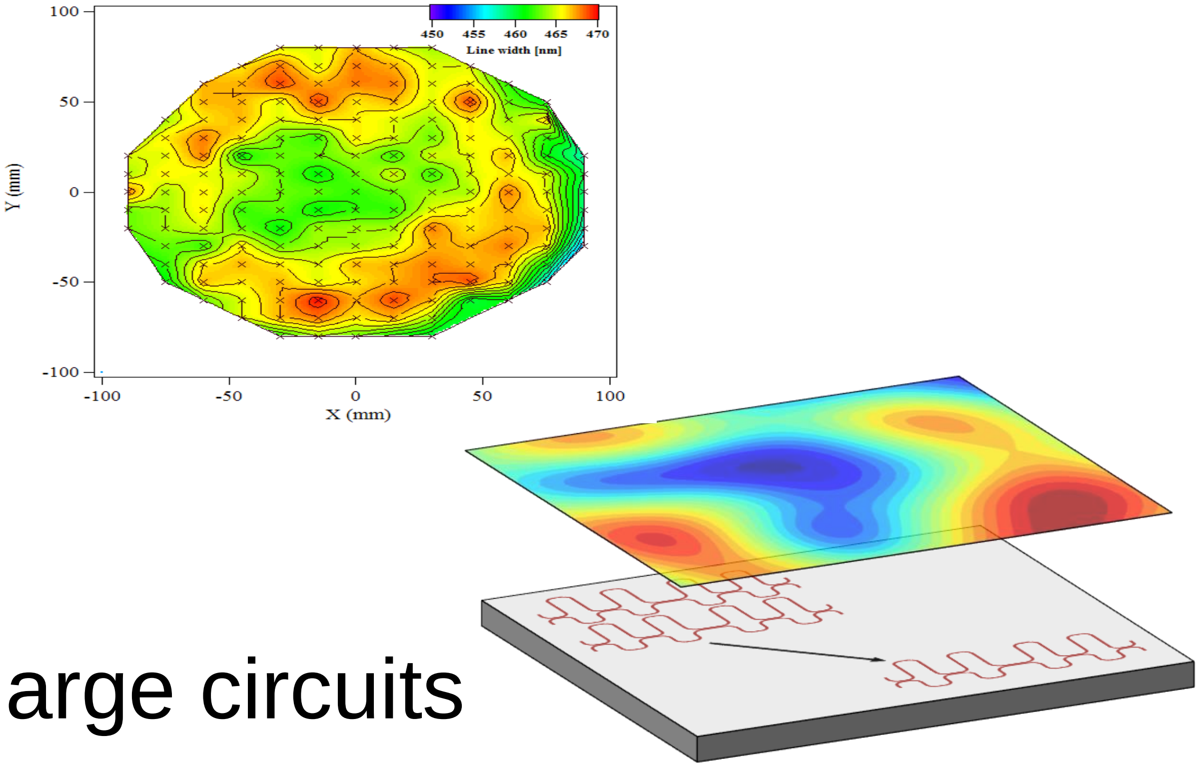


Yield specifications:

- $\Delta\lambda_{peak} < 40GHznm$
- $rejection < -15dB$
- $pass\ band\ ripple < 1dB$
- $transmission > 1dB$

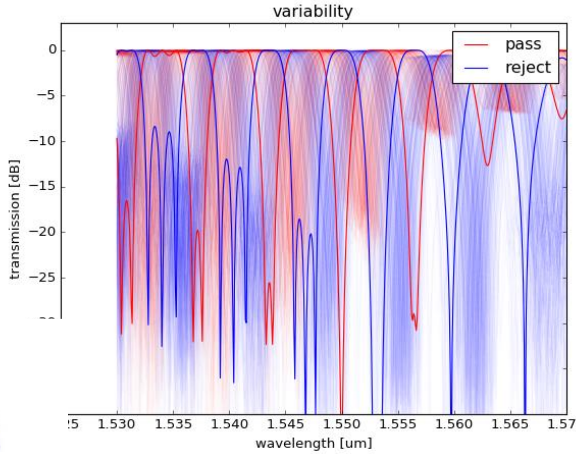
SUMMARY

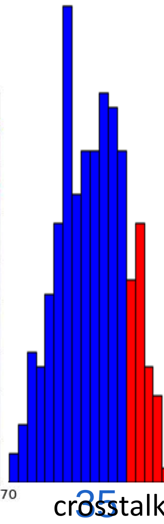
- Fabrication Imperfections
    - Variability



- Variability determines yield in large circuits
    - Variability should be considered at design stage

- Need layout awareness for yield prediction





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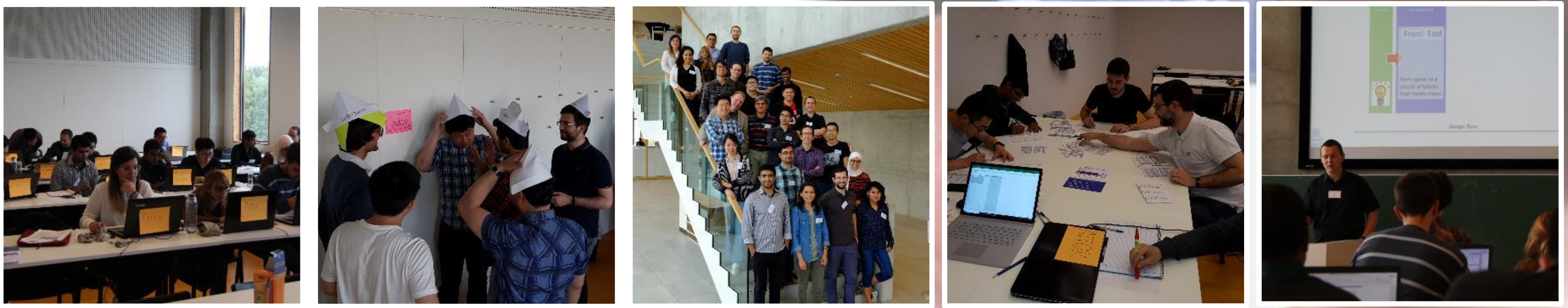
- Circuits, components, simulation, layout, tape-outs, …
- 5 days hands-on design labs
- Get a design fabricated and measured

http://epixfab.eu/trainings/upcoming-trainings/spdc19/



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