Behavioural Models, Parameter Extraction and Yield Prediction for Silicon Photonic Circuits

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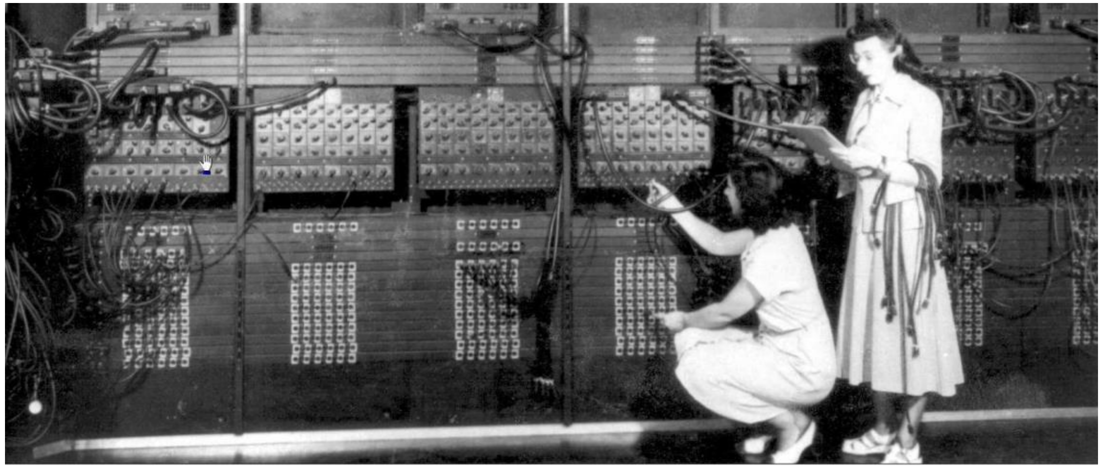
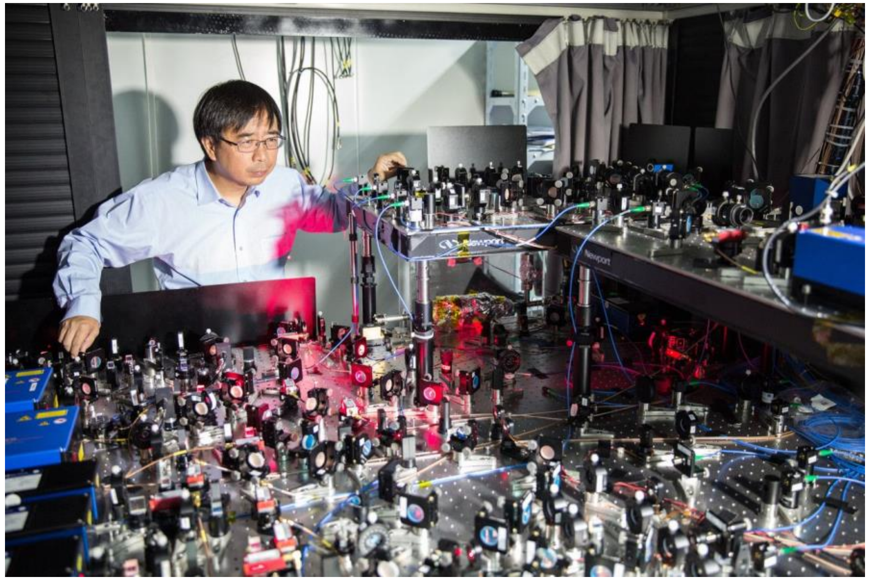
MAGIC OF INTEGRATION

Discrete
Circuit



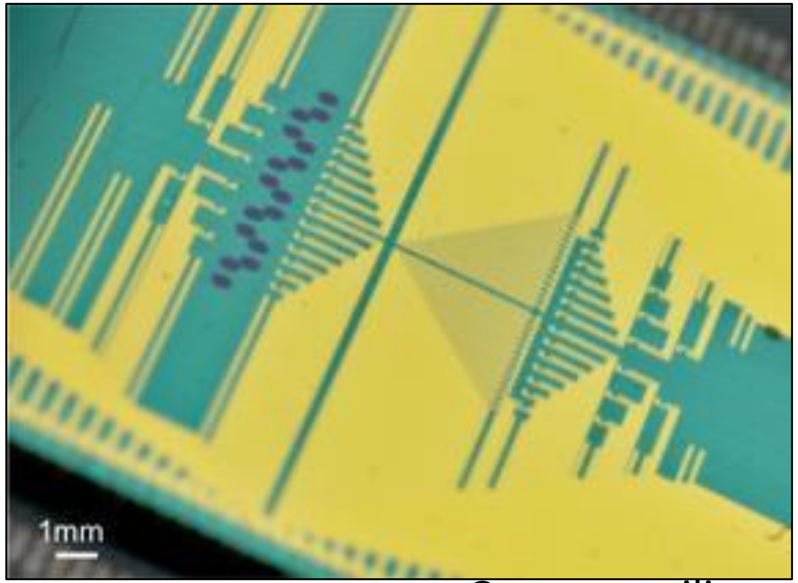
ENIAC



Quantum computer prototype

Integrated
Circuit

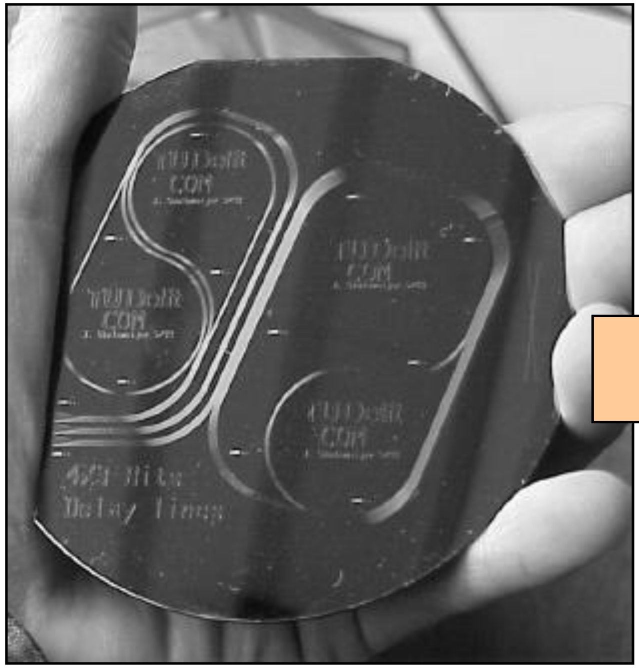
Intel Core i9



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

Silicon photonics circuits

1999

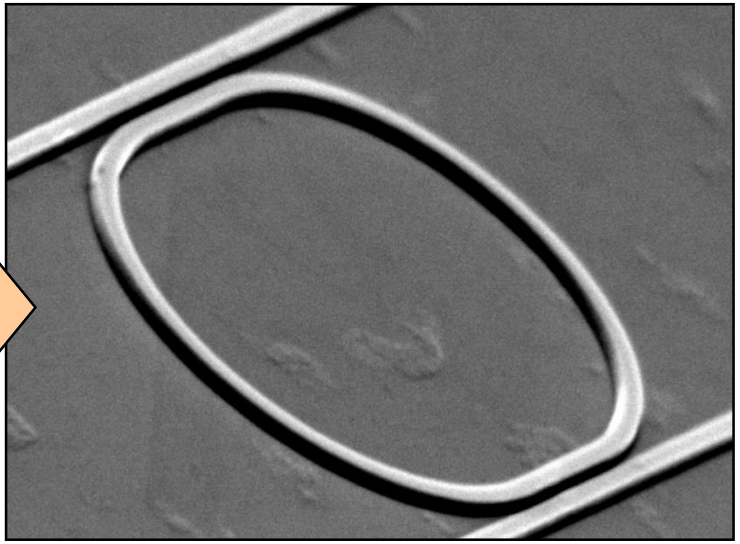


Silica-on-Silicon

Contrast: 1.46 to 1.44

Bend radius = 2cm

2003: ‘Photonic wire’



Silicon-on-Insulator

Contrast: 3.45 to 1

Bend radius = 5µm

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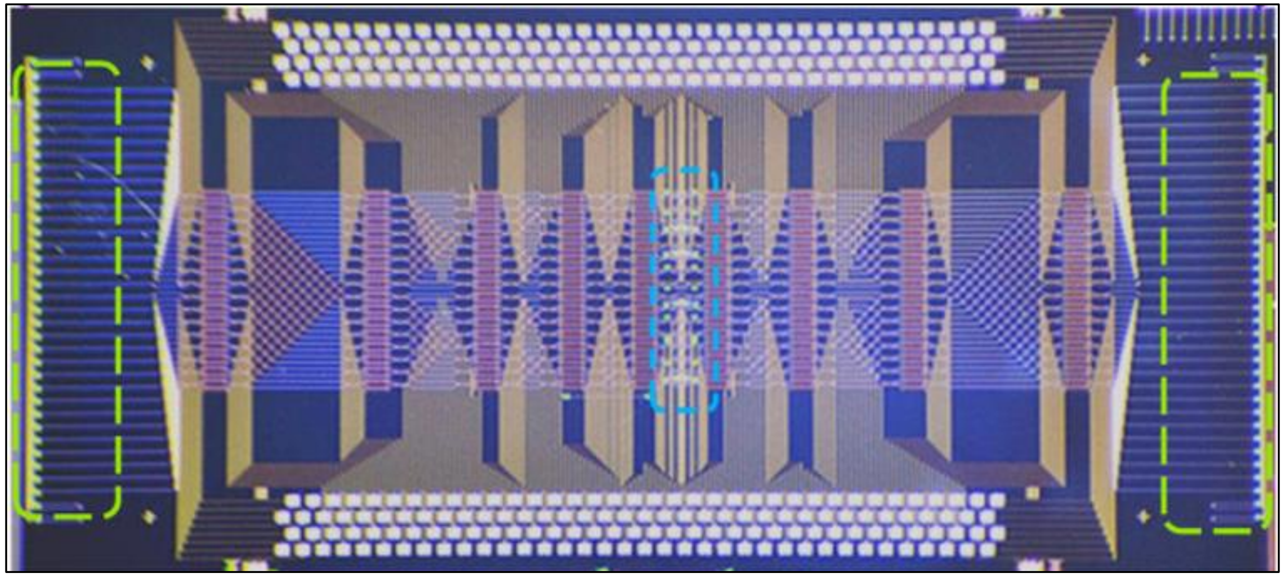
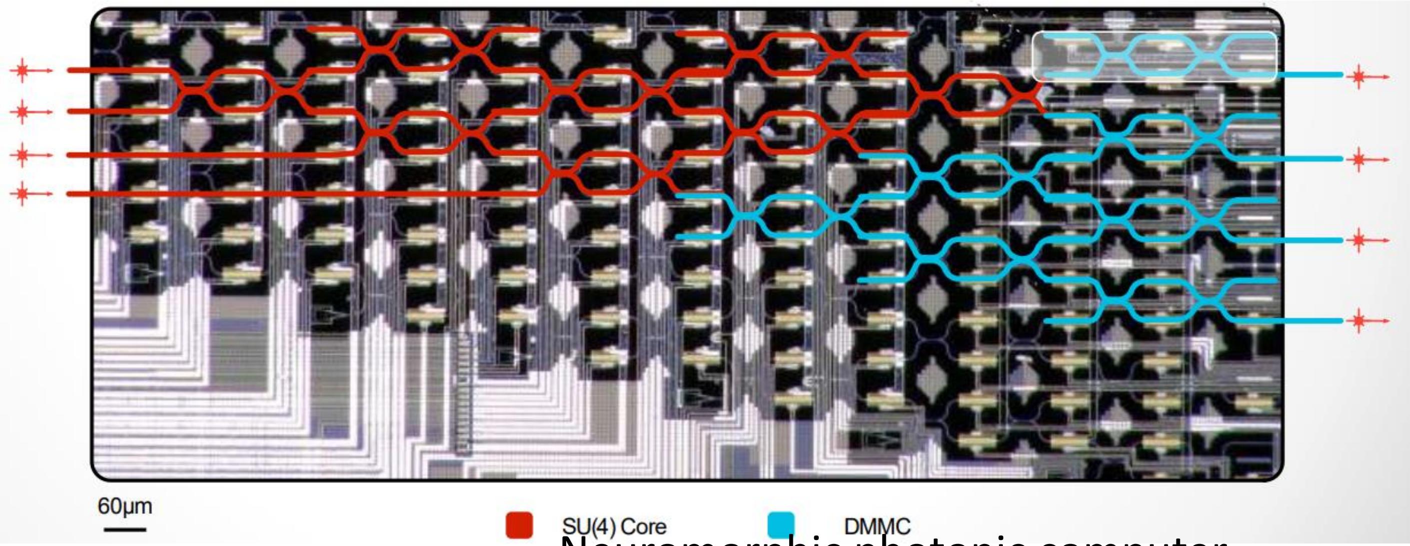
LARGE-SCALE PHOTONIC INTEGRATION IS HERE



Large-scale integration

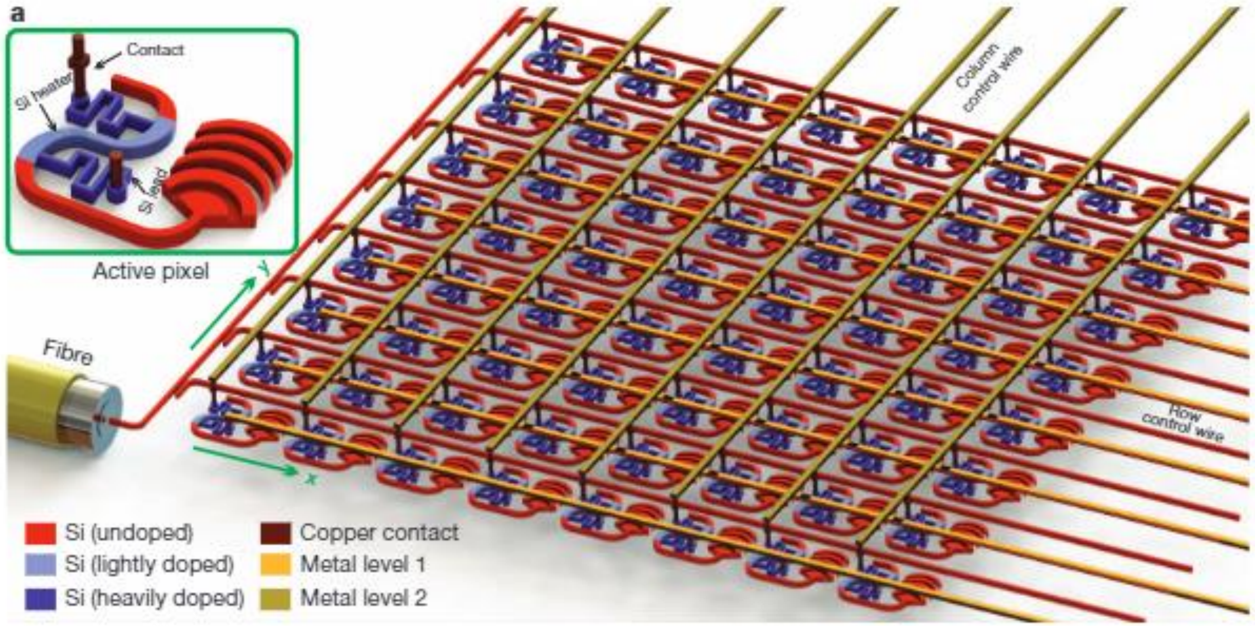
- Complexity
- Functionality

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



Neuromorphic photonic computer
Y. Shen and N. Harris et al, *Nature Photonics 2017*

THE SIZE OF LARGE-SCALE PHOTONIC CIRCUIT



Large-scale nanophotonic phased array
J. Sun, *Nature* 2013

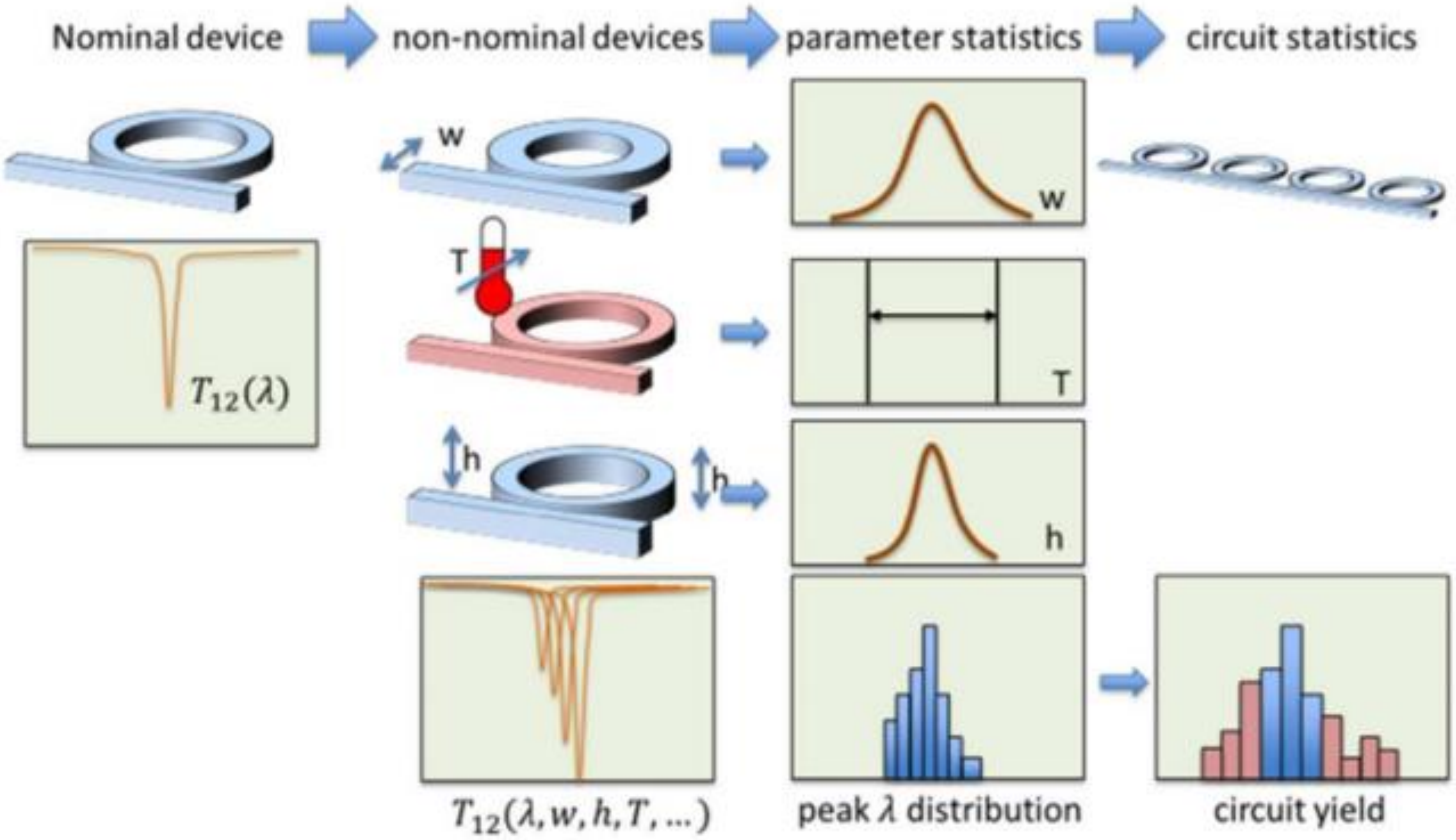
4096 optical components

SILICON PHOTONICS ARE SENSITIVE

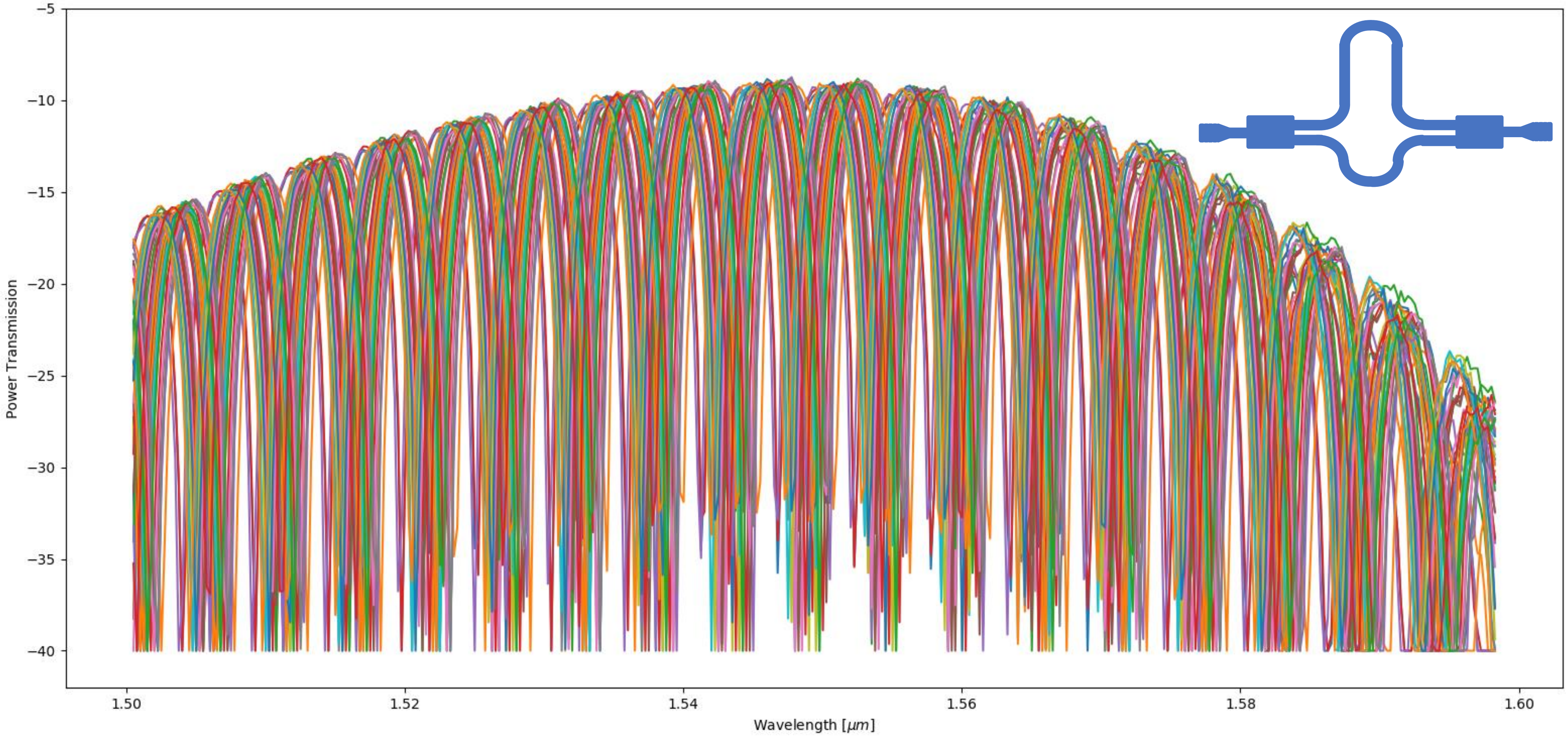
- Process variation
    - 2 nm variation in width

      ⇒ 1 nm shift in resonance
    - 1 nm variation in thickness

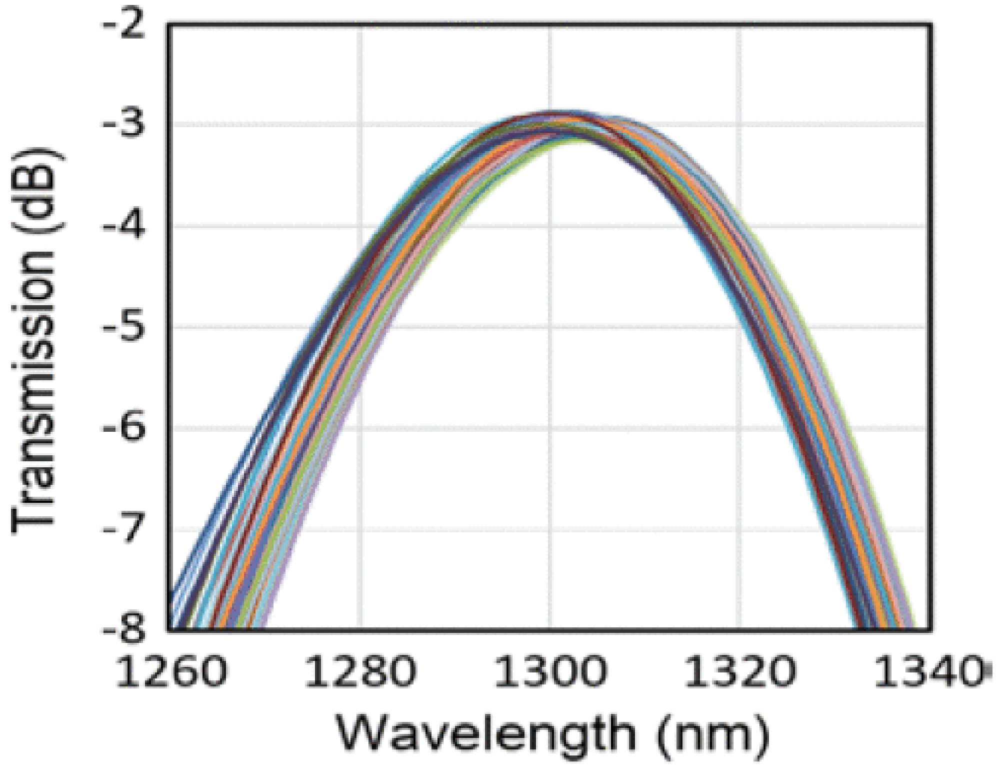
      ⇒ 1 nm shift in resonance
- Operational condition: Temperature



Transmission spectrum of MZI copies on a die

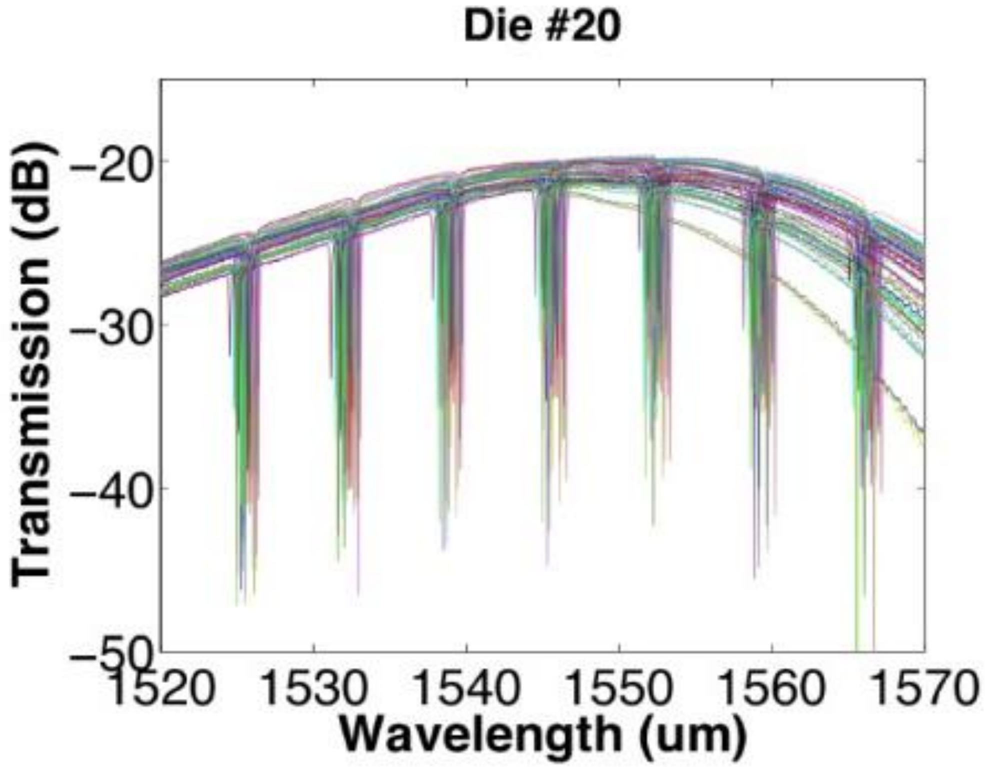


GC variation on 300 mm wafer



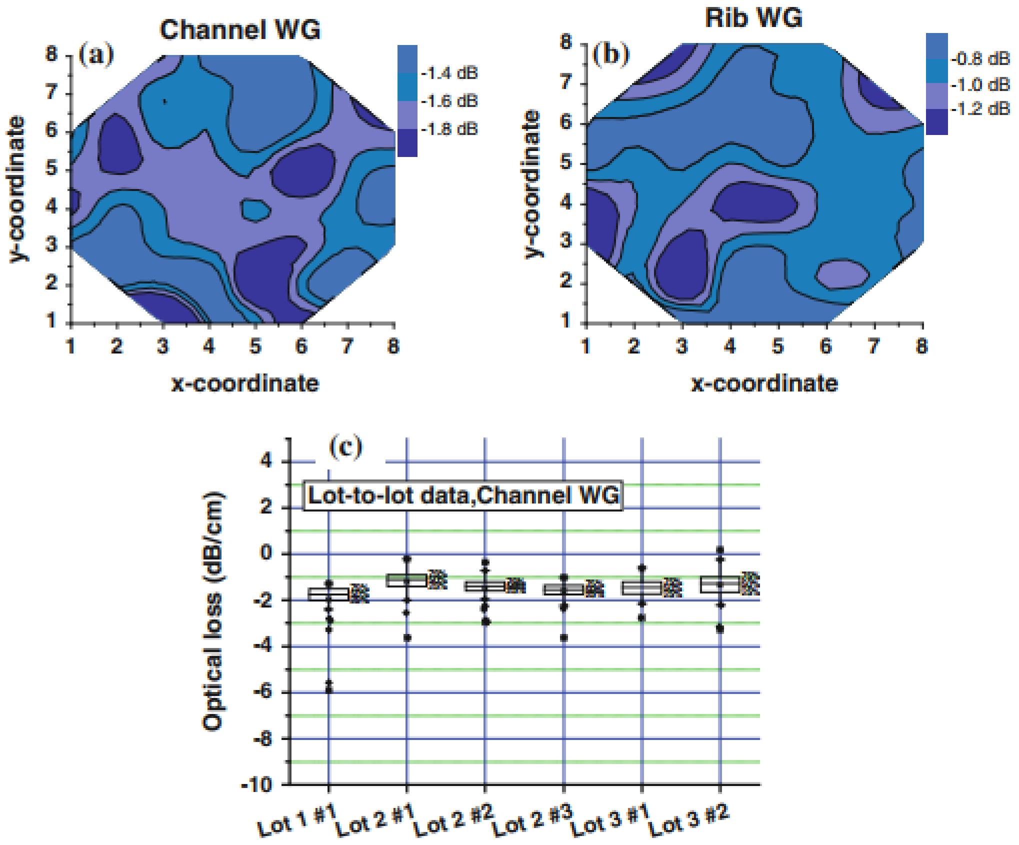
A 300-mm Silicon Photonics Platform for Large-Scale Device Integration, T. Horikawa et al, *JSTQE* 2018

Ring resonance on a die



Performance prediction for silicon photonics integrated circuits with layout-dependent correlated manufacturing variability, Z. Lu et al, *OE* 2017

Waveguide unit-length loss map



Path to Silicon Photonics Commercialization: The Foundry Model Discussion,
A. Lim et al., *Silicon Photonics iii* 2015

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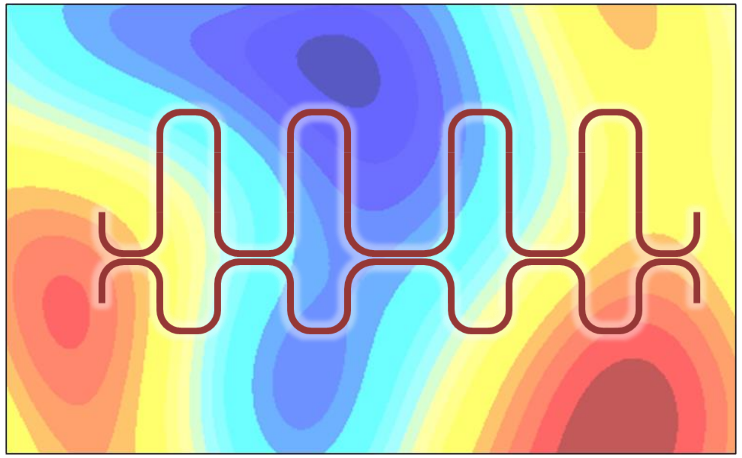
A QUICK ESTIMATION

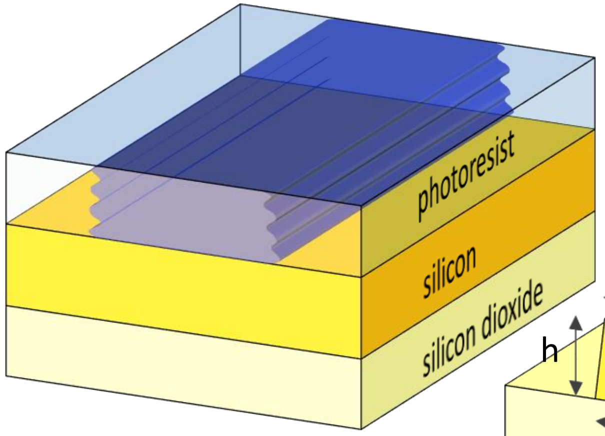
- A circuit: 100 components
- 1% failure for each component
- Cascaded circuit: almost 100% failure



- Even every component works
- Continuous contribution
- Variation propagates and accumulates

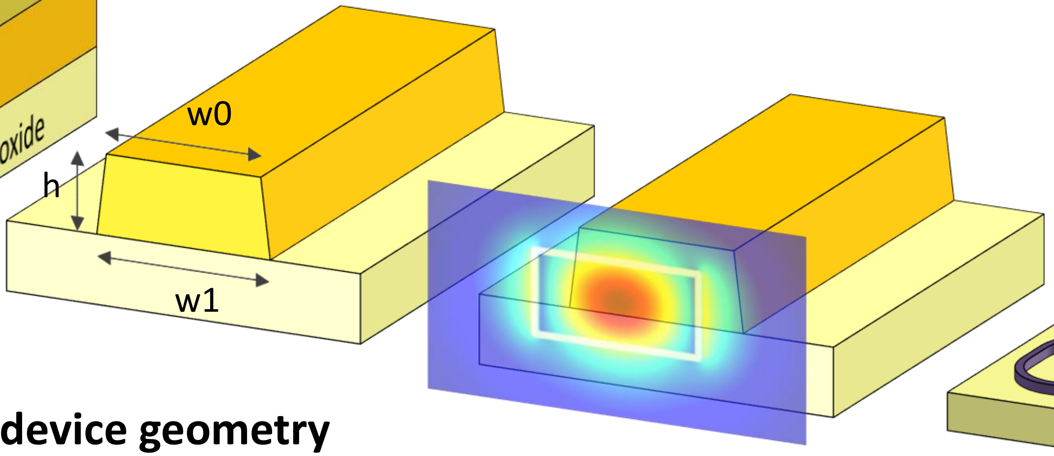
VARIABILITY AT DIFFERENT LEVELS

This is what we need to predict yield (during design)



process conditions

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

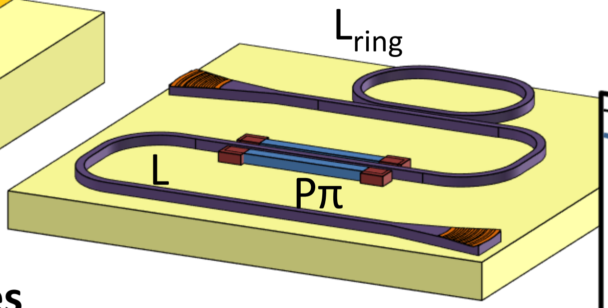


device geometry

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

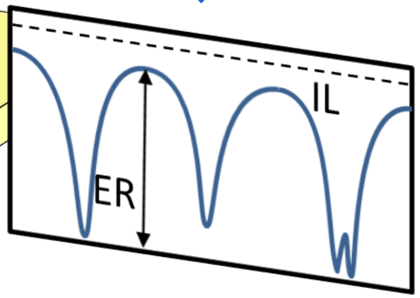
optical device properties

- 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
- …

This is what we measure

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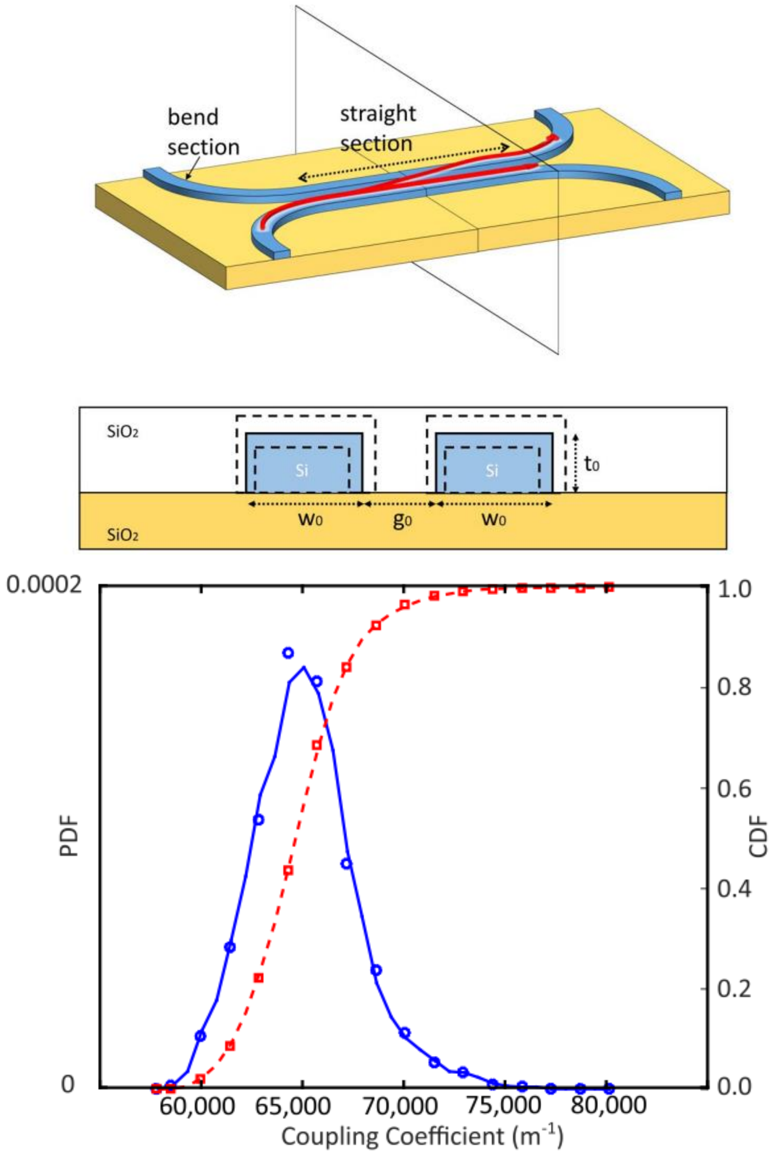
Bogaerts & Chrostowski, LPR 2018

VARIATION: RANDOM?



- Variation
  - totally random (linewidth, thickness)
  - Normal distribution
- Monte-Carlo: using the normal distribution
- Stochastic analysis method to reduce prediction cost
- ? Is variation random?
- ? How can we know the statistics of linewidth and thickness?

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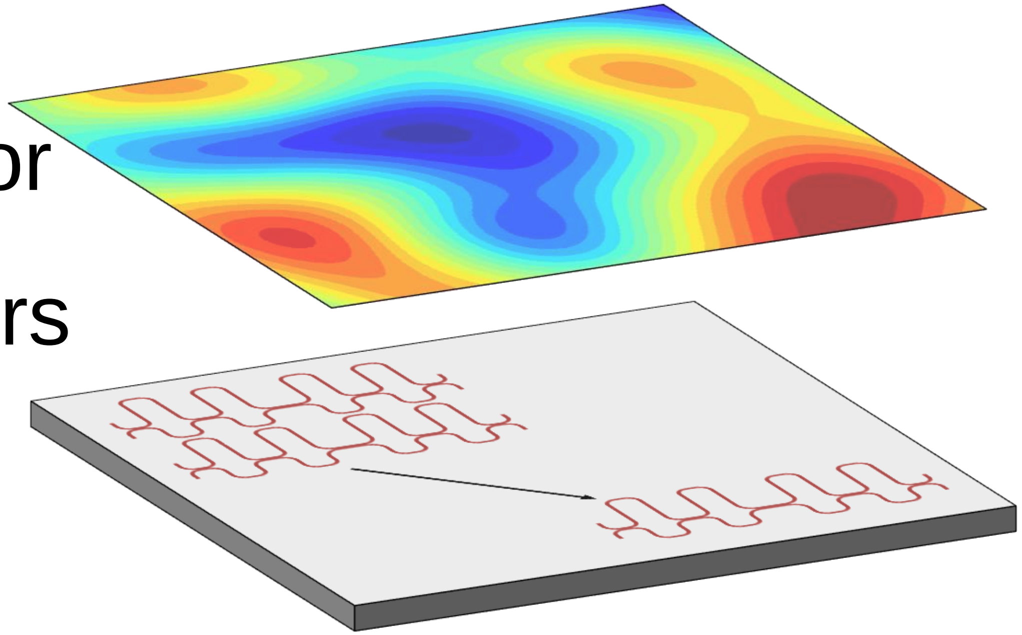
Not random: location-dependent

Circuit parameters are not random, they are correlated:

- Systematic + random
- Nearby circuits have similar behavior
- The exact location of a circuit matters



➡ We need wafer maps!

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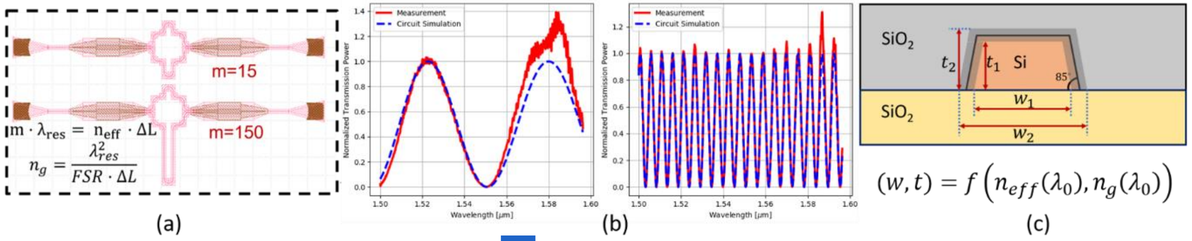
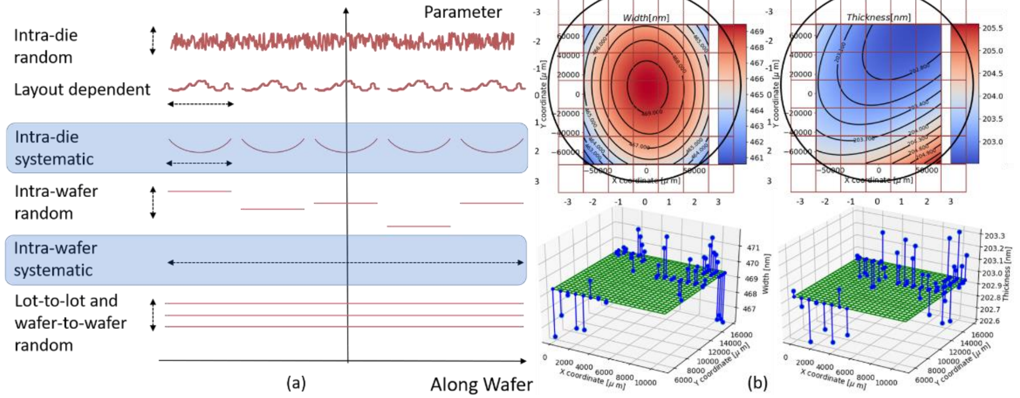
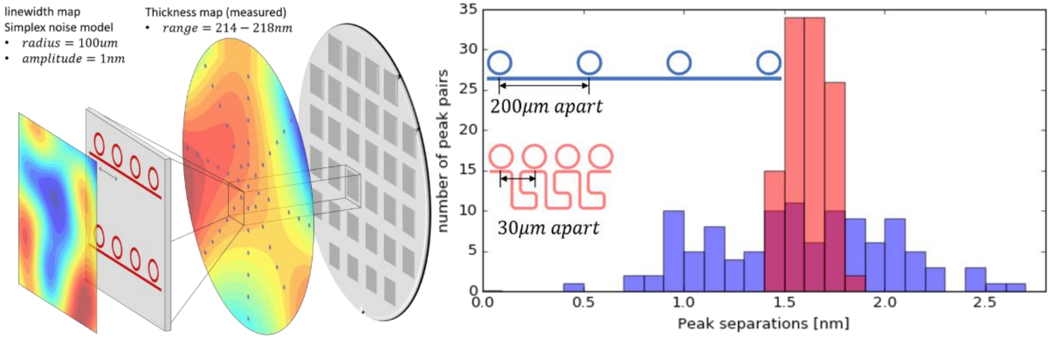
Three components of realistic yield prediction



Detailed Parameter Extraction



Spatial Variation Model



Location and Layout-Aware Yield Prediction

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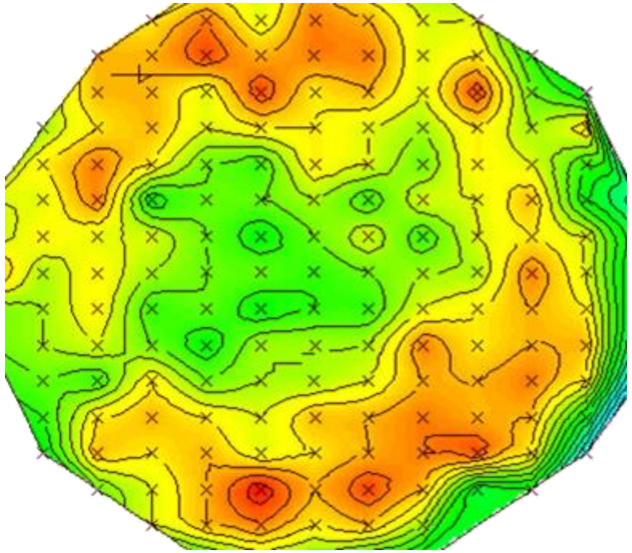
Parameter extraction

Parameter Map

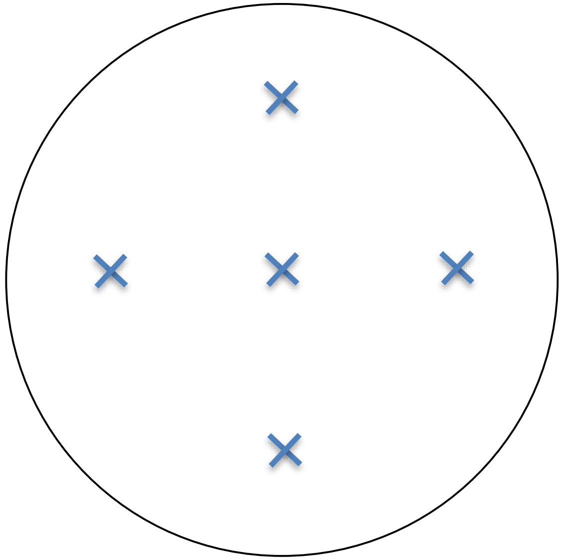
Inline Metrology

Expected



- Detailed
- Accurate
- Non-destructive

Reality



Number of measurement sites:

- Width: 5 (CD-SEM)
- Thickness: 9 or 49 obtained before the lithography (profilometer)

Not on the site of interest

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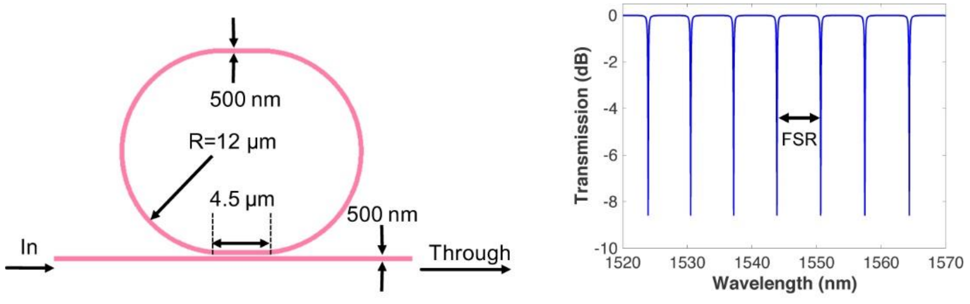
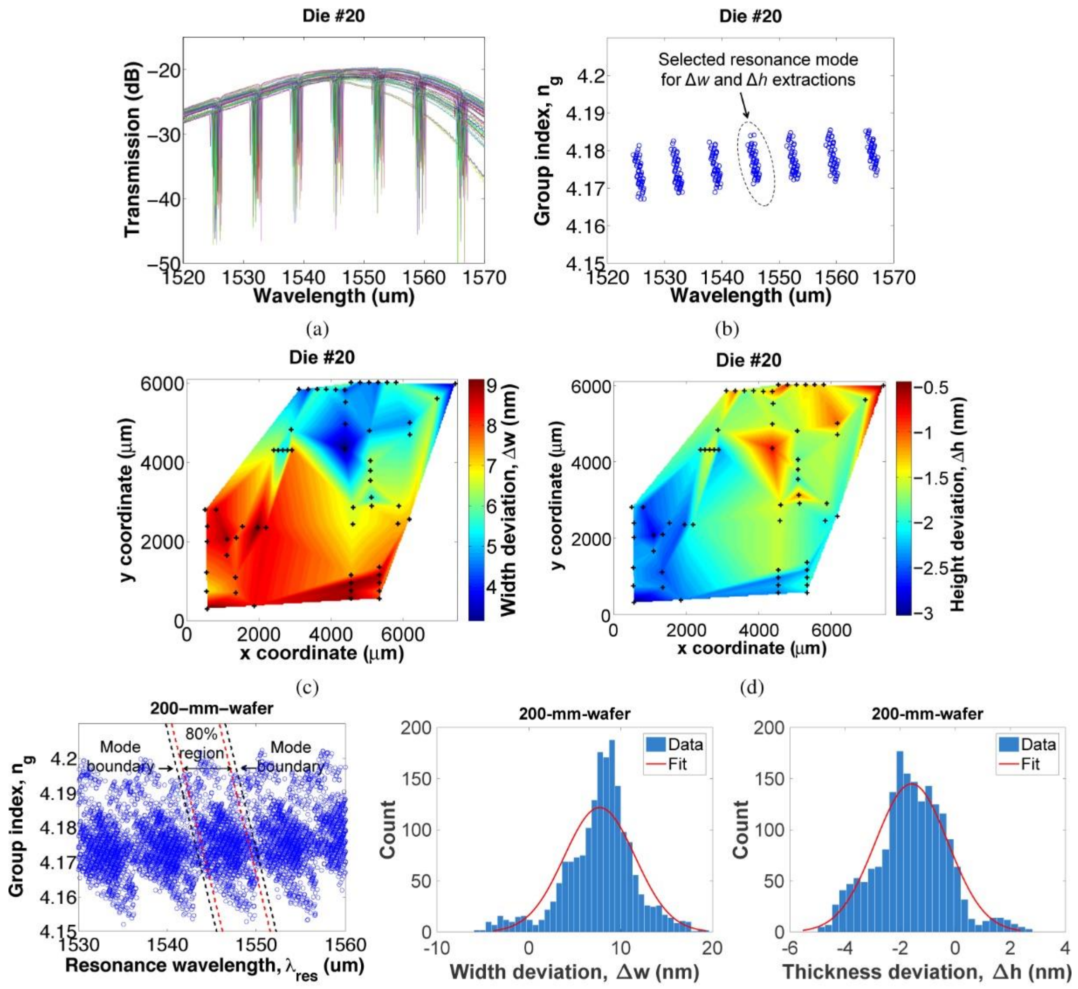
Optical Measurements of Rings



(a) (b)



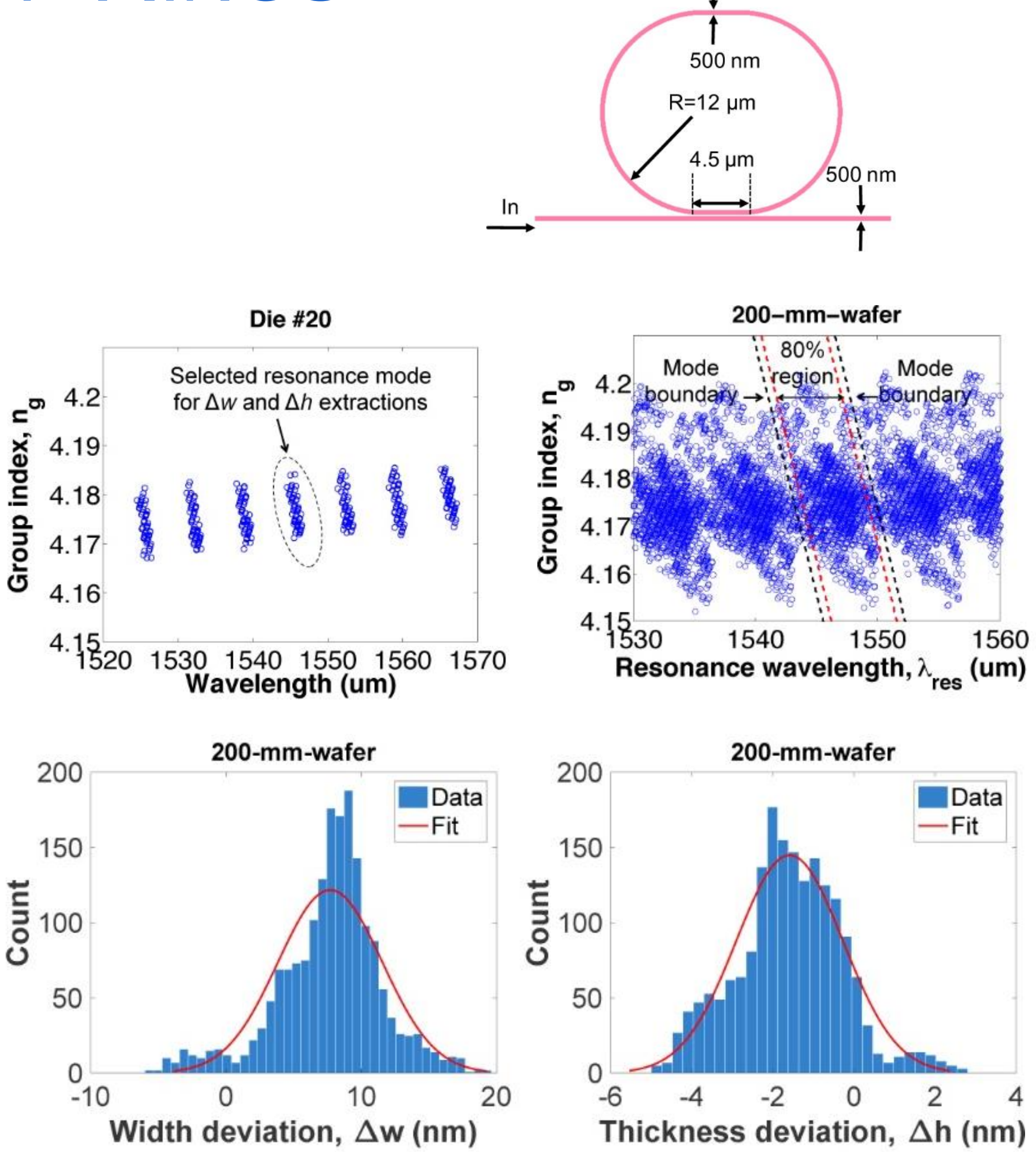
(a) (b) (c) (d) (e) (f) (g)

- 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

Lu, Optics Express 2017

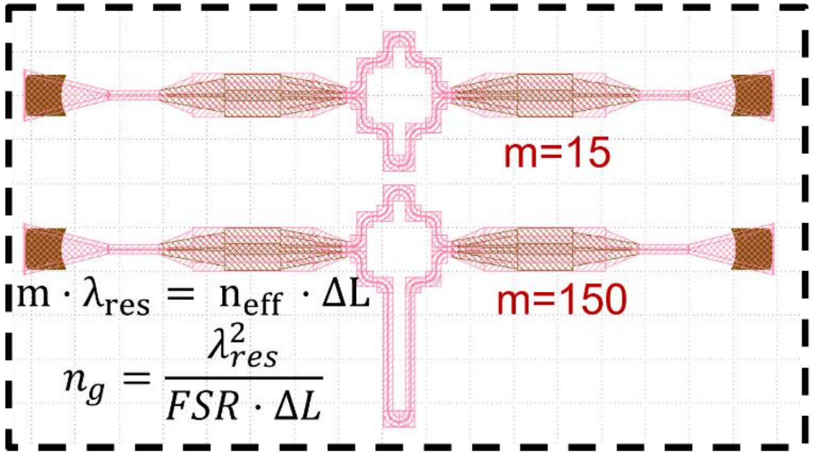
OPTICAL MEASUREMENTS OF RINGS

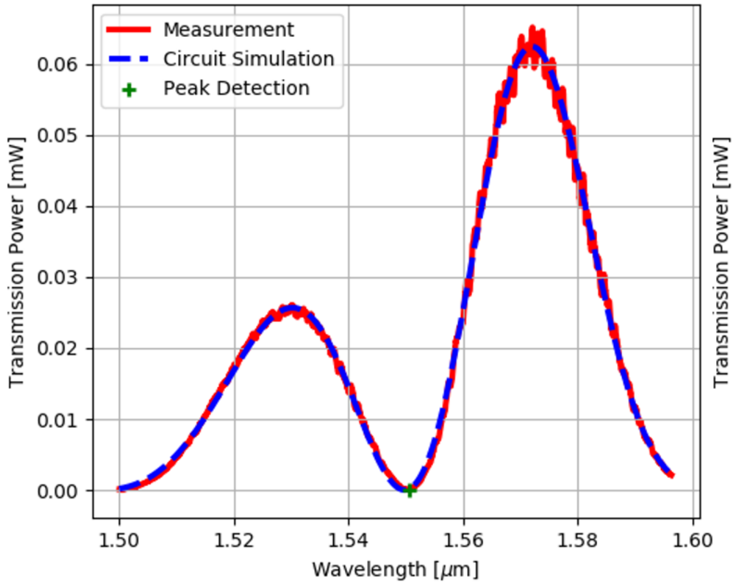
- Cannot separate straight and bend waveguide
- Accuracy: ~nm
- Cannot decide the interference order (right effective index)
- 20% data are discarded

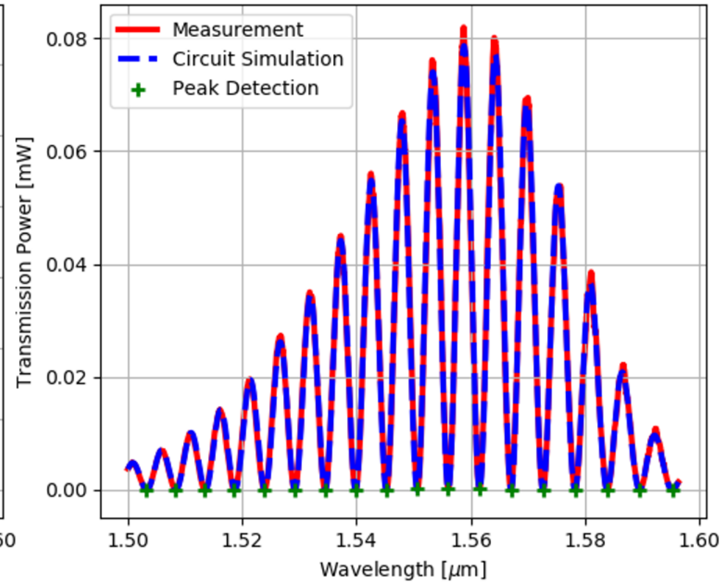


Lu, Optics Express 2017

Optical Measurements of Two MZIs







Xing et al., Photonics Research 2018

Spectrum

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

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

Low order

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

High order

- Accurate extraction of group index and effective index

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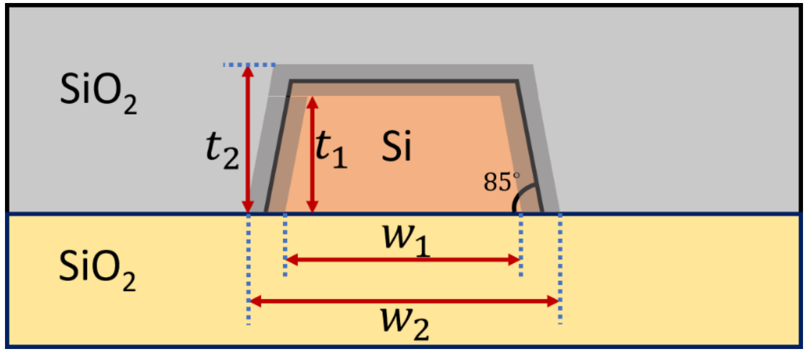
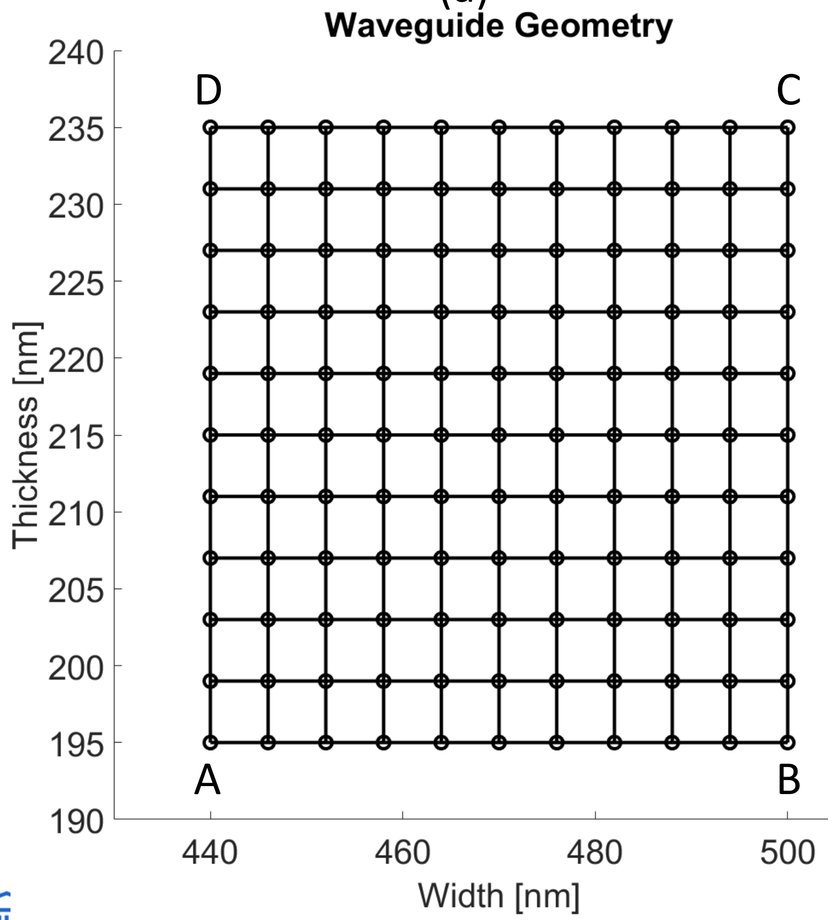
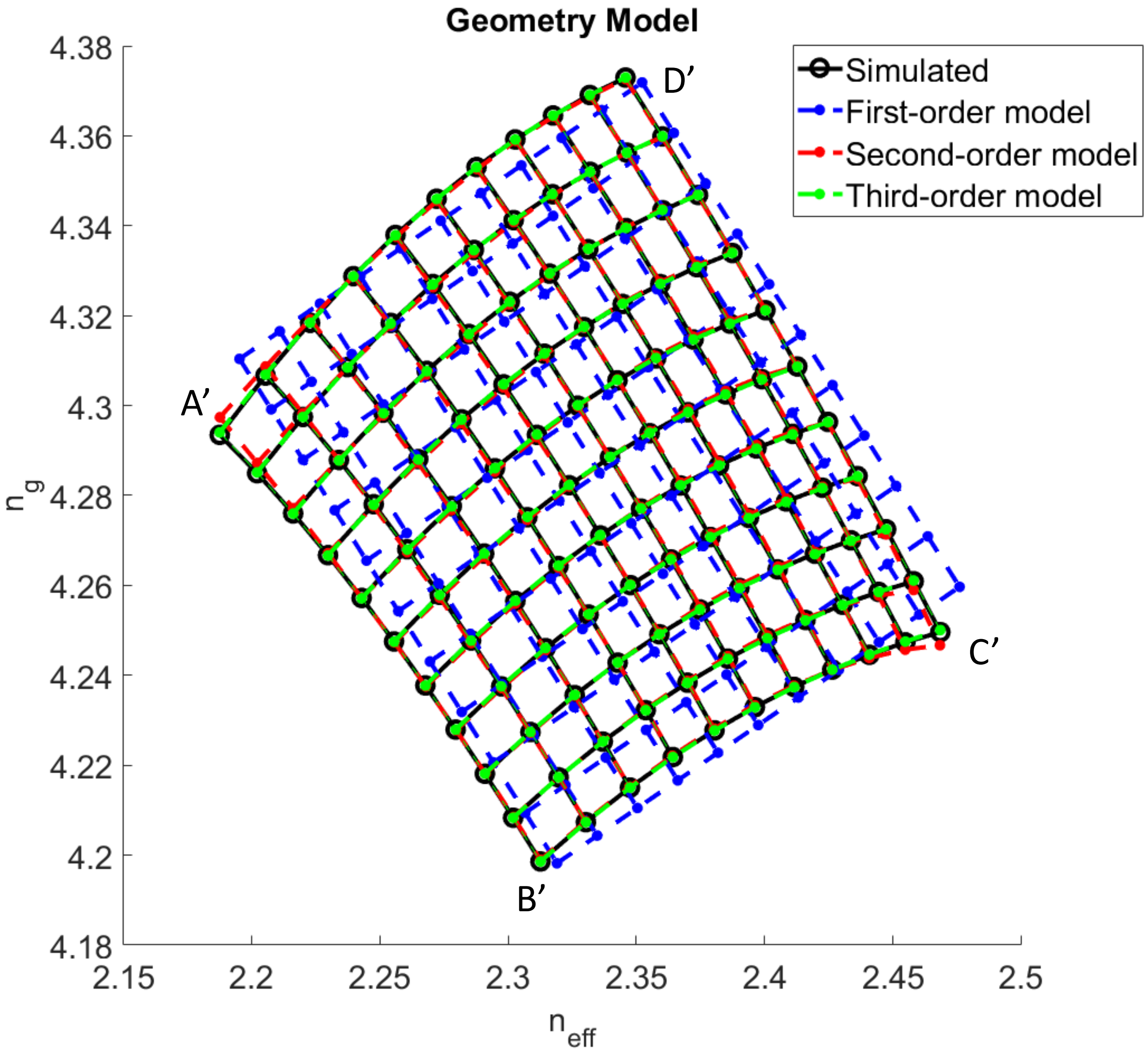


(a)



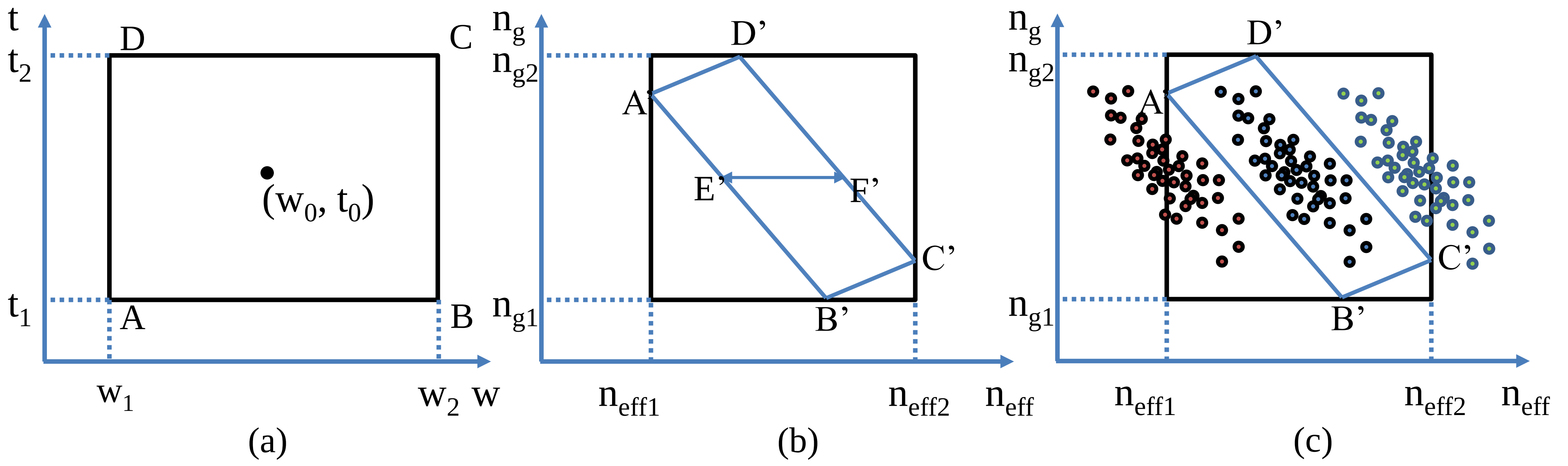
(b)



(c)

Xing et al., Photonics Research 2018

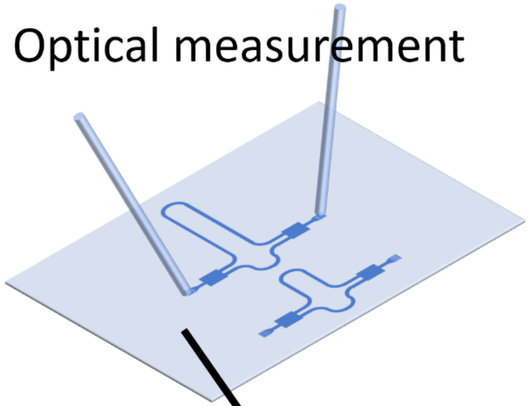
Discussion on parameter boundary



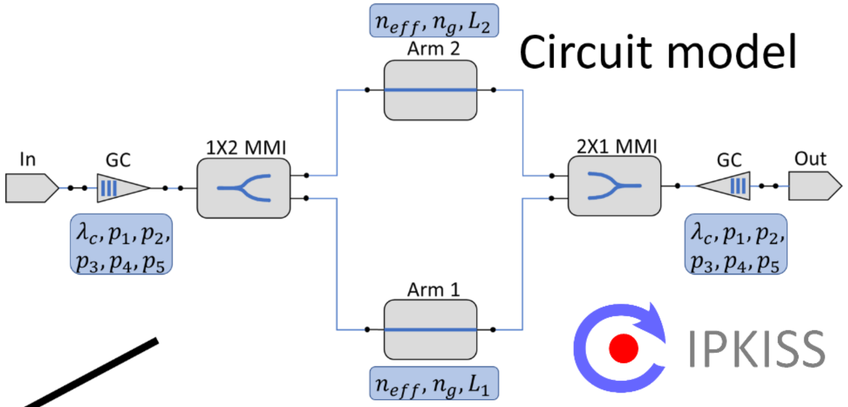
- Determine n_{eff} with information on n_g
- Allow to use higher-order MZI for to reduce extracted parameter uncertainty

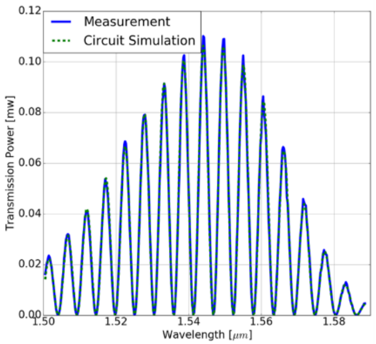
WORKFLOW TO EXTRACT GEOMETRY PARAMETERS

Optical measurement



Circuit model

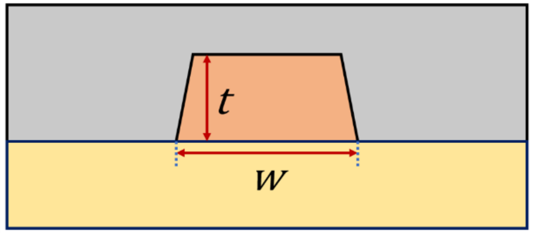




Match optical measurement with circuit simulation to extract behavior parameters

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

Obtain geometry parameters



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

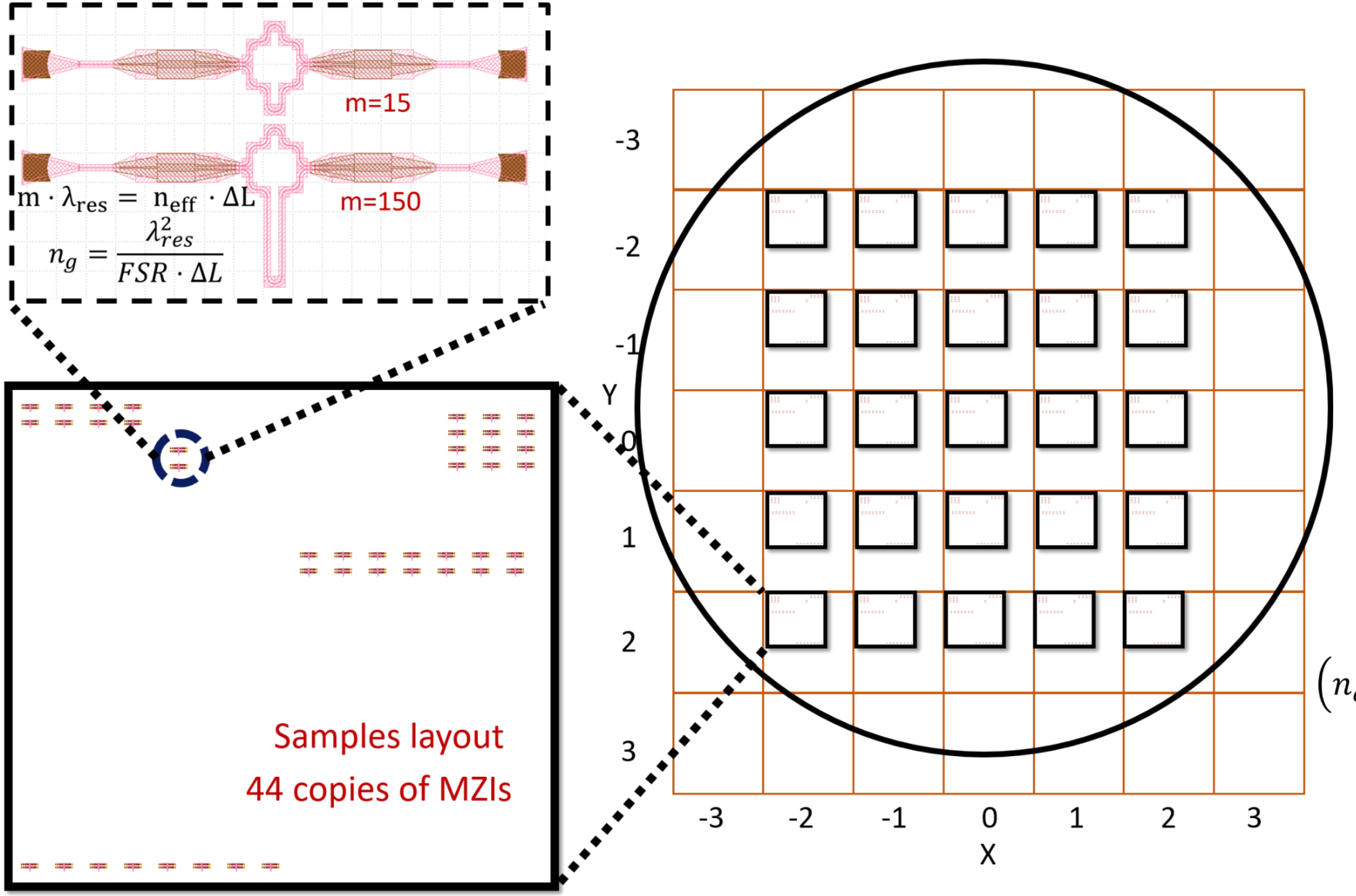
Extraction uncertainty:

Width: 0.37 nm

Thickness: 0.26 nm

Xing et al., Photonics Research 2018

Measurement sites



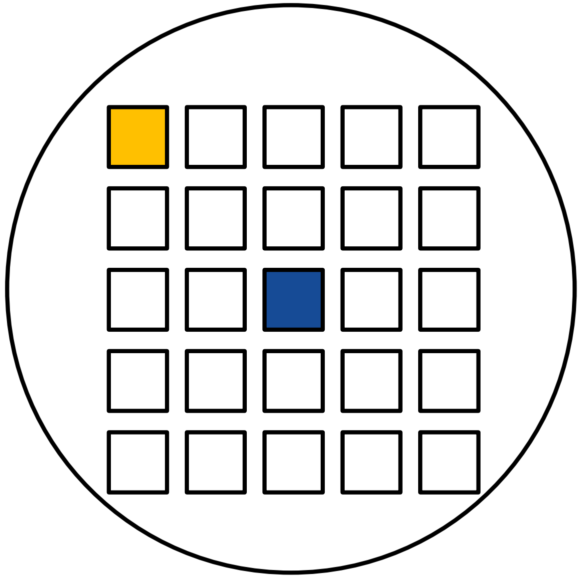
25 dies

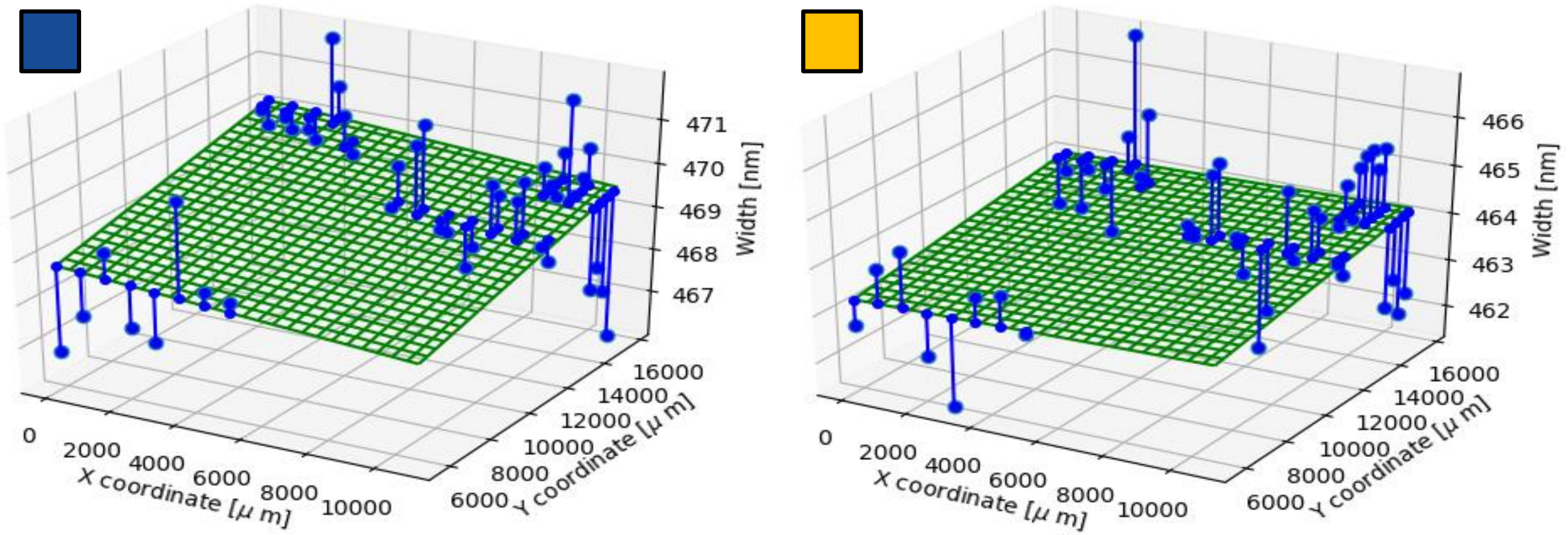
44 copies of MZI pairs per die

Obtain geometry parameters

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

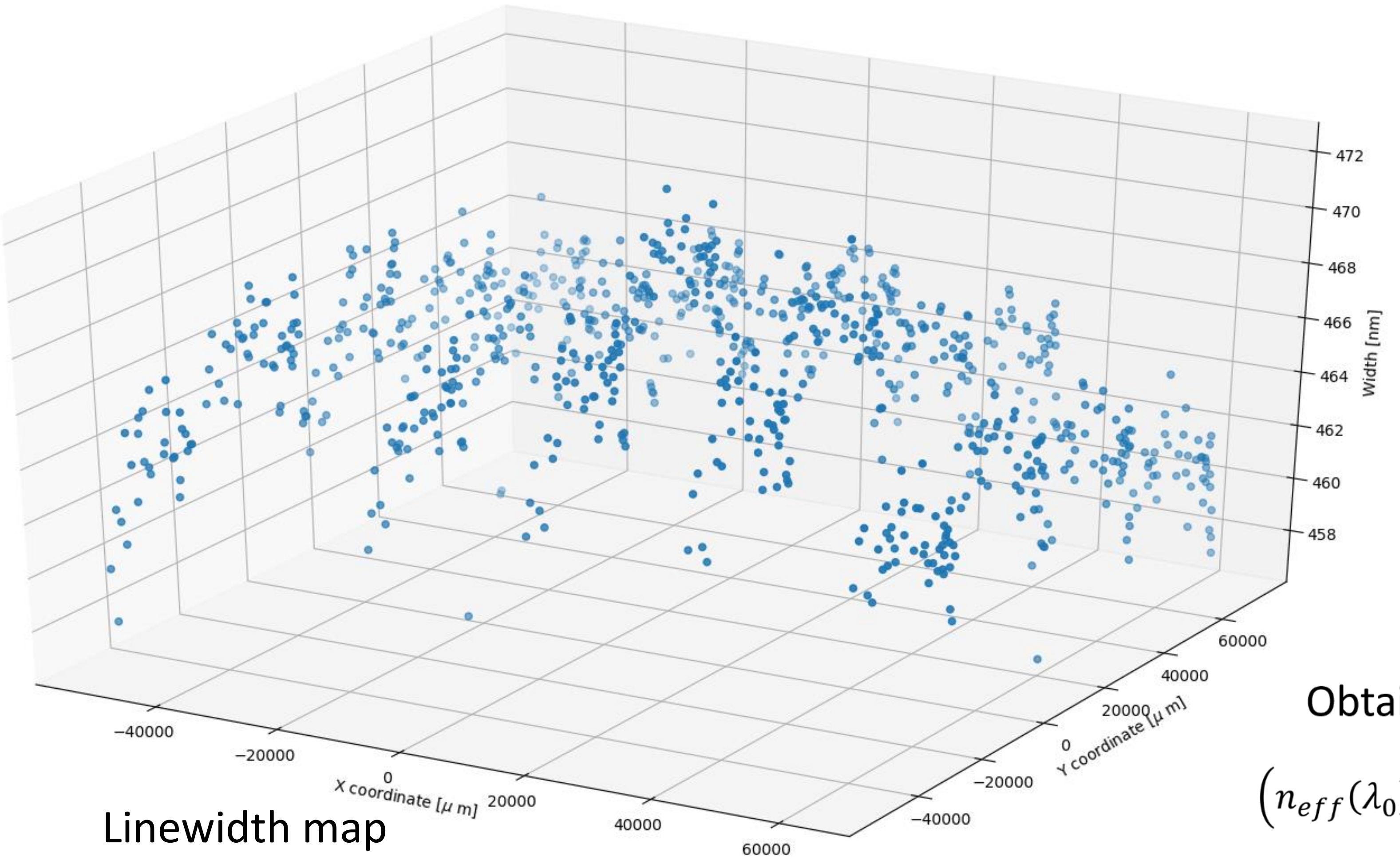
LINEWIDTH DIE MAP





(a) (b)

Extracted fabricated linewidth wafer map



Linewidth map

Obtain geometry parameters

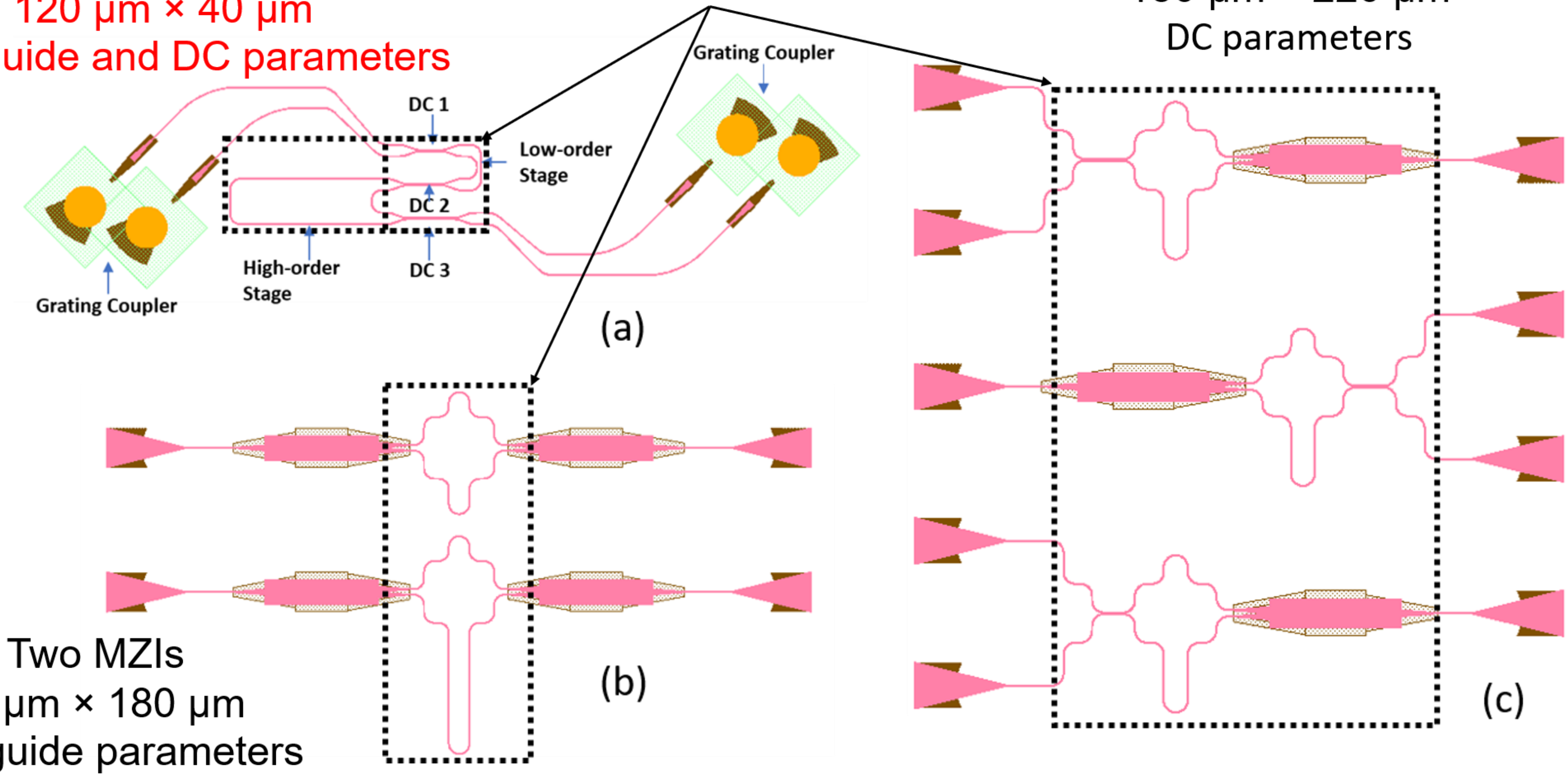
$$\left(n_{eff}(\lambda_0), n_g(\lambda_0)\right) \xRightarrow{(w,t)=f\left(n_{eff}(\lambda_0), n_g(\lambda_0)\right)} (w,t)$$

IMPROVED PROCESS CONTROL MONITORING CIRCUIT

New folded MZI design
120 µm × 40 µm
Waveguide and DC parameters

Regions monitoring process variation

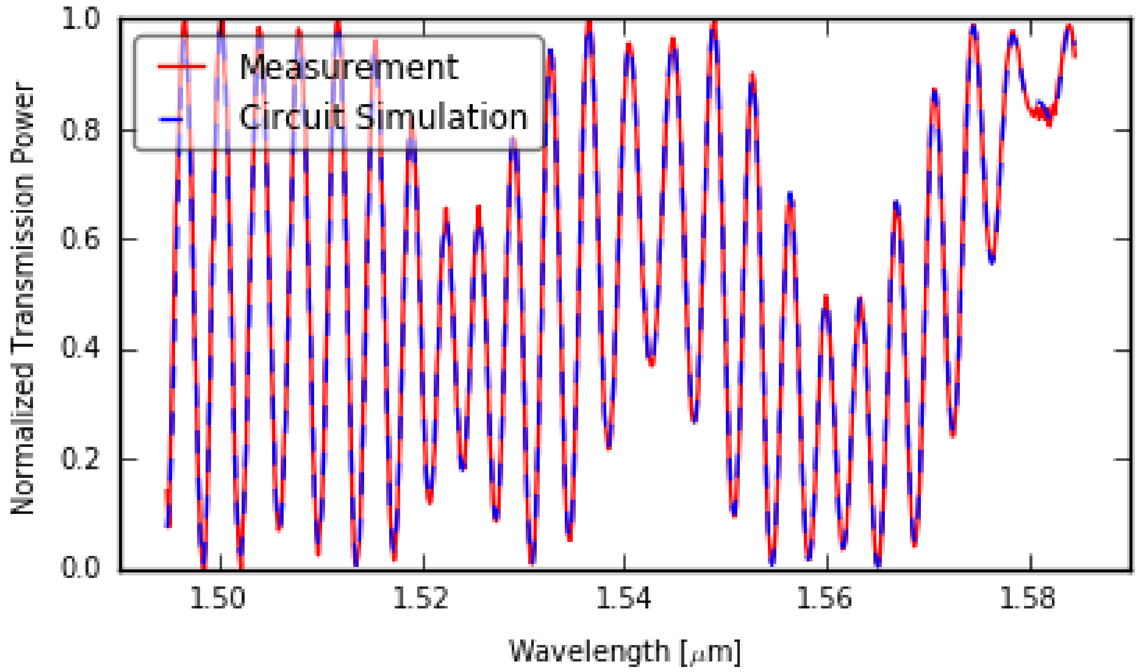
3 DCs with increasing coupler length
150 µm × 220 µm
DC parameters



Two MZIs
55 µm × 180 µm
waveguide parameters

Fitting curve using global optimization algorithm

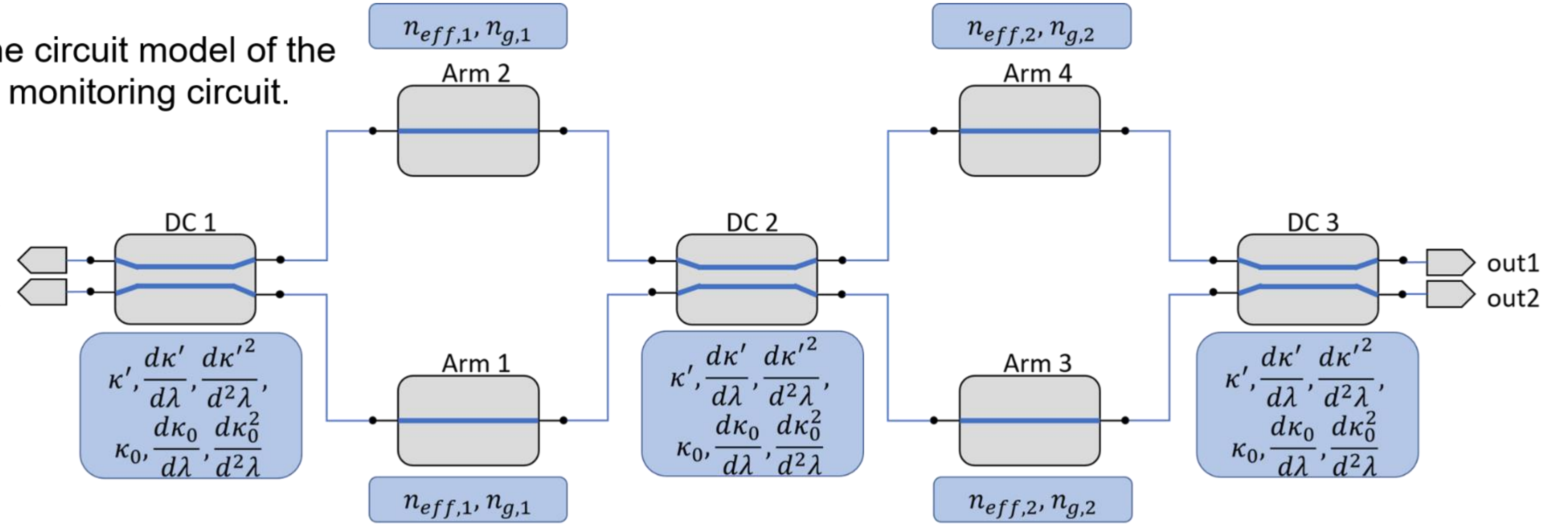
- Conventional curve fitting methods fail to find the global optimum
- Global optimization algorithm such as CMA-ES or EGO
- Find solution with less than 20,000 evaluations

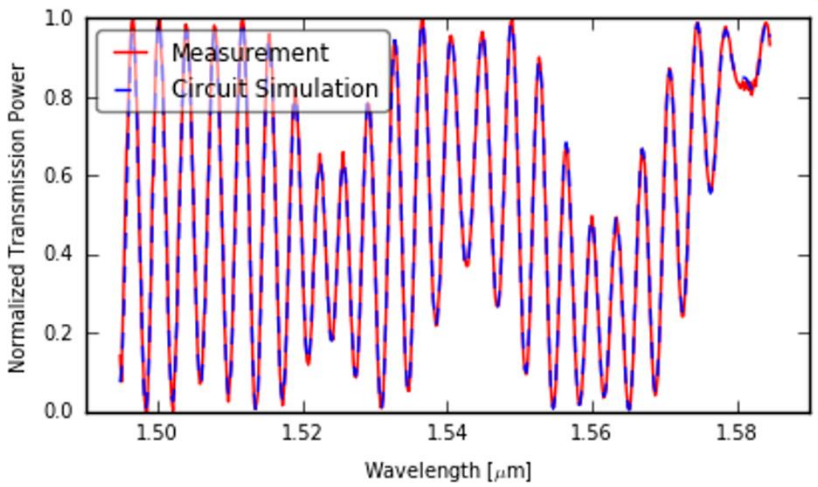


Xing et al., submitted to OE

Process monitoring circuit

The circuit model of the monitoring circuit.

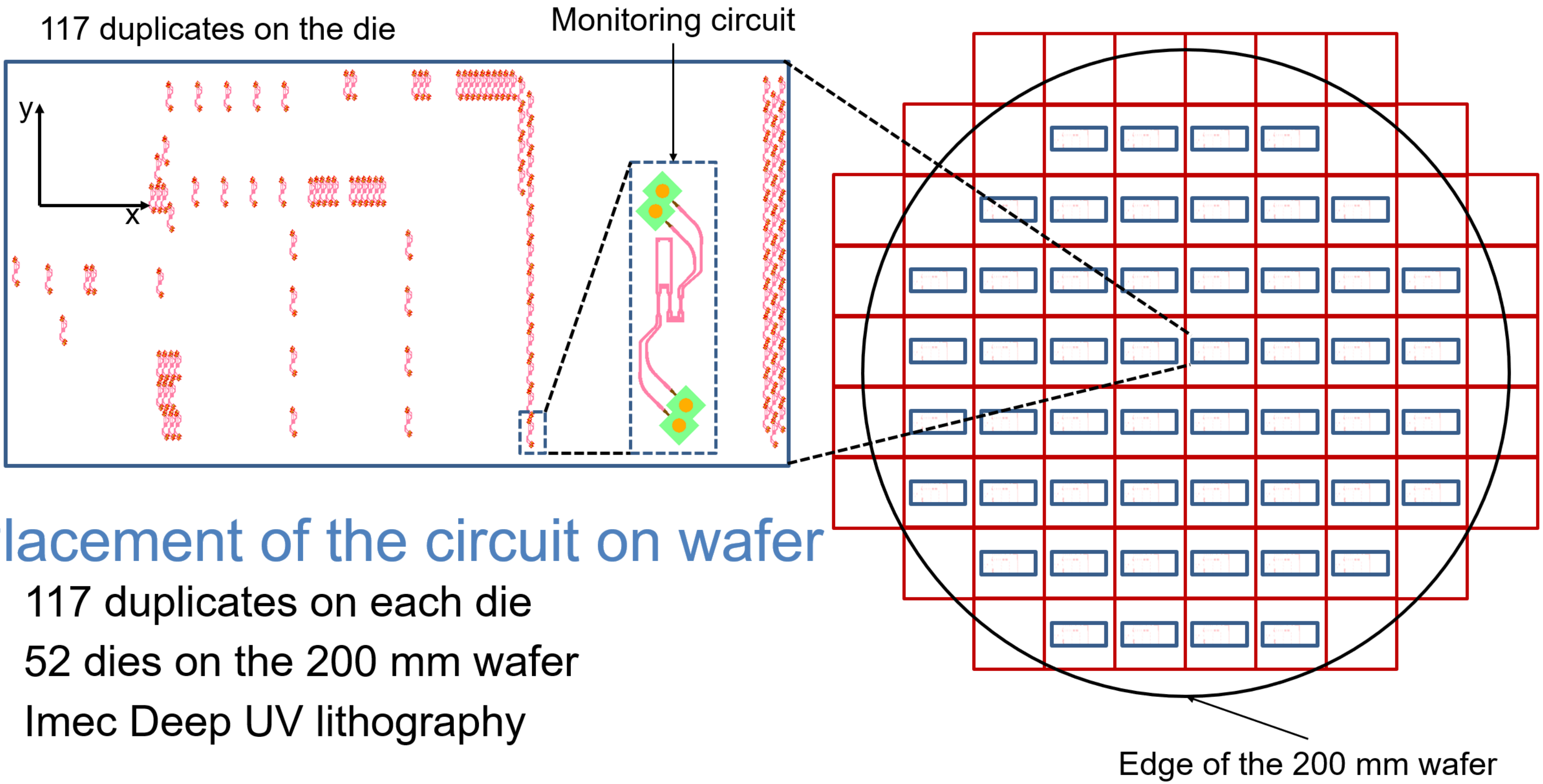




Obtained parameter values and fitting errors using the Restart CMA-ES method.

	Obtained Value	Fitting Error		Obtained Value	Fitting Error
$n_{eff,1}$	2.356	1.456e-6	$\frac{d\kappa'}{d\lambda}$	2.149e-1	9.147e-5
$n_{g,1}$	4.228	1.322e-4	$\frac{d\kappa'^2}{d^2\lambda}$	1.990	4.060
$n_{eff,2}$	2.356	2.284e-7	κ_0	2.315e-1	7.852e-5
$n_{g,2}$	4.220	2.105e-5	$\frac{d\kappa_0}{d\lambda}$	1.438	1.266e-2
κ'	4.173e-2	5.863e-6	$\frac{d\kappa_0^2}{d^2\lambda}$	8.110e-1	6.325e-2

Very small fitting error



Placement of the circuit on wafer

- 117 duplicates on each die
- 52 dies on the 200 mm wafer
- Imec Deep UV lithography

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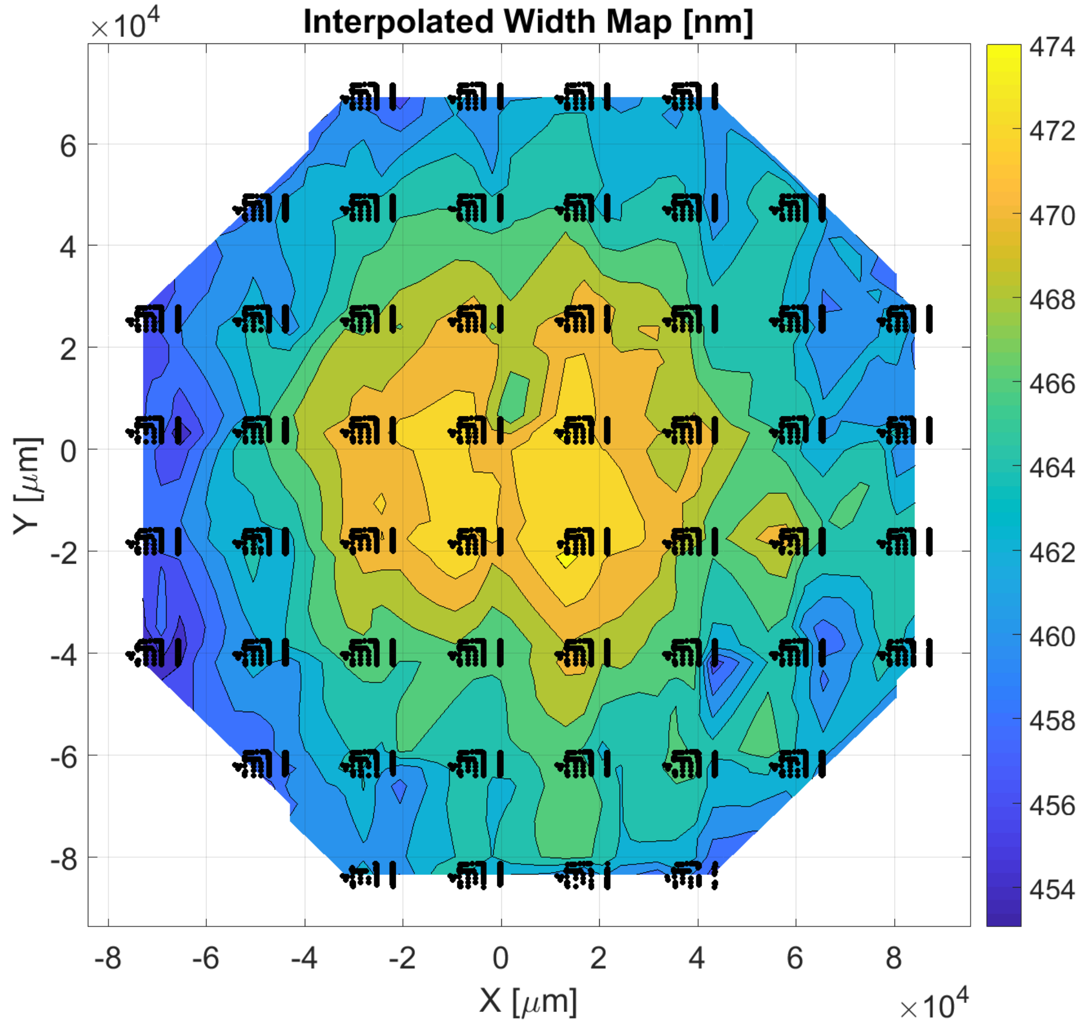
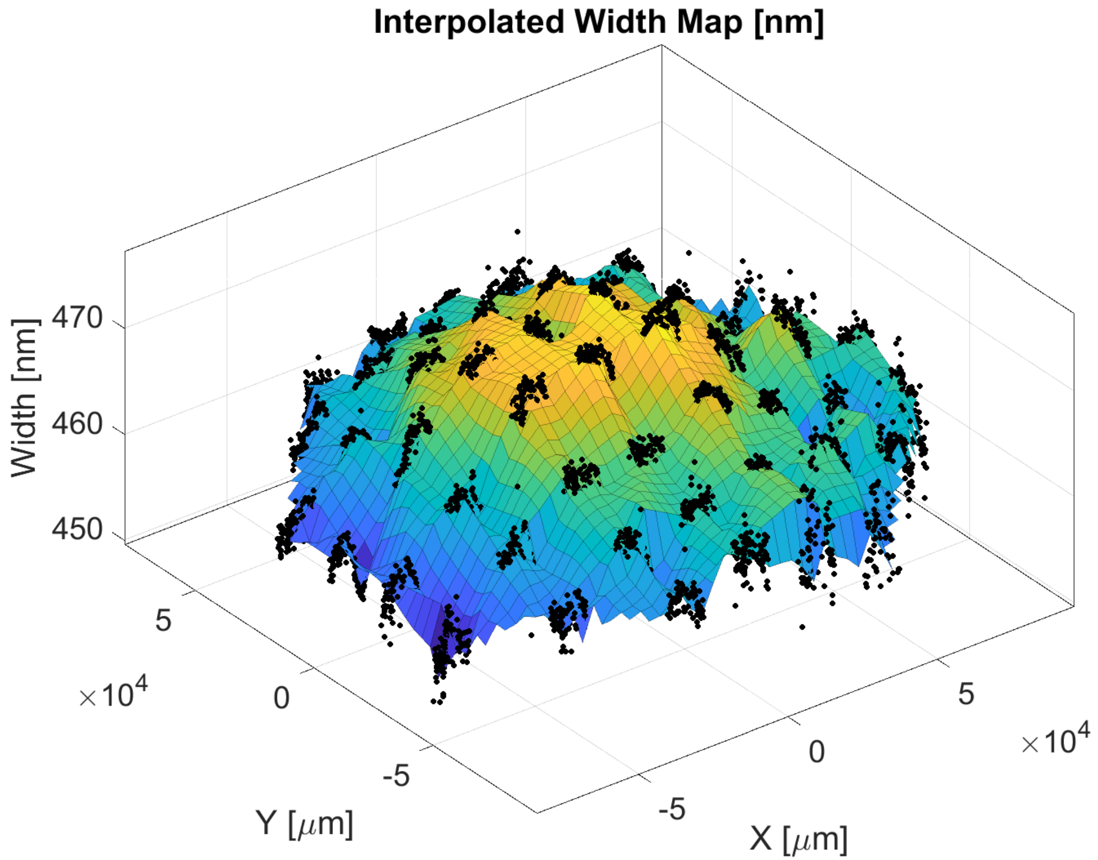
INTERPOLATED WIDTH MAP





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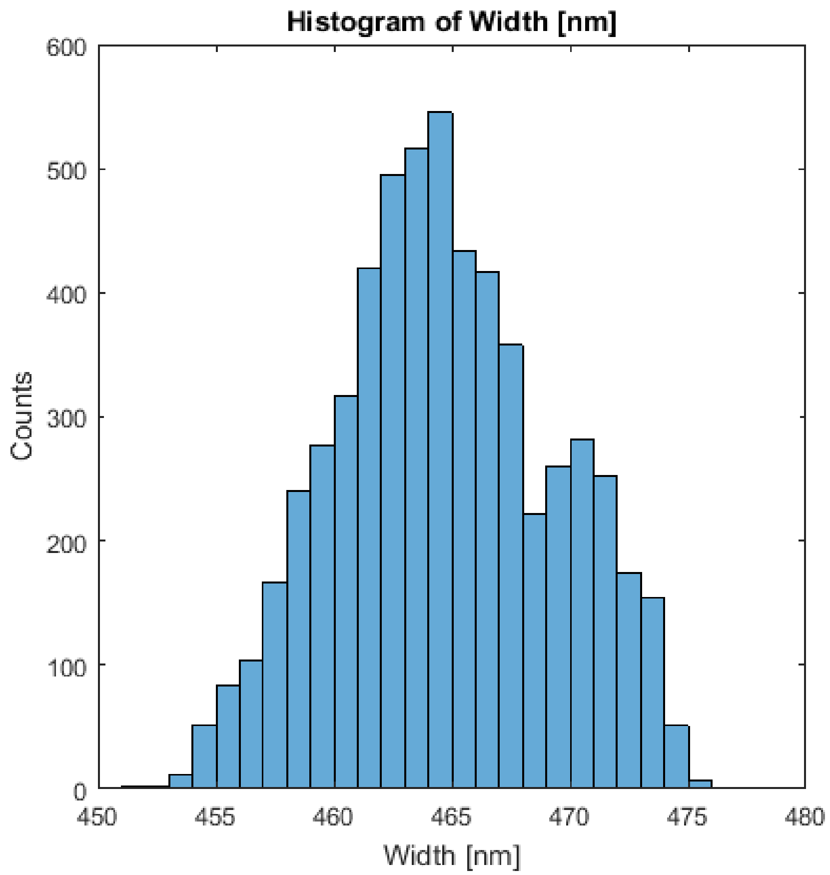
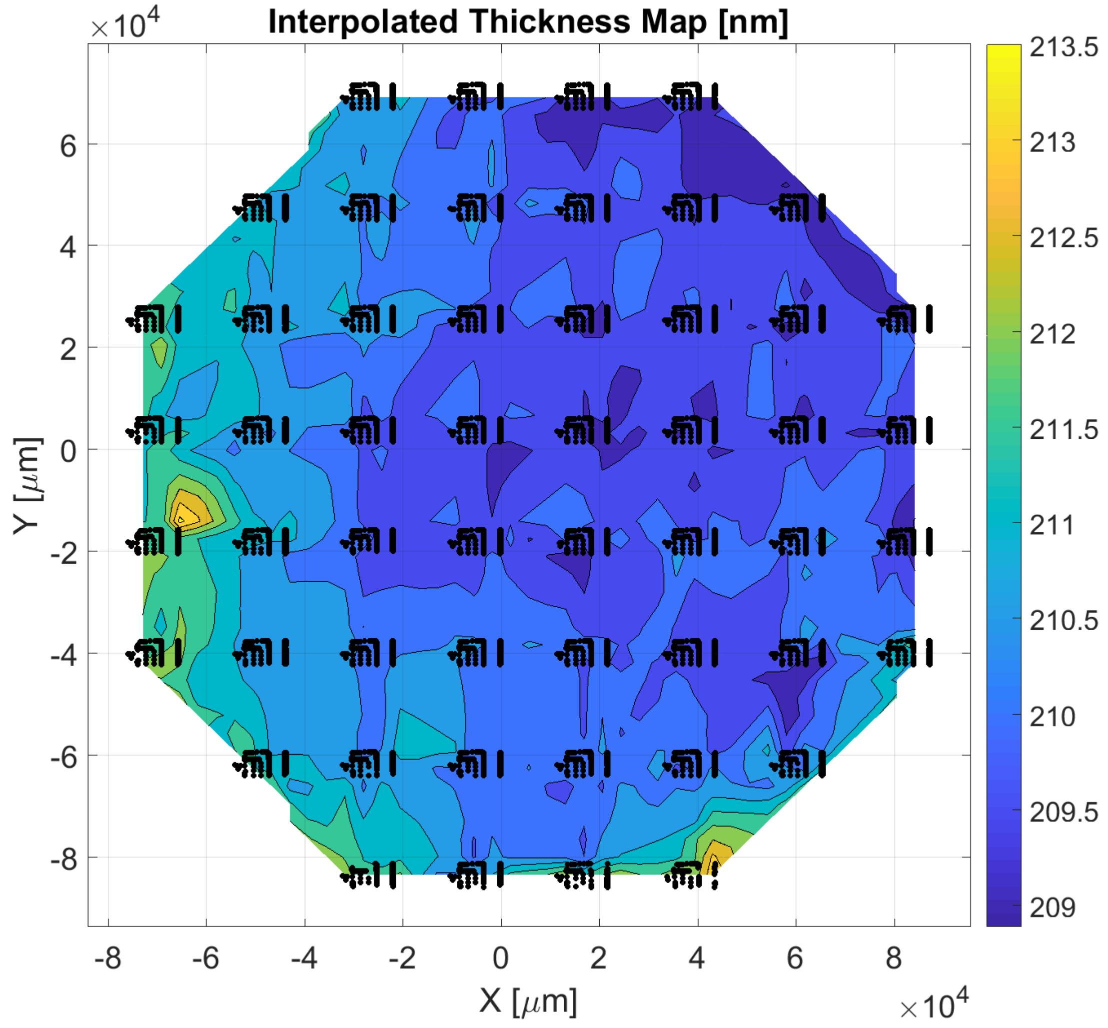
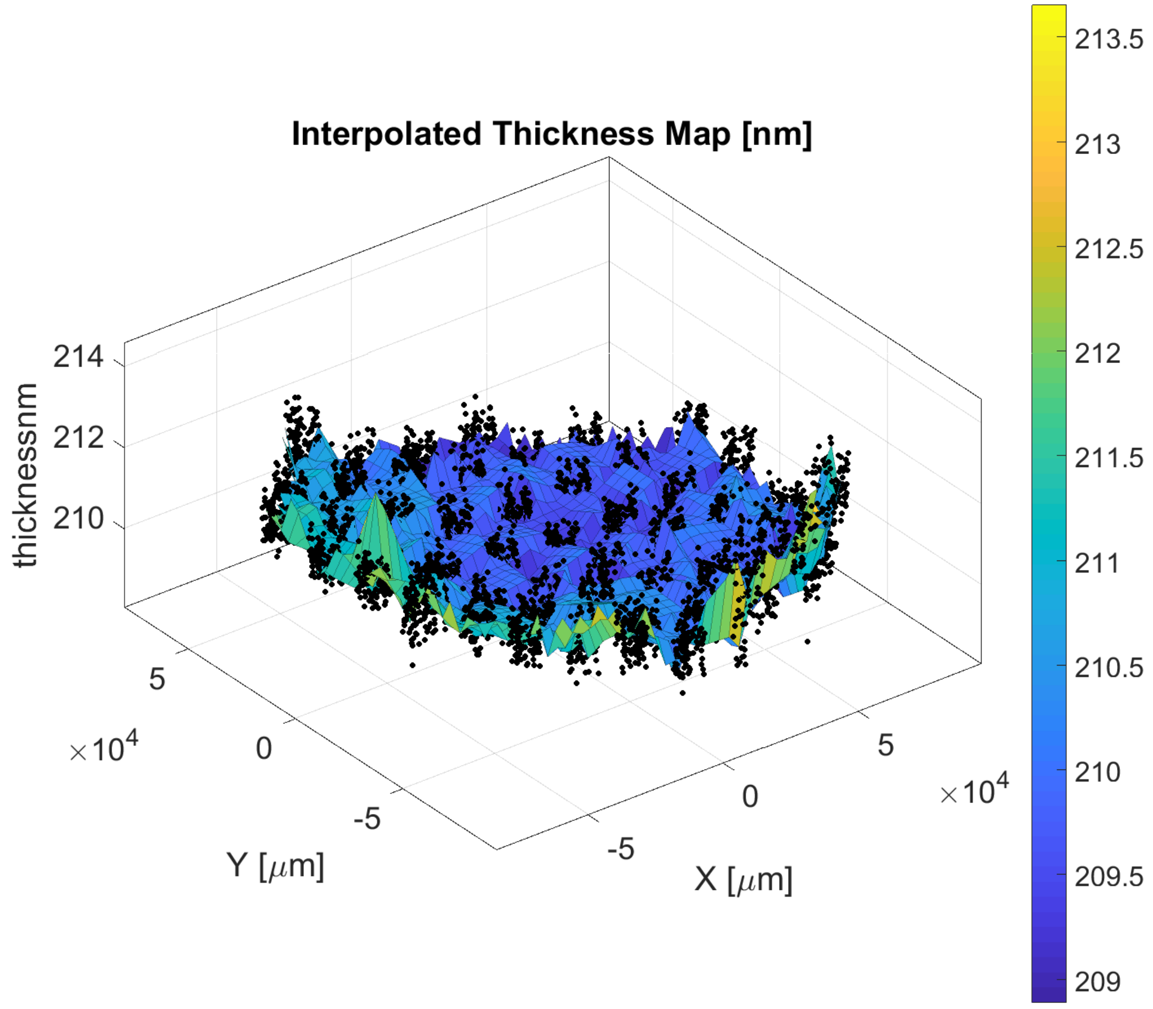
Width



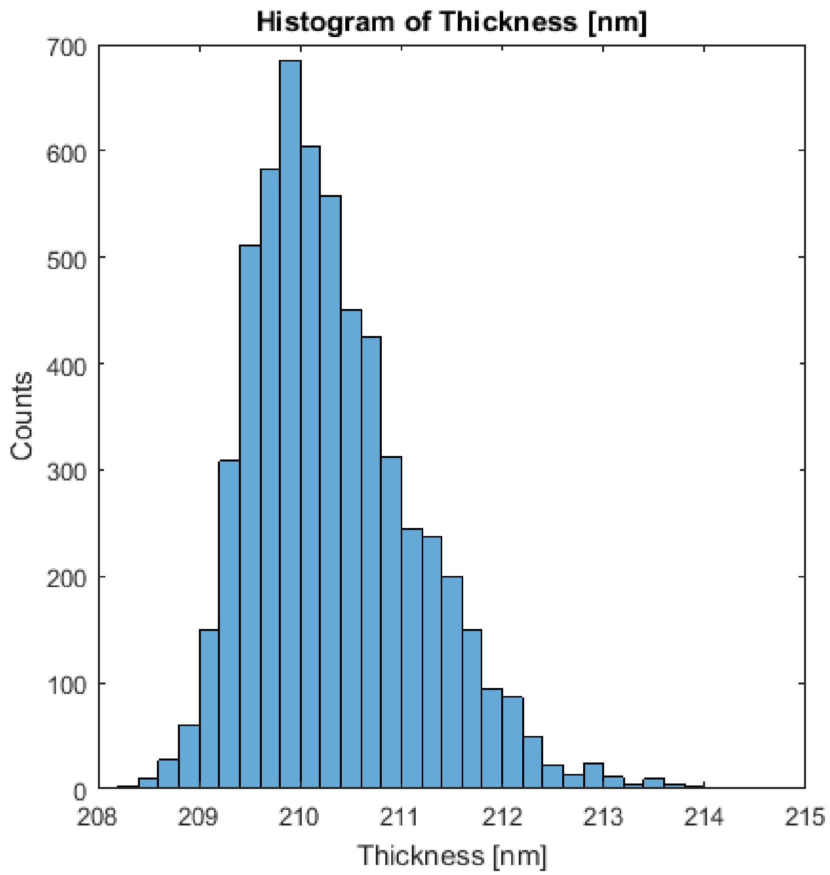
number	5841
Mean [nm]	464.6792
Std [nm]	4.5894
Max [nm]	476.0061
Min [nm]	450.8493
Max-Min [nm]	25.1568
Mid [nm]	464.4049

Interpolated thickness map





Thickness



number	5841
Mean [nm]	210.3328
Std [nm]	0.8249
Max [nm]	214.2786
Min [nm]	208.3510
Max-Min [nm]	5.9276
Mid [nm]	210.1934

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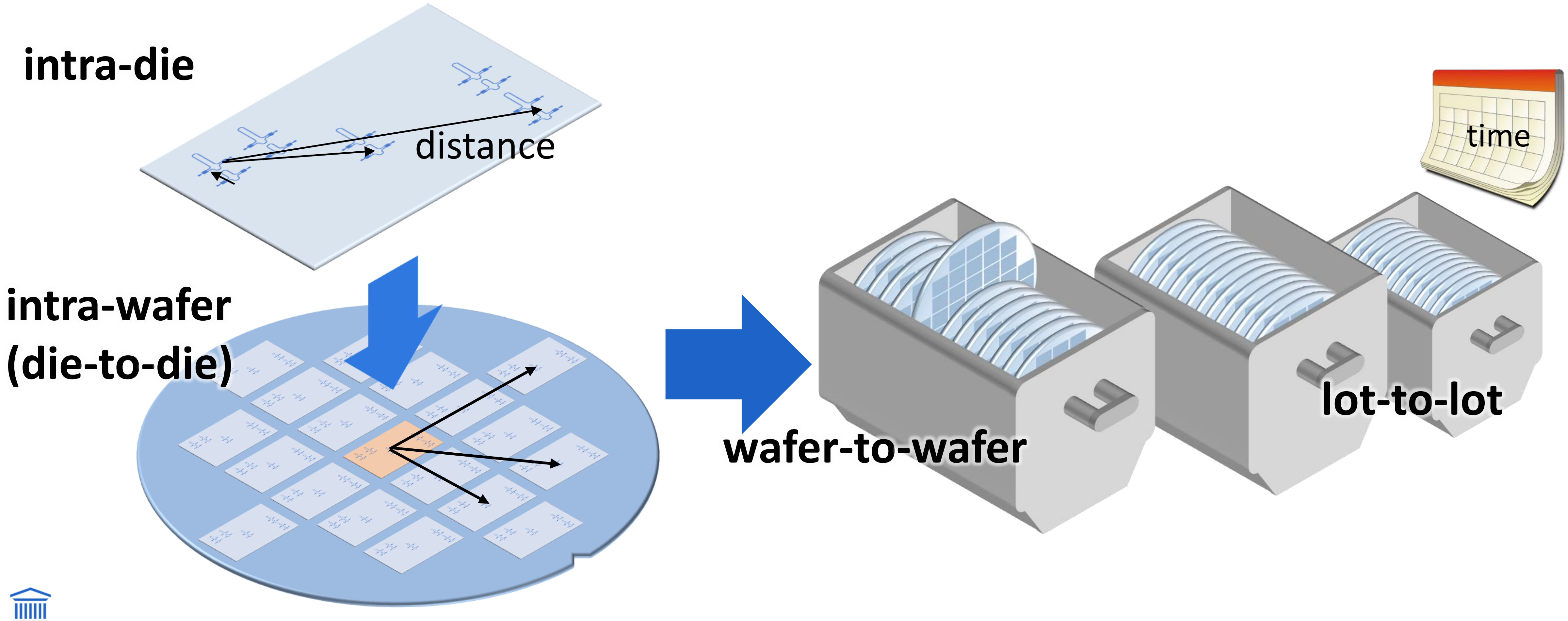
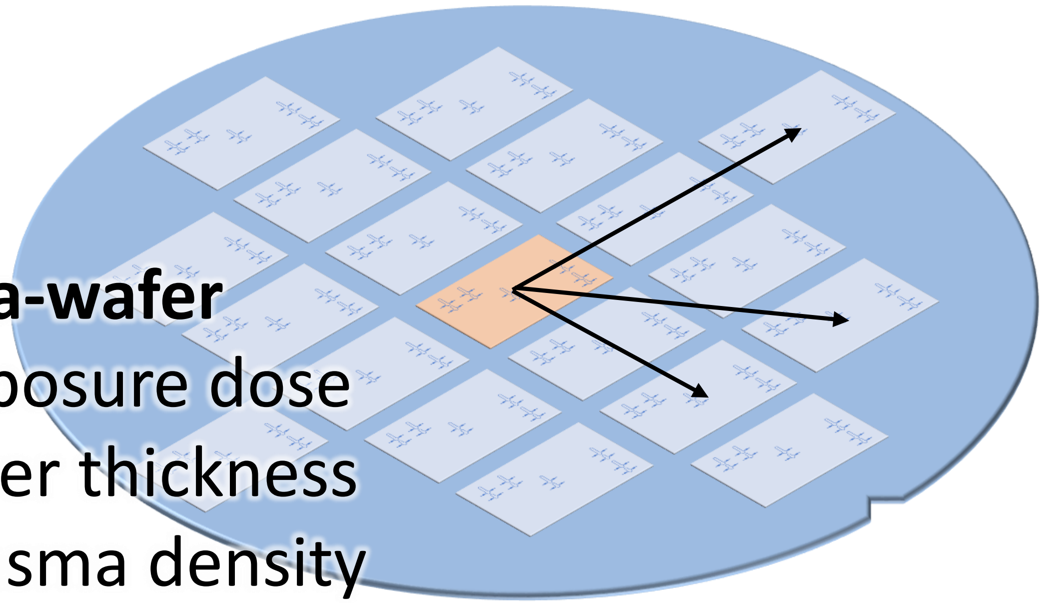
SPATIAL VARIATION MODEL

Variability effects work on different scales



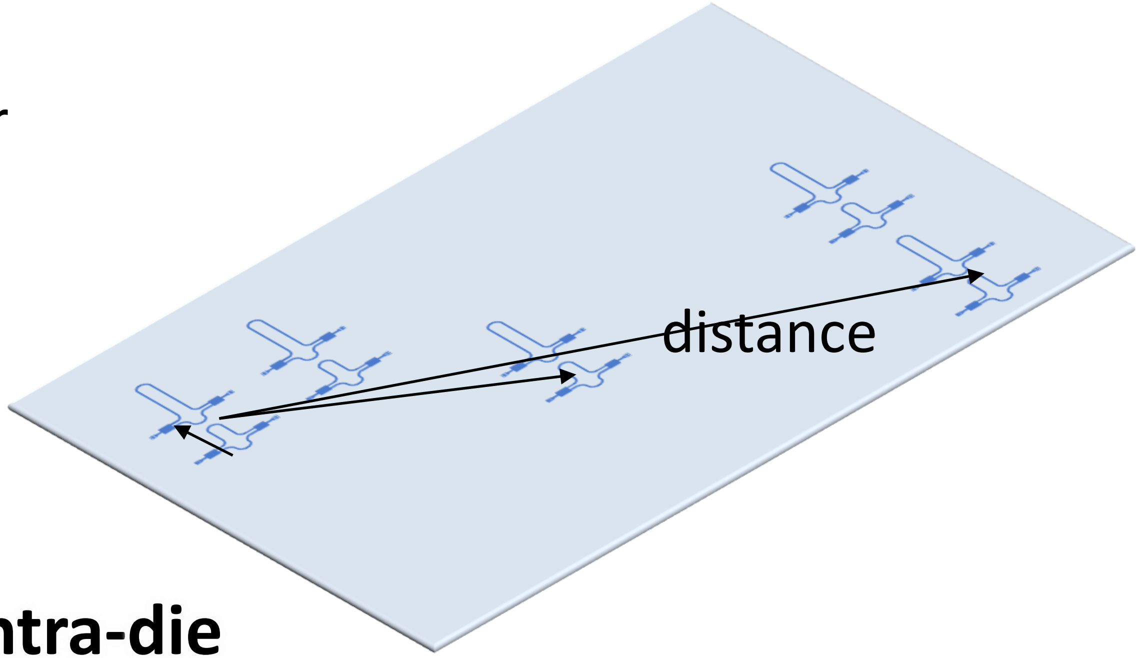
INTRA-WAFER VARIATION

- A symmetric radial pattern
- Random die-to-die variation: fluctuation in lithography exposure dose and imaging focus



INTRA-DIE VARIATION

- Systematic variation
  - Low frequency change in layer thickness
  - Local pattern density
  - Error in the photomask
- Random variation
  - Intrinsic randomness in layer thickness
  - Roughness in sidewalls



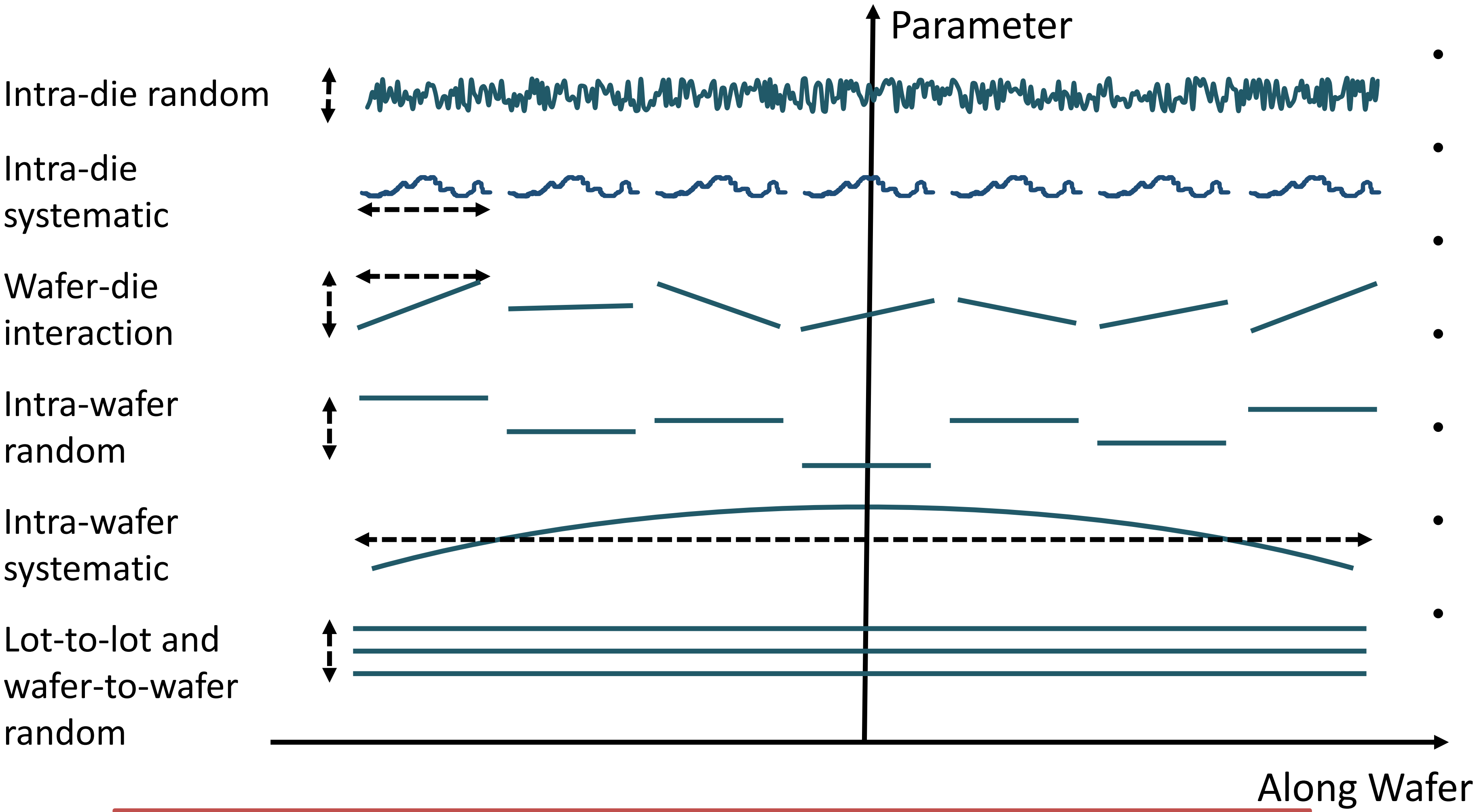
intra-die

local pattern density

layer thickness

lithography nonuniformity

HIERARCHICAL SPATIAL VARIATION MODEL



- V_{LTL}: *Lot-to-lot*
- V_{WTW}: *Wafer-to-wafer*
- V_{IWS}: *Intra-wafer systematic*
- V_{IWR}: *Intra-wafer random*
- V_{IDS}: *Intra-die systematic*
- V_{IDR}: *Intra-die random*
- V_{WDI}: *Wafer-die interaction*

$$Data_{mea} = Design + V_{LTL} + V_{WTW} + V_{IWS} + V_{IWR} + V_{IDS} + V_{IDR} + V_{WDI}$$

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Measured raw data

1. Generate simple wafer map by bi-variate polynomial fitting
2. IWS is the average of simple wafer maps

→ IWS

3. IDS is the averaging residuals from step 2 on each unique position on all the dies

→ IDS

4. Fit residual from step 3 on each die with a plane
5. IWR is the center of the fitted plane

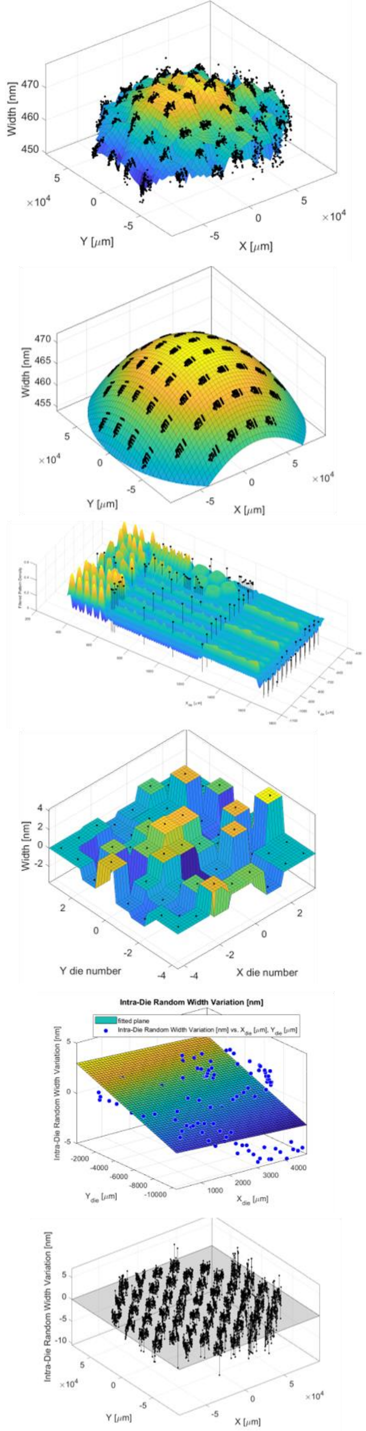
→ IWR

6. WDI is the fitted plane subtracting the value at the die centre

→ WDI

7. Residual from the fitting is the IDR

→ IDR



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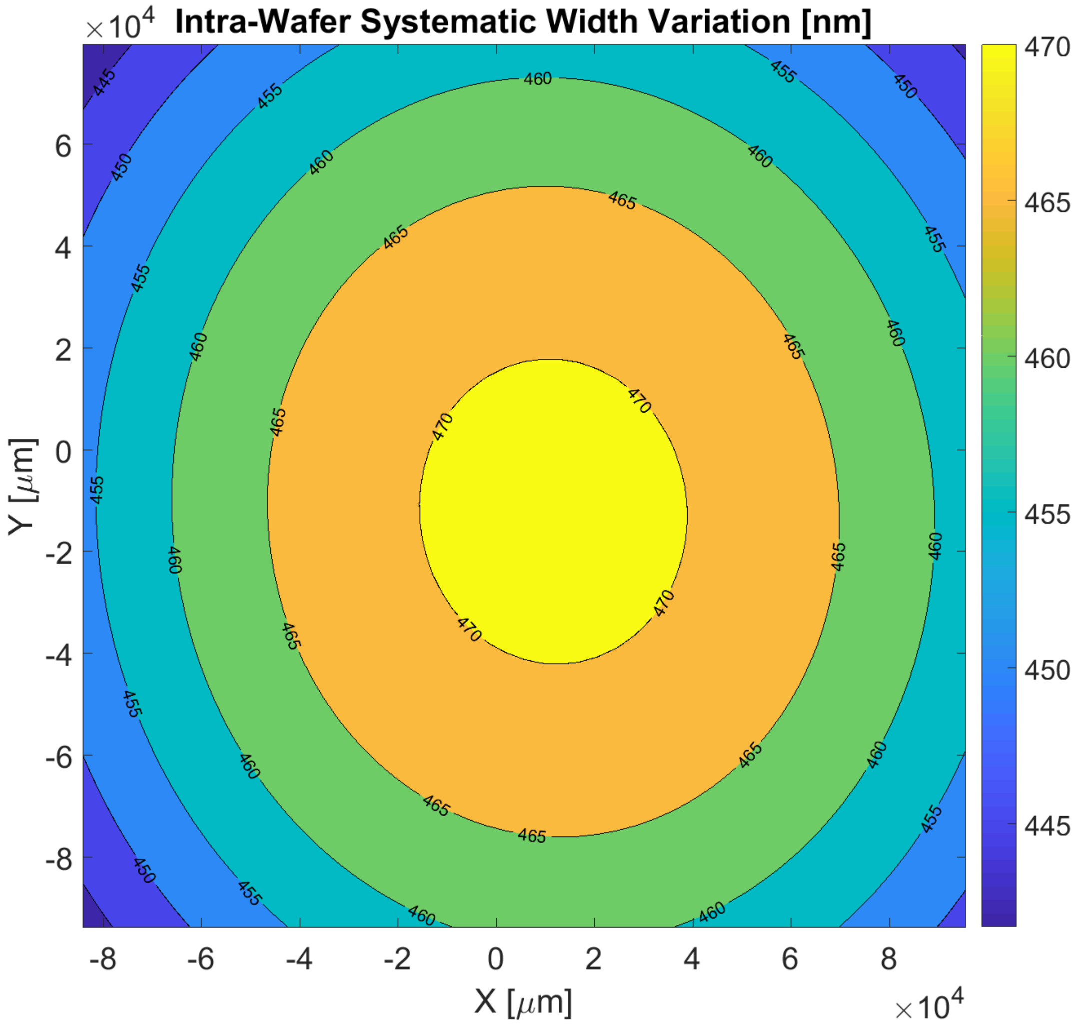
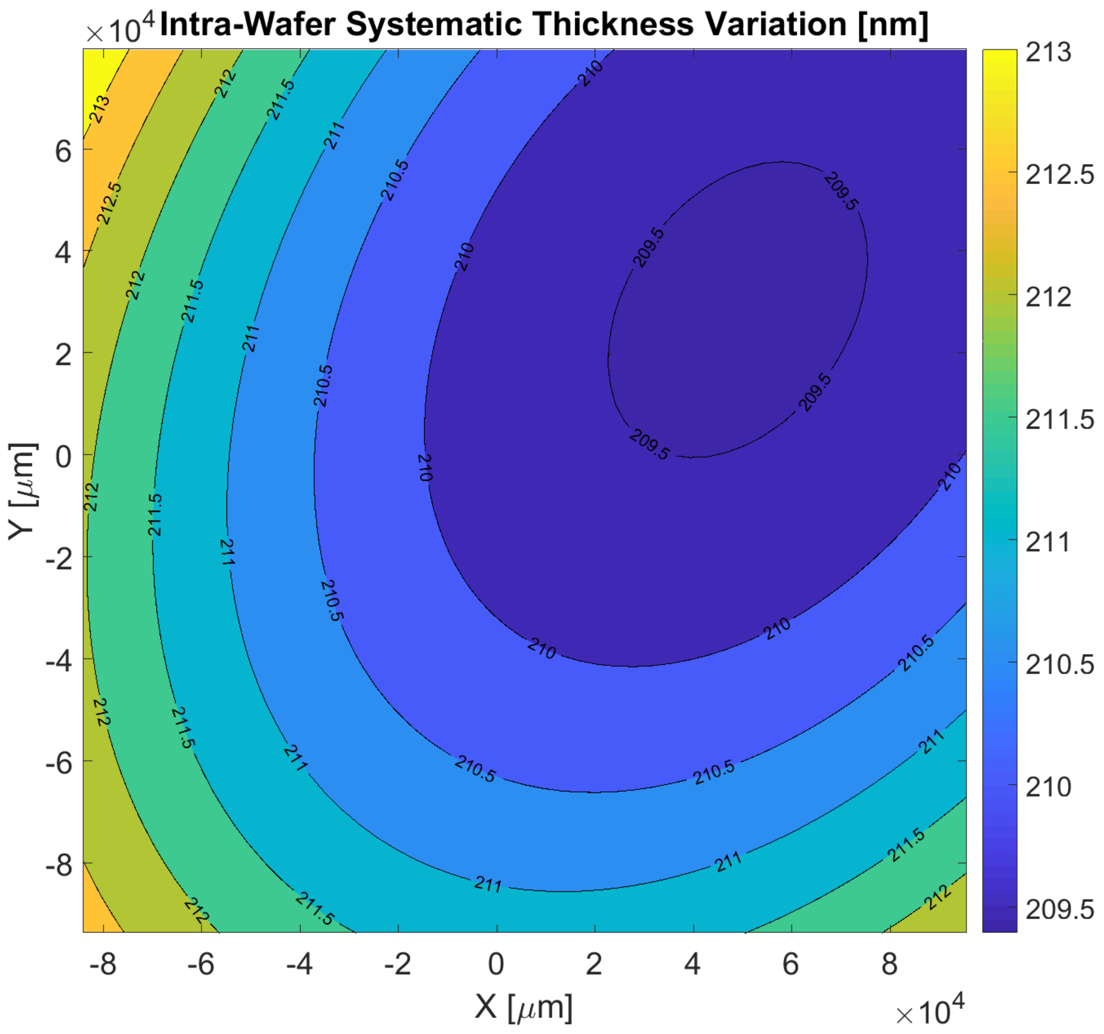
IWS WIDTH MAP



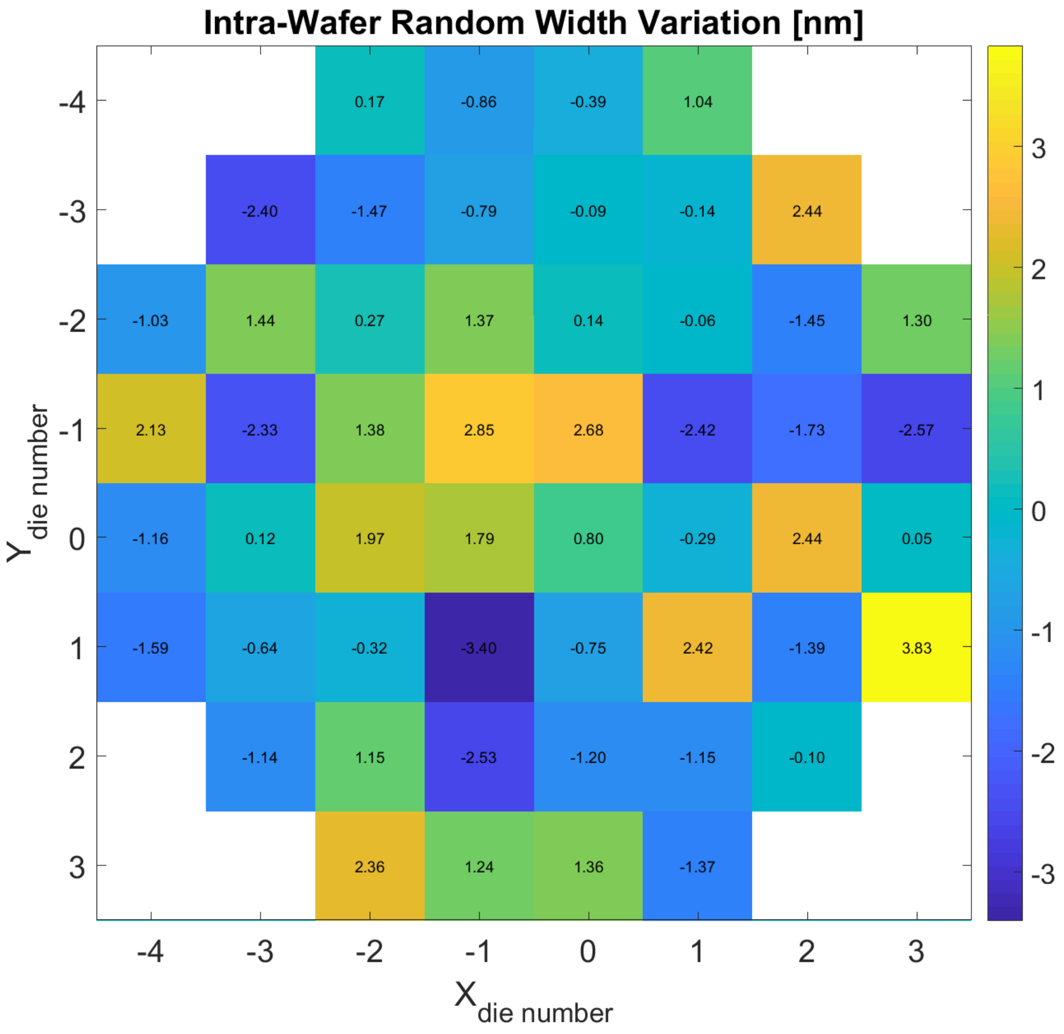
Width_IWS	nm
Max	471.3835
Min	454.9698
Max_interp	471.4
Min_interp	452.0
Max-Min	16.4137

IWS THICKNESS MAP



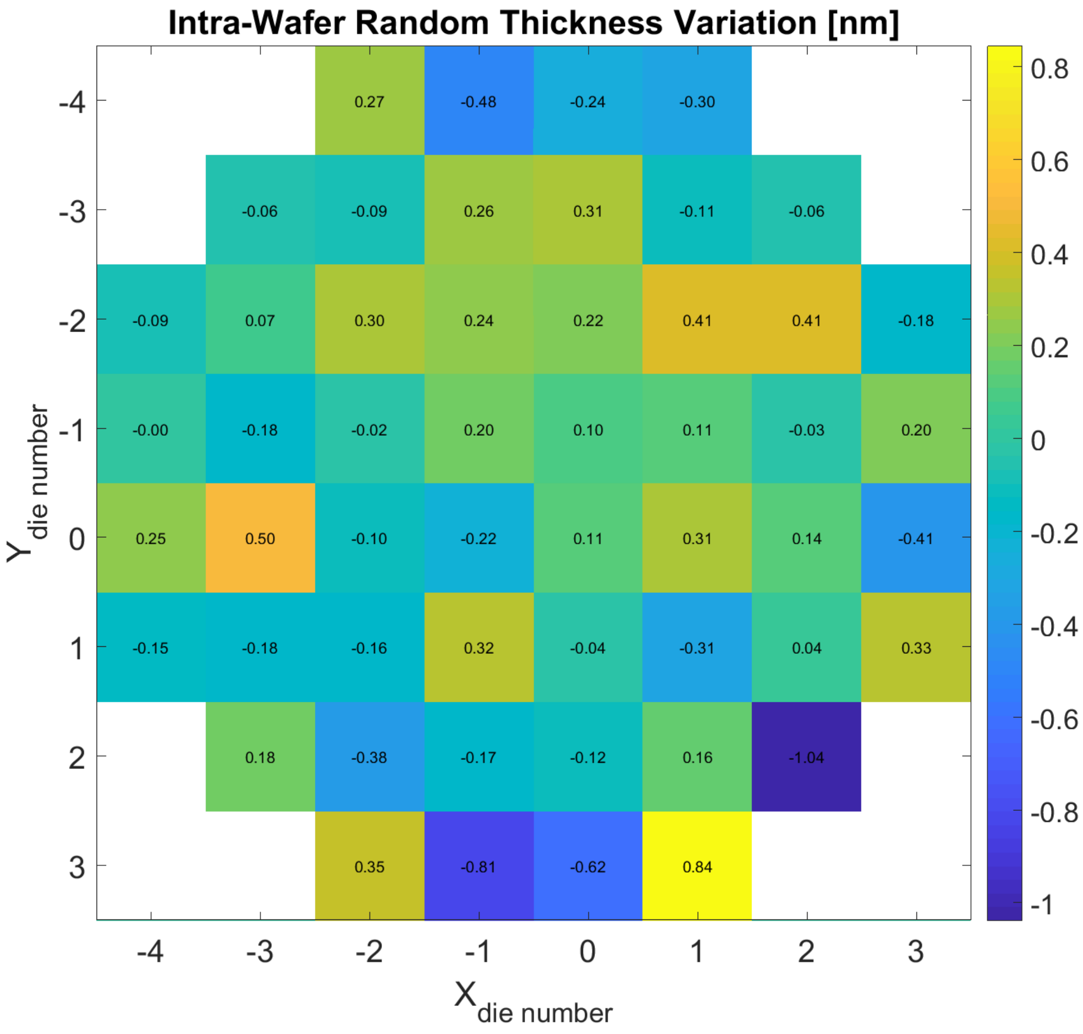
Thickness_IWS	nm
Max	211.9885
Min	209.4005
Max_interp	212.6
Min_interp	209.4
Max-Min	2.5880

IWR WIDTH MAP



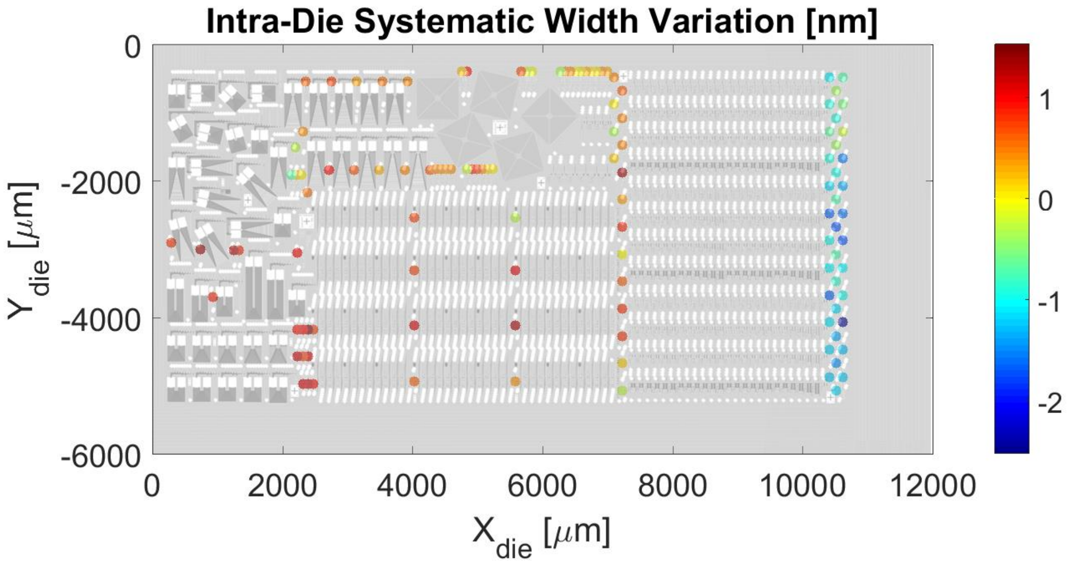
Width_IWR	nm
Max	3.8284
Min	-3.3994
Max-Min	7.2278
Mean	0.0383
STD	1.6760

IWR THICKNESS MAP



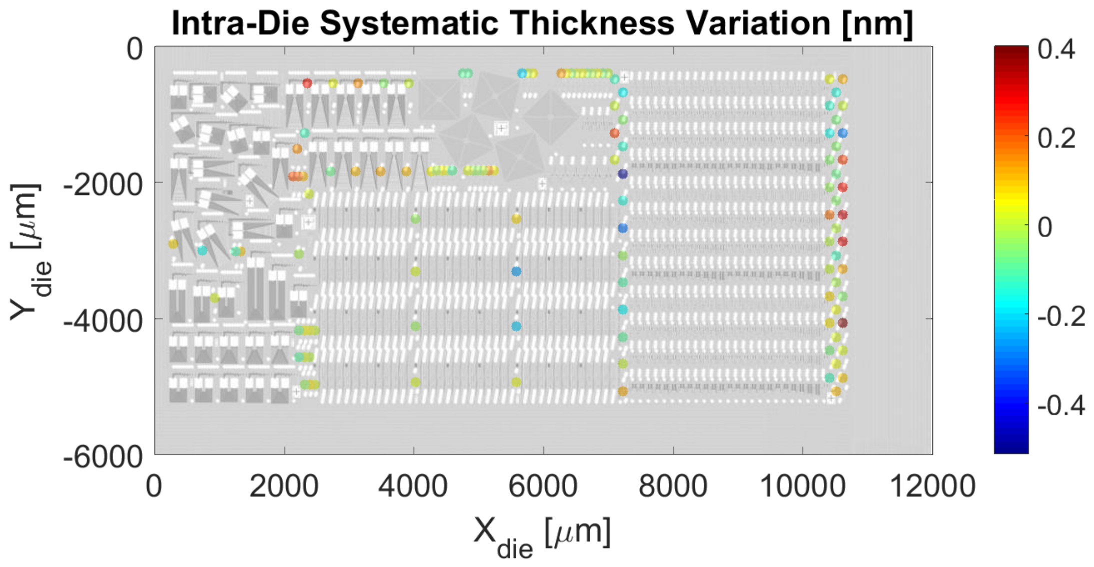
Thickness_IWR	nm
Max	0.8449
Min	-1.0382
Max-Min	1.8831
Mean	0.0014
STD	0.3316

IDS WIDTH VARIATION



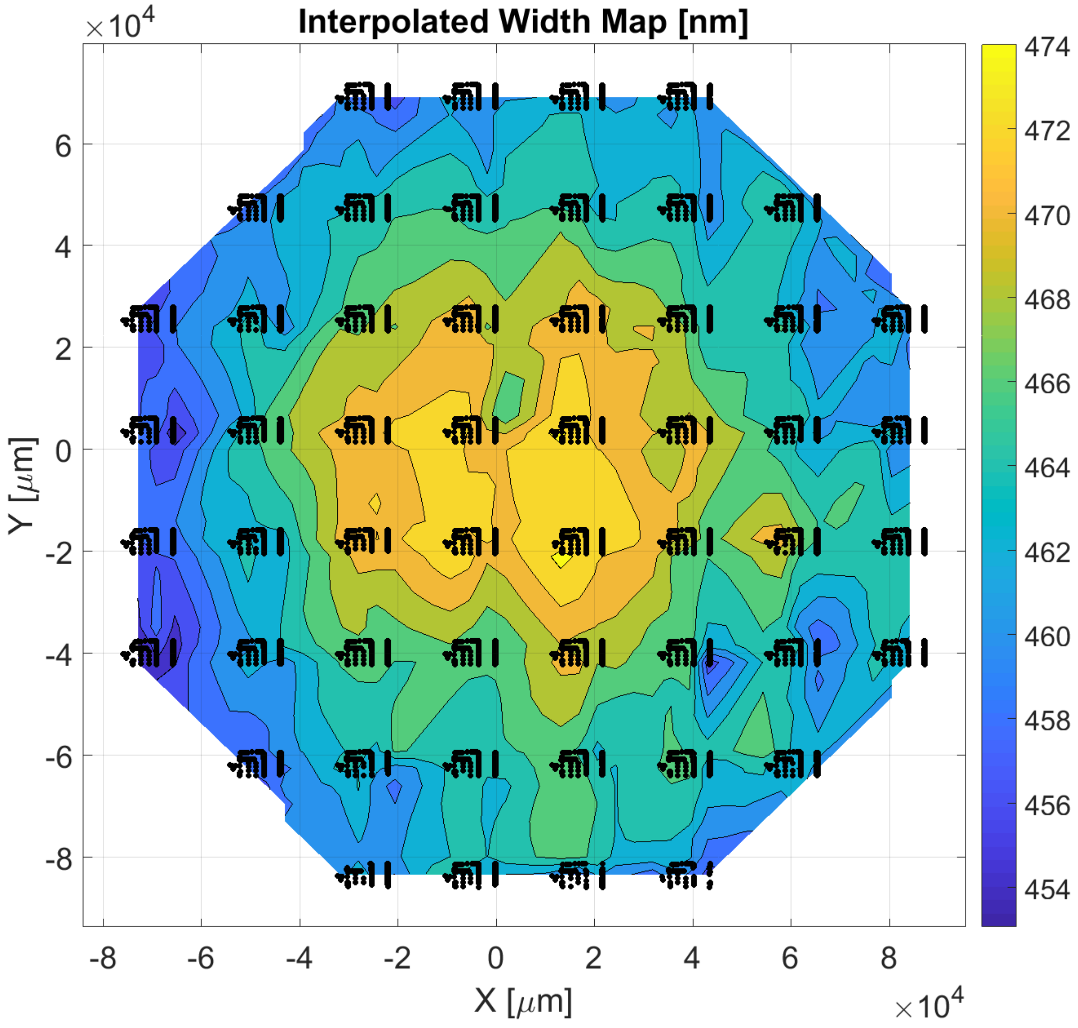
Width_IDS	nm
Max	1.52
Min	-2.52
Max-Min	4.04

IDS THICKNESS MAP



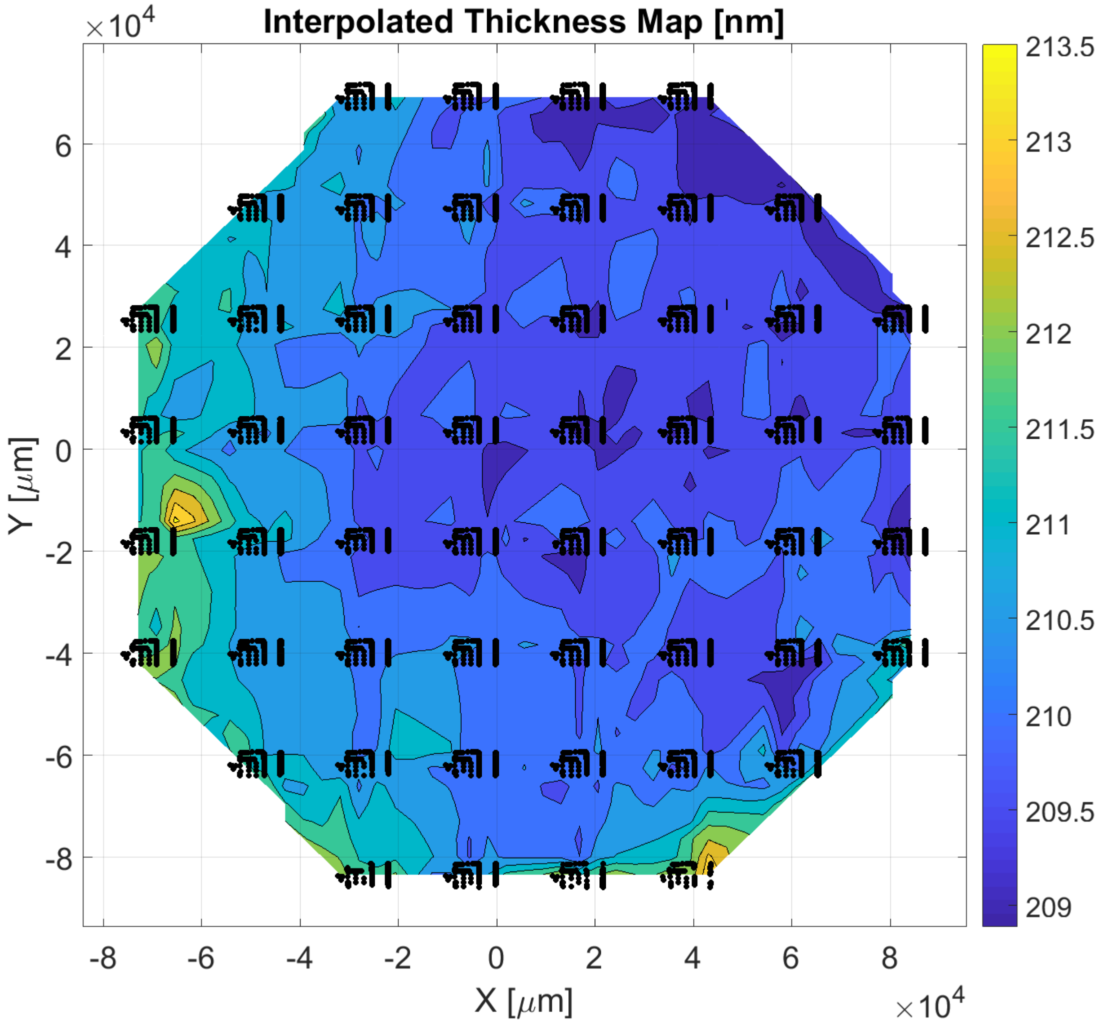
Thickness_IDS	nm
Max	0.40
Min	-0.51
Max-Min	0.91

Interpolated Width Map



Variation	nm
IWS	15.79
IDS	3.87
WDI	1.87
IWR	1.47
IDR	1.10

Interpolated Thickness Map



Variation	nm
IWS	2.53
IDS	0.86
WDI	0.31
IWR	0.34
IDR	0.34

Systematic variation dominates in the process variation

	Variation		Percentage [%]			
	Width	Thickness	Width		Thickness	
IWS [nm]	16.41	2.59	65.1	81.1	43.9	59.3
IDS [nm]	4.04	0.91	16.0		15.4	
IWR [nm]	1.68	0.33	5.2	19.9	10.6	40.7
IDR [nm]	1.10	0.34	3.4		10.9	
WDI_{block} [nm]	3.4	0.6	10.5		19.2	
Max Variation Measured [nm]	25.2	5.9				

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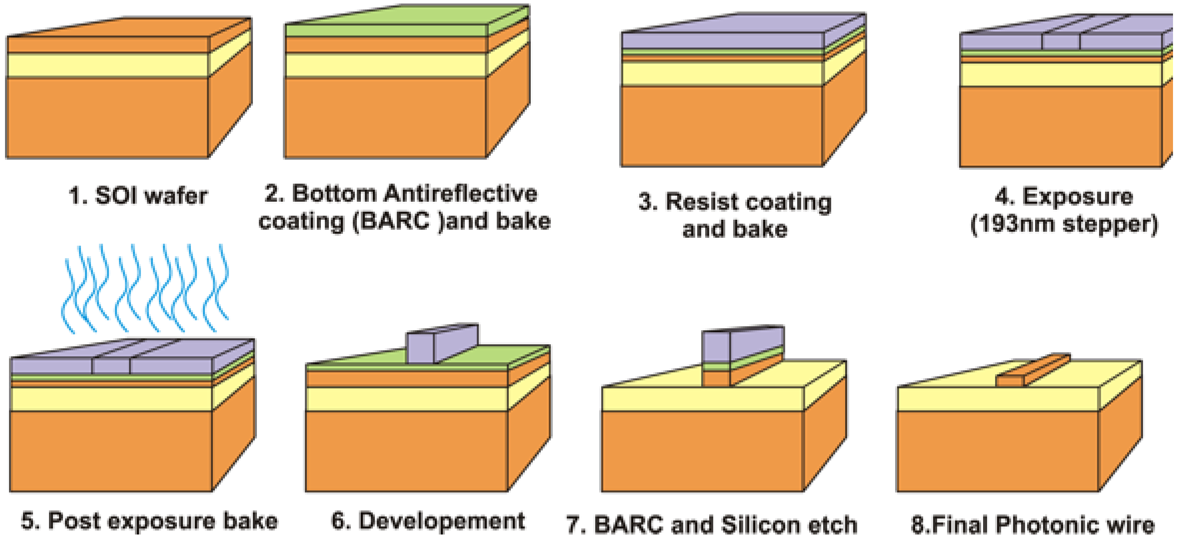
IDS VARIATION

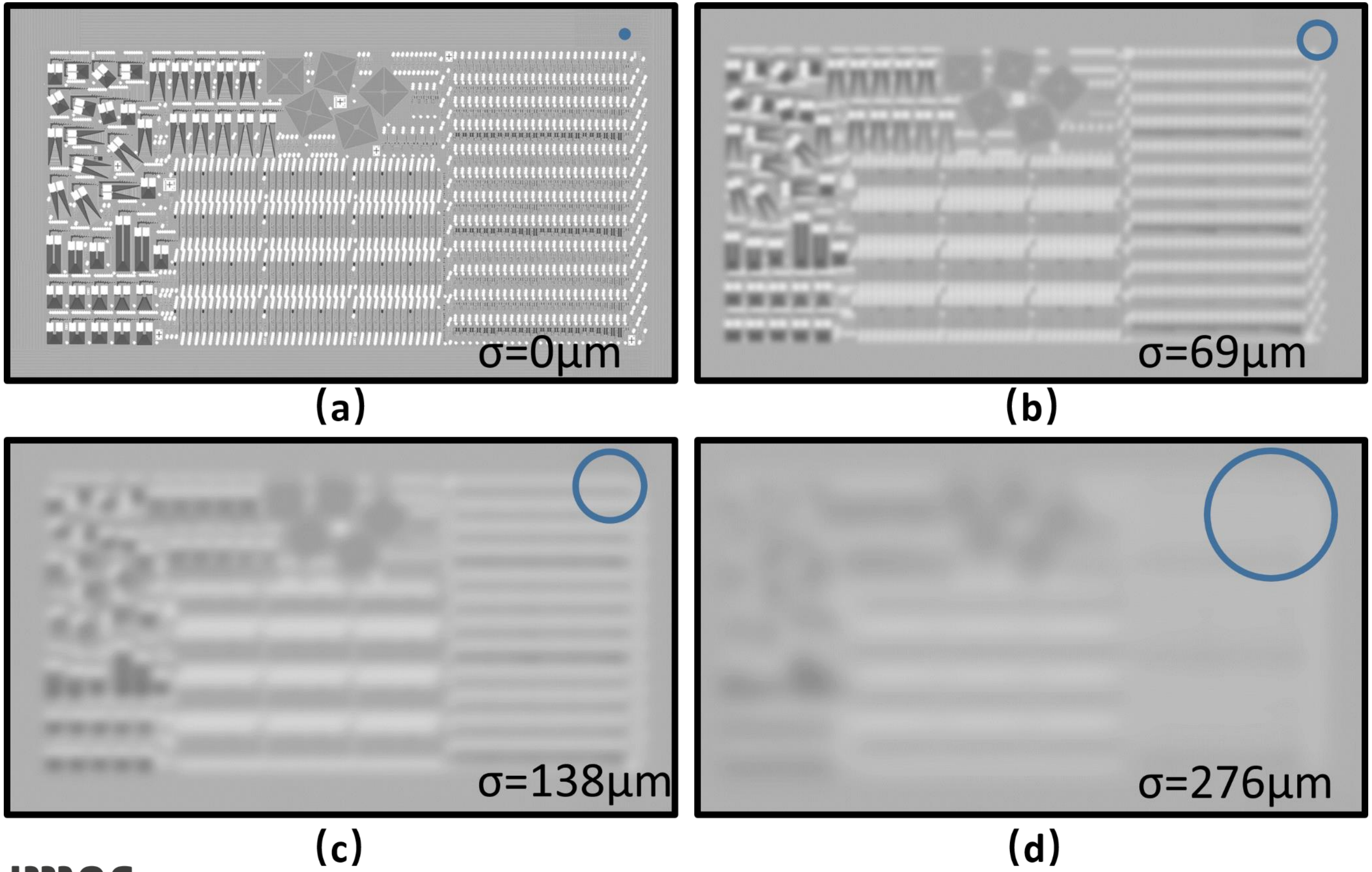
- errors in the photomask
  - pattern stitching errors
  - writing errors
  - particles on the mask
- aberrations in the lithography projection optics
- designed layout patterns, pattern density



Pattern density related variation

- chemistry of the plasma
  - photoresist/etch waste products
  - etch rate, selectivity and anisotropy
  - a variation in etch depth and line width
  - local over-etching => attack on the sidewalls
- Chemical Mechanical Polishing (CMP)
  - Planarization: the presence and density of the material to be polished
  - Large areas without patterns => erosion and dishing => different remaining thickness

Pattern density map vs Gaussian filter radius



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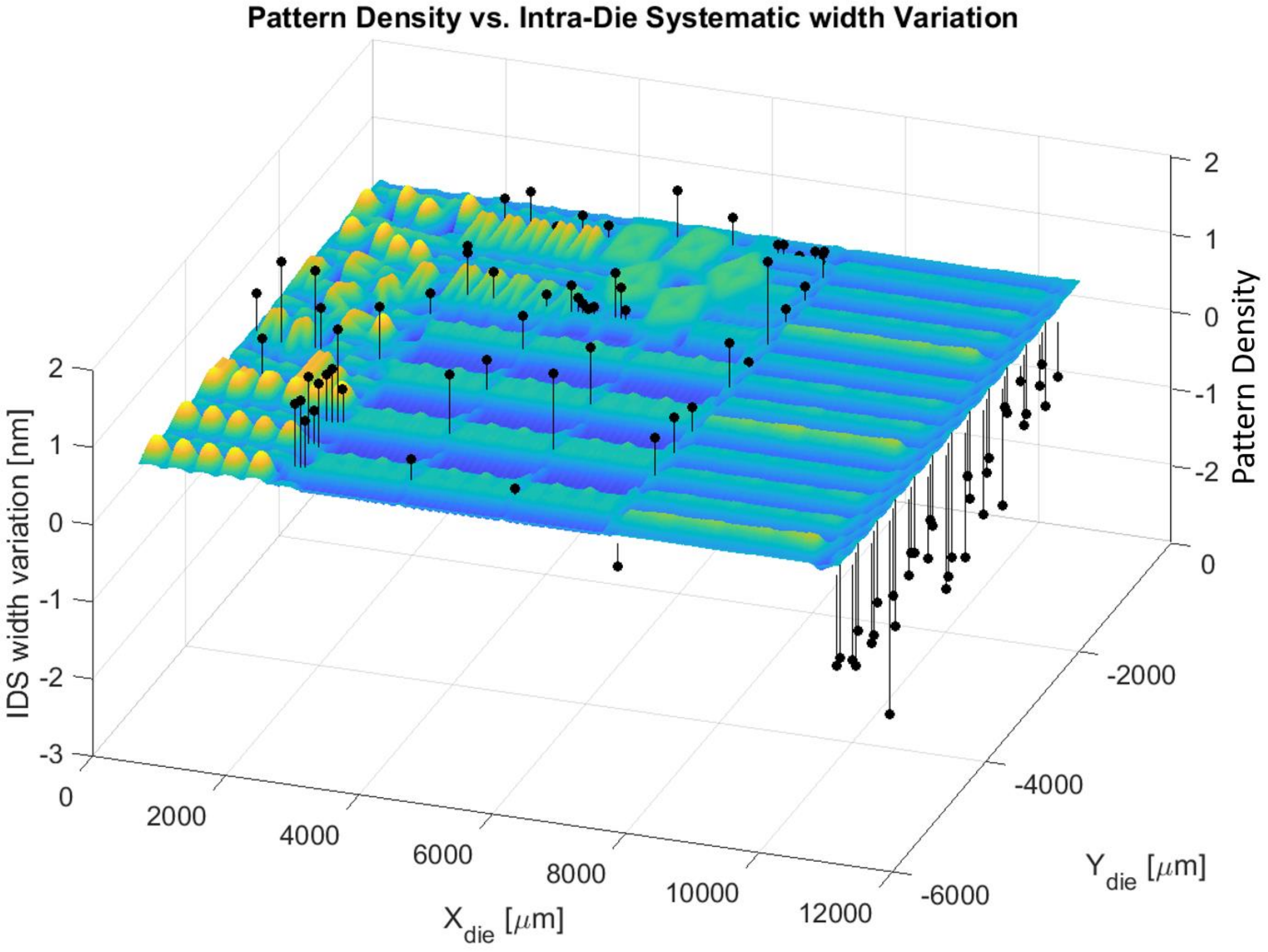
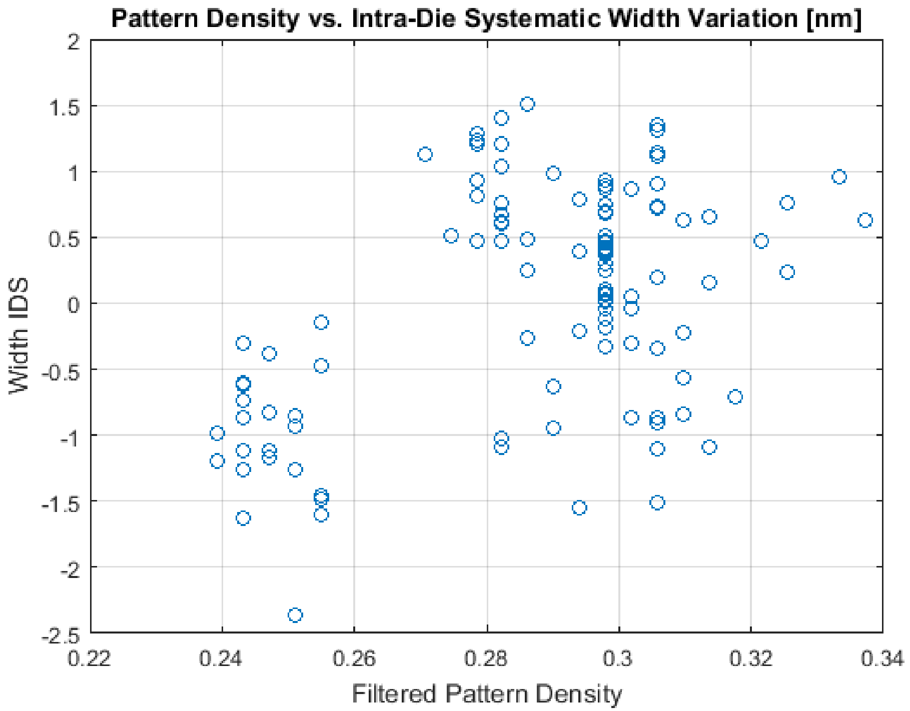
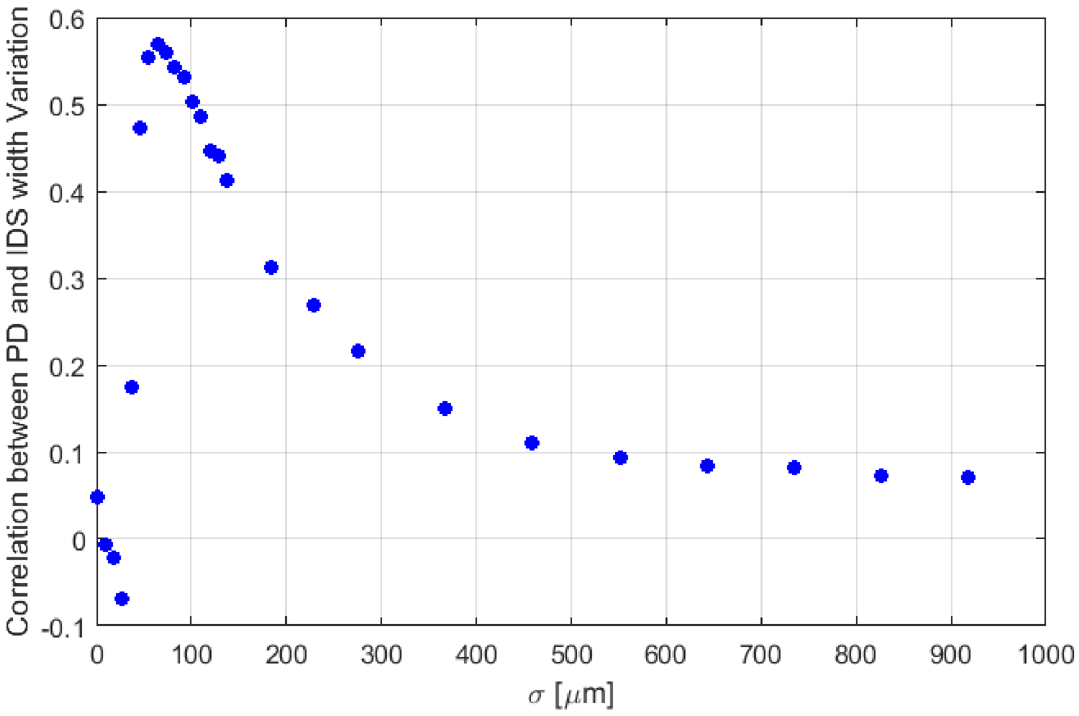
Pattern Density vs. IWS Width





CORRELATION VS GAUSSIAN FILTER RADIUS

- IDS width correlates most with the pattern density within a radius of ~200 µm (σ=69µm)
- No correlation between pattern density and the IDS thickness
- to predict photonic circuit yield
- to optimize the circuit layout to minimize the effect of local pattern density



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Monte-Carlo simulations for Yield prediction

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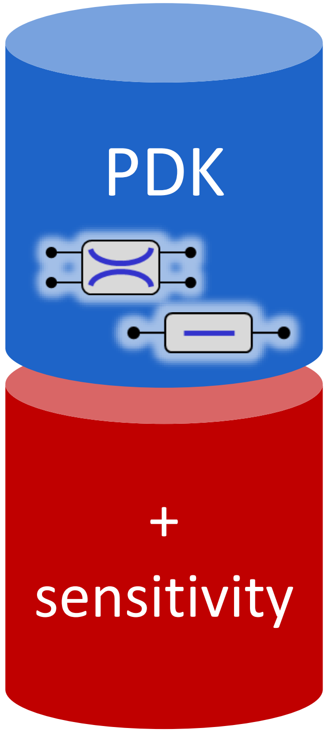
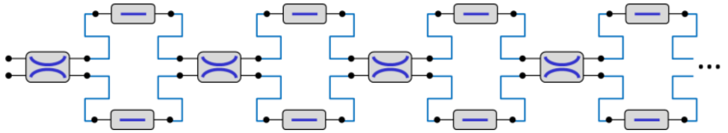
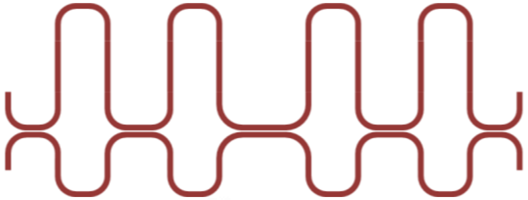
Yield Prediction scheme



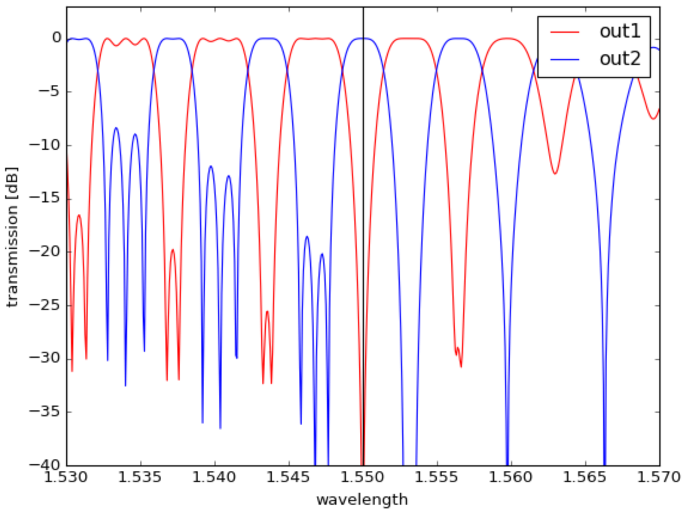
building blocks
+ models



circuit netlist + layout

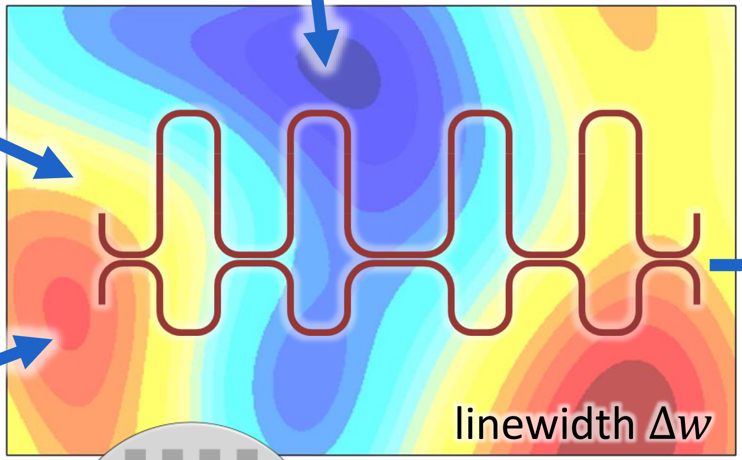


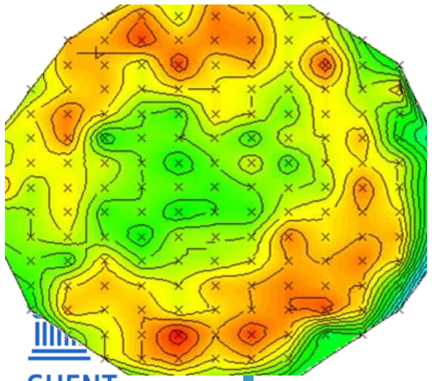
circuit simulation



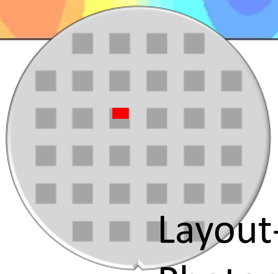
sensitivity of model parameters
to fabrication parameters

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



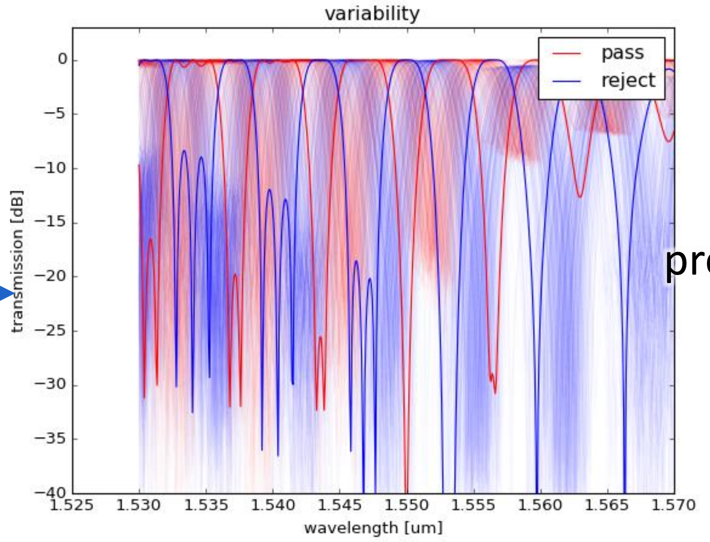


wafer maps
(or model)
for fabrication parameters



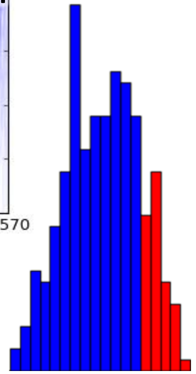
place circuit on wafer
and adjust model parameters

variability



Monte-Carlo on
dies and wafers

Yield
prediction



Layout-Aware Variability Analysis, Yield Prediction and Optimization in Silicon Photonic Circuits, W. Bogaerts et al., *JSTQE* 2019

crosstalk

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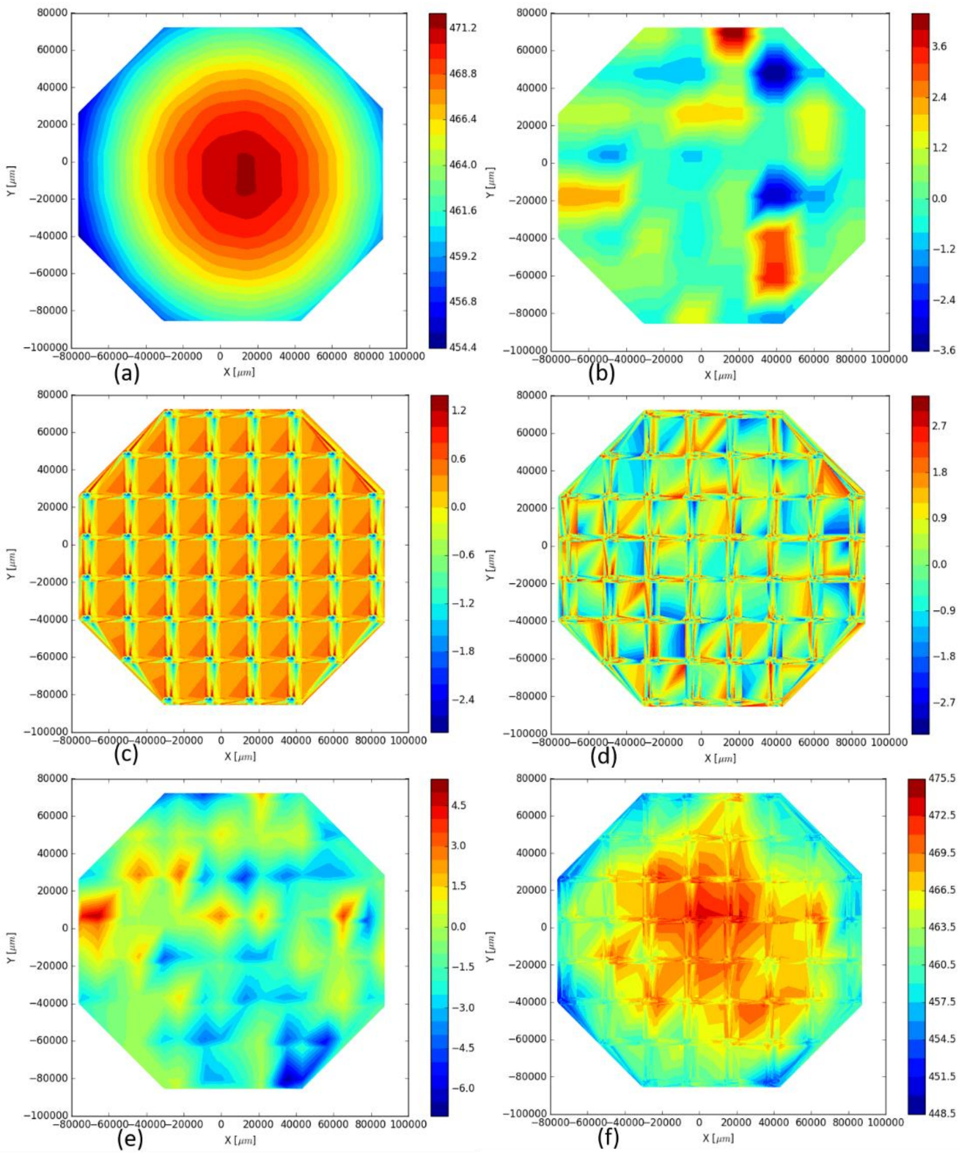
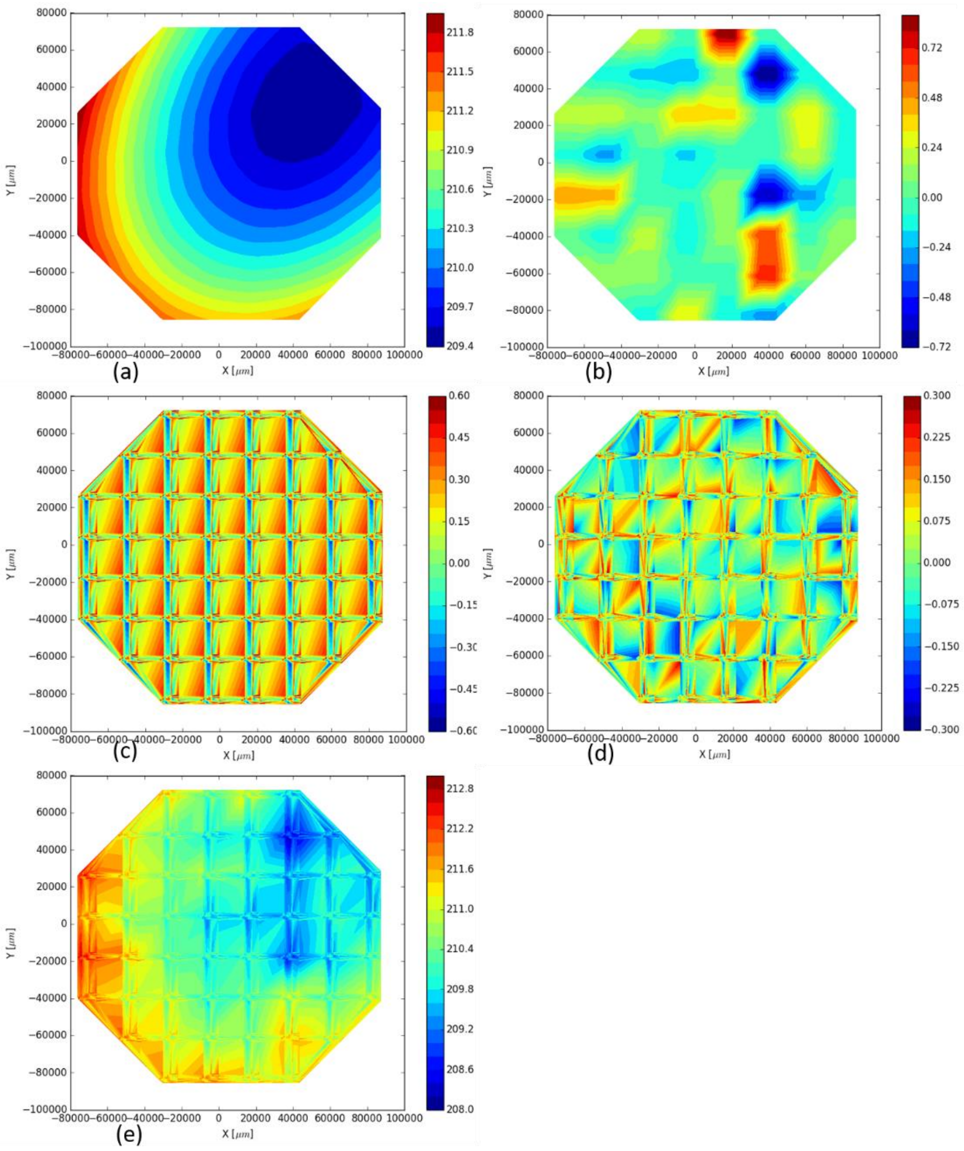
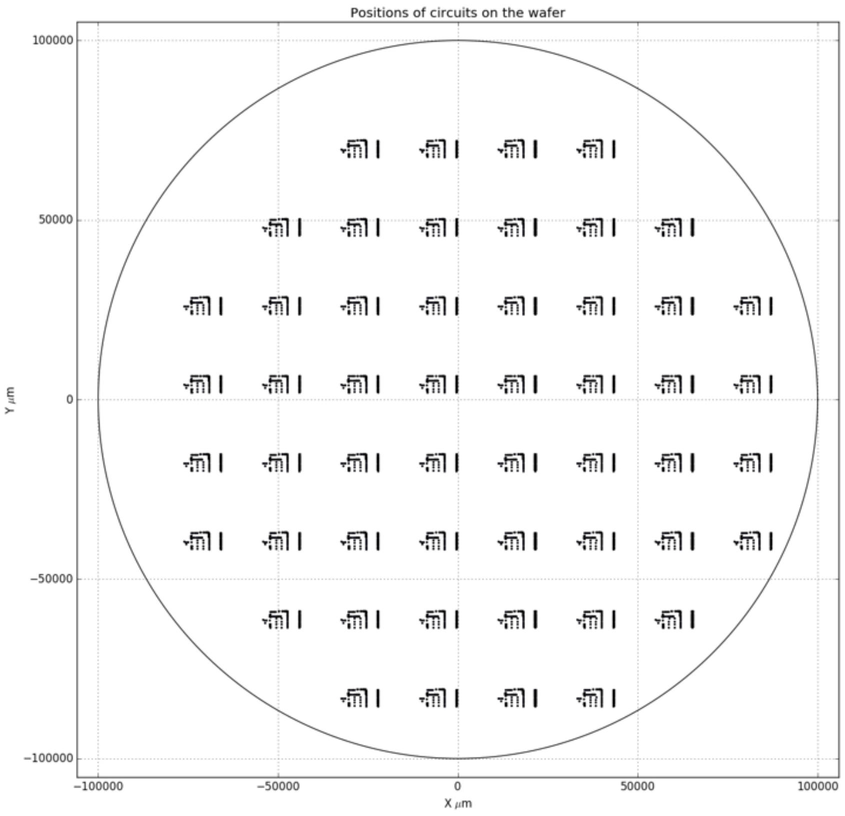
CONSTRUCT VIRTUAL WAFER MAPS

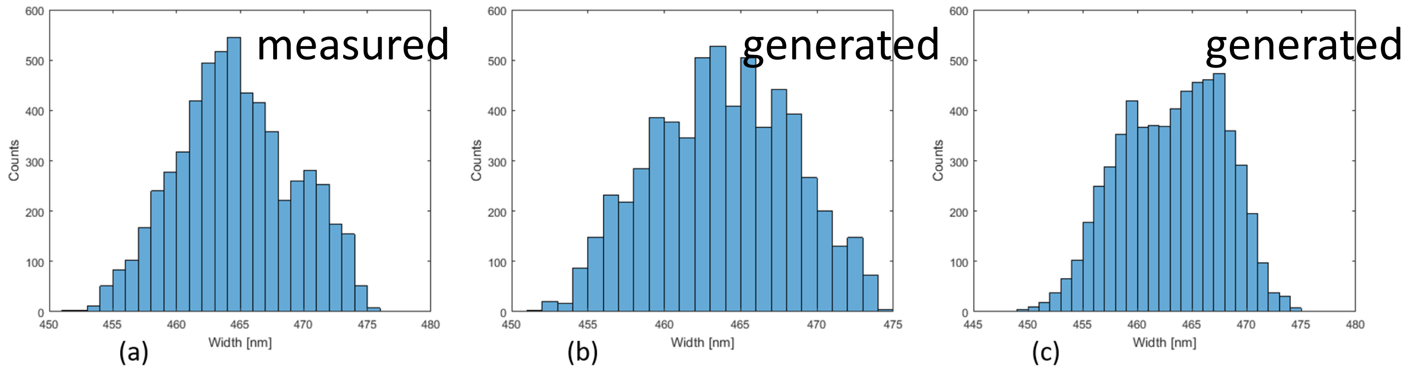


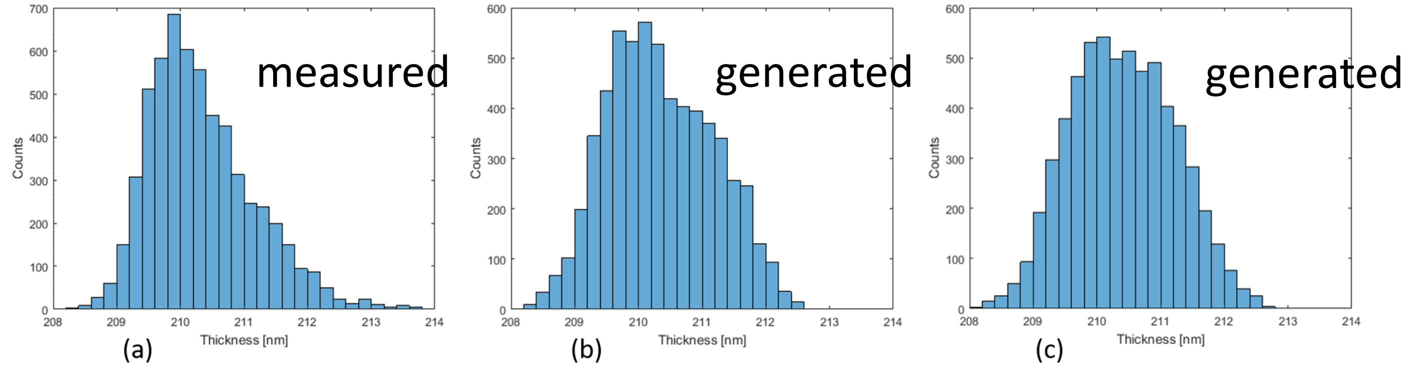
Width map



Thickness map







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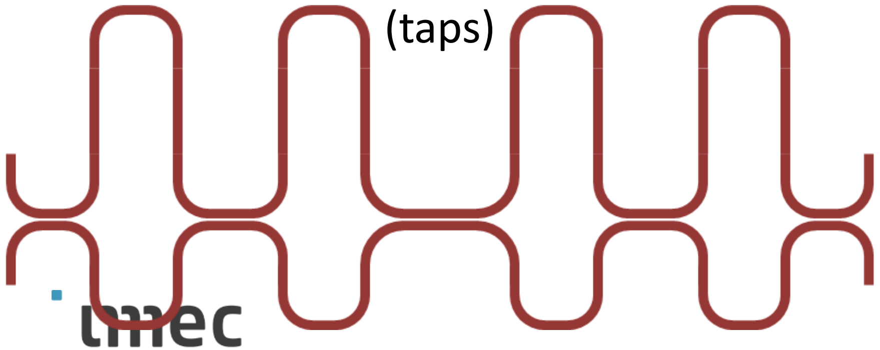
Example: MZI Lattice Filter

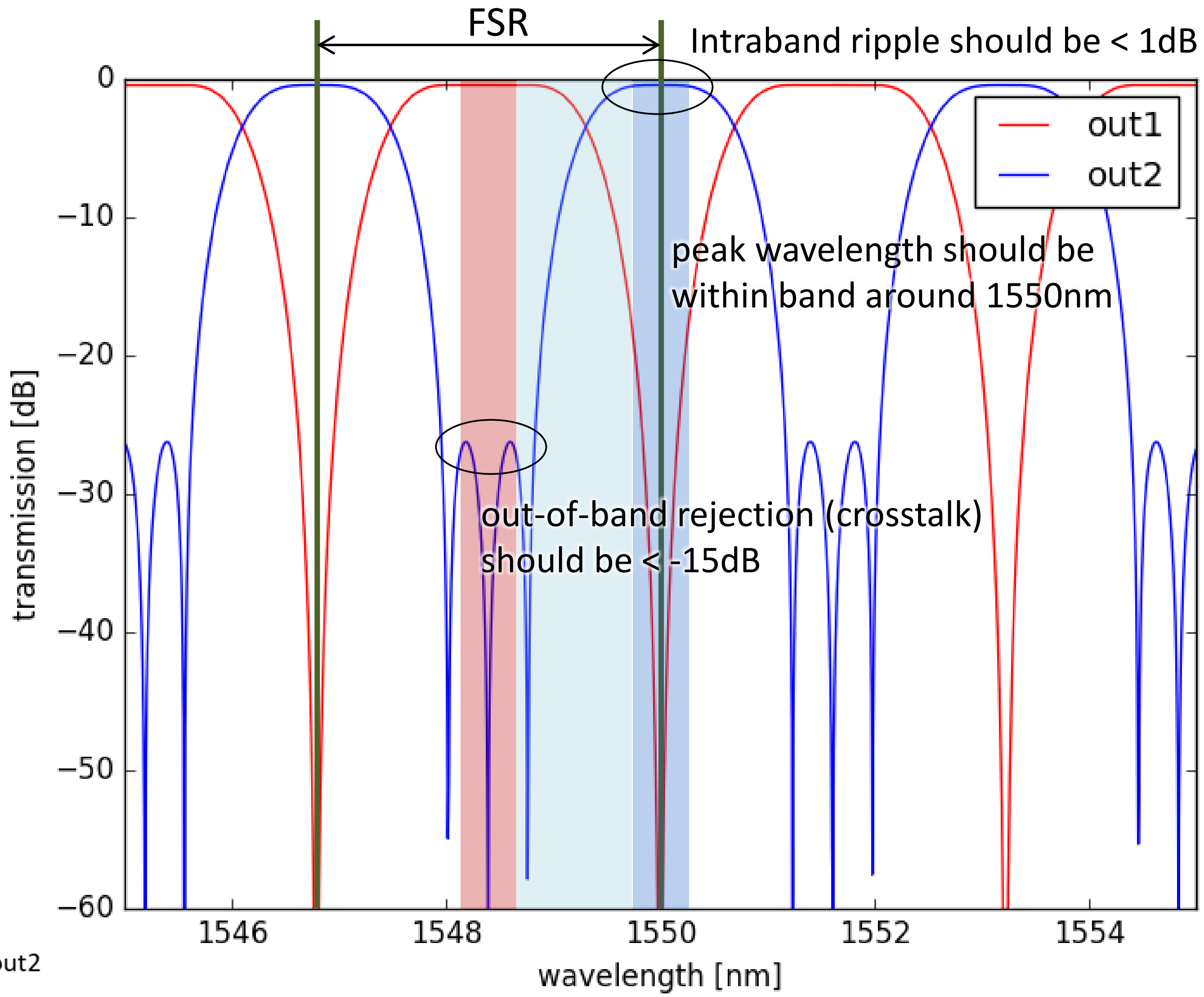
Simple (but sensitive) building blocks

- directional couplers
- waveguide delay lines

Requirements:

- peak wavelength within band
- rejection ratio
- FSR
- intraband ripple





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Filter implementation

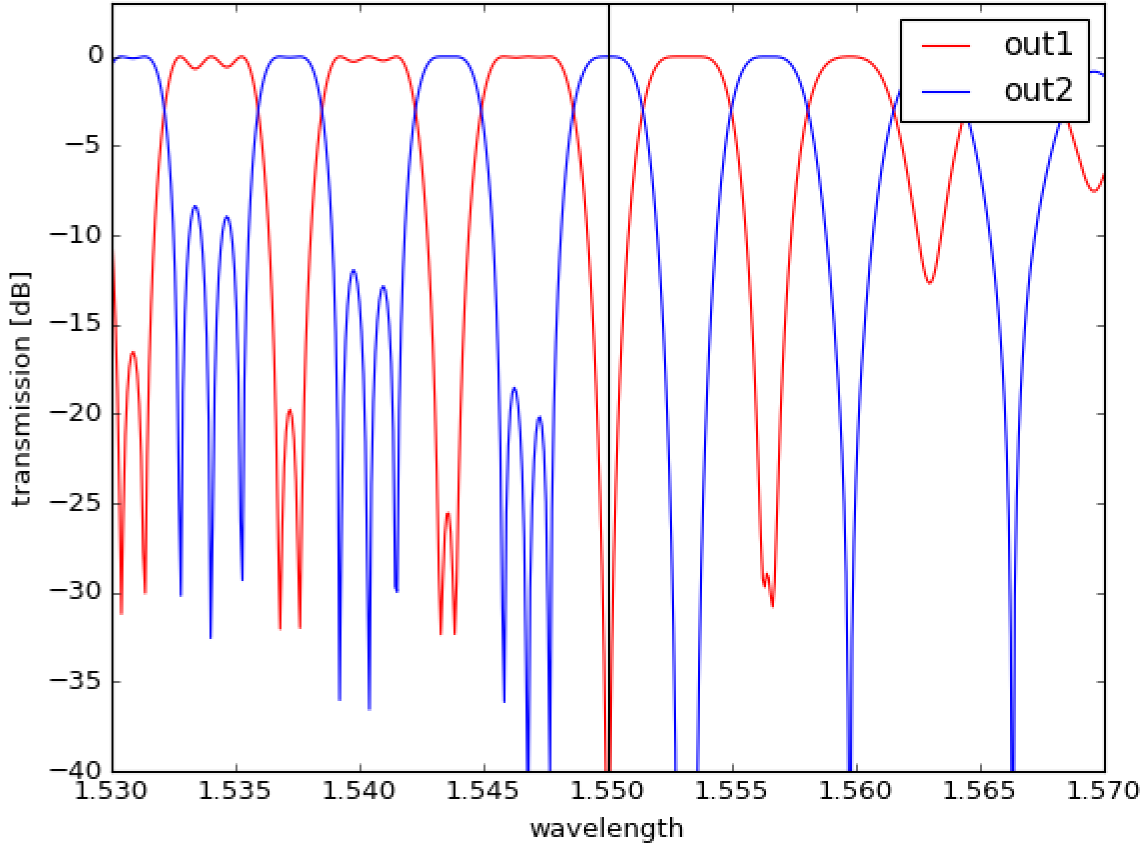
FSR = 800GHz (~6.4nm)

Pass-band = 80GHz

Guard band = 80GHz

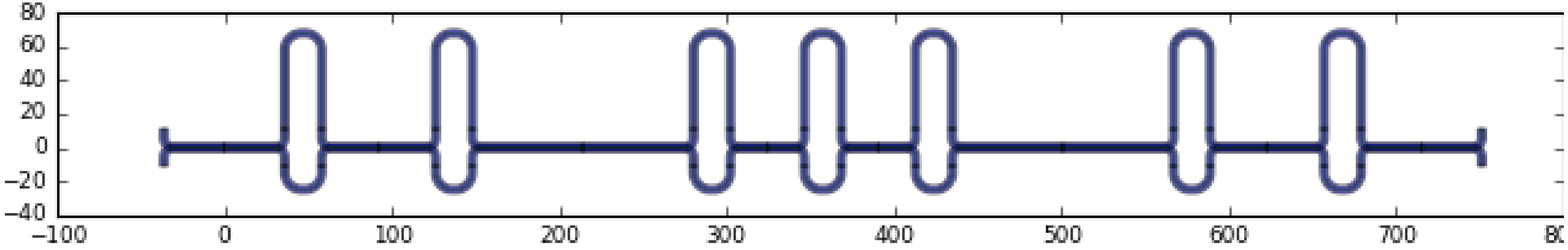
Crosstalk (rejection) = -15dB

Center wavelength = 1.55um



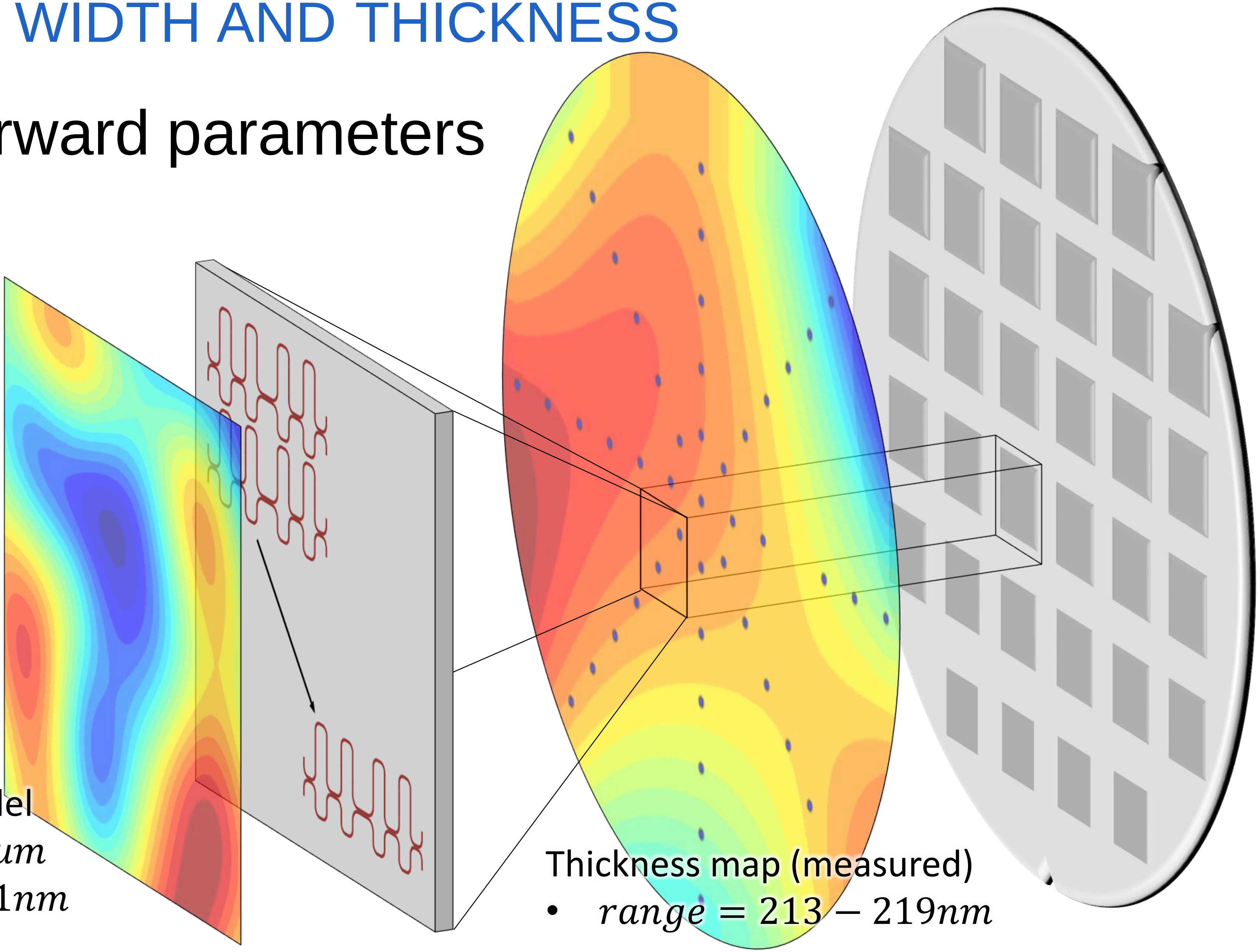
Long directional couplers

- 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)
- $range = 213 - 219nm$

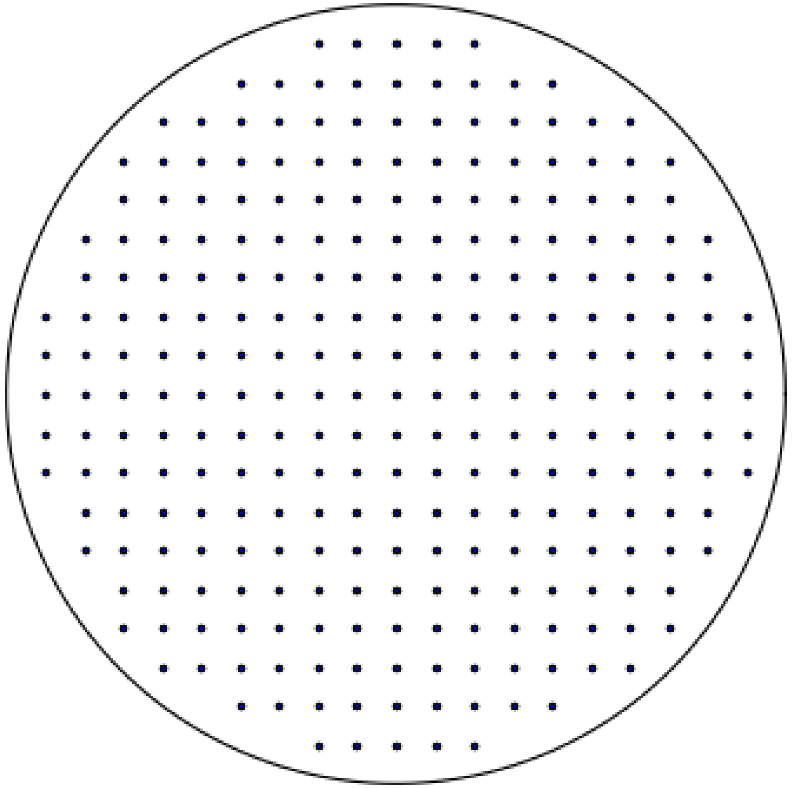
MONTE-CARLO SIMULATIONS OVER A WAFER

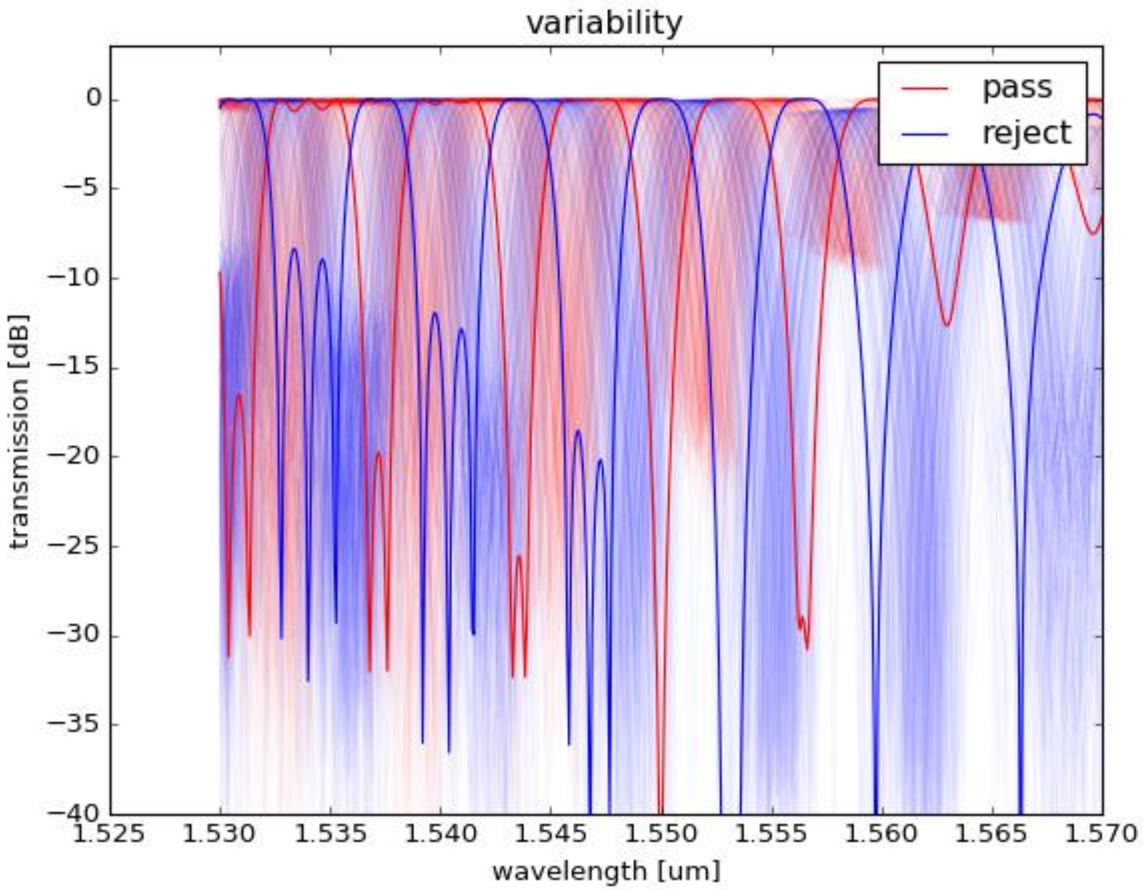
10mm spacing

277 dies on a wafer

Using CAPHE circuit simulator (Luceda)

1000 wavelength points



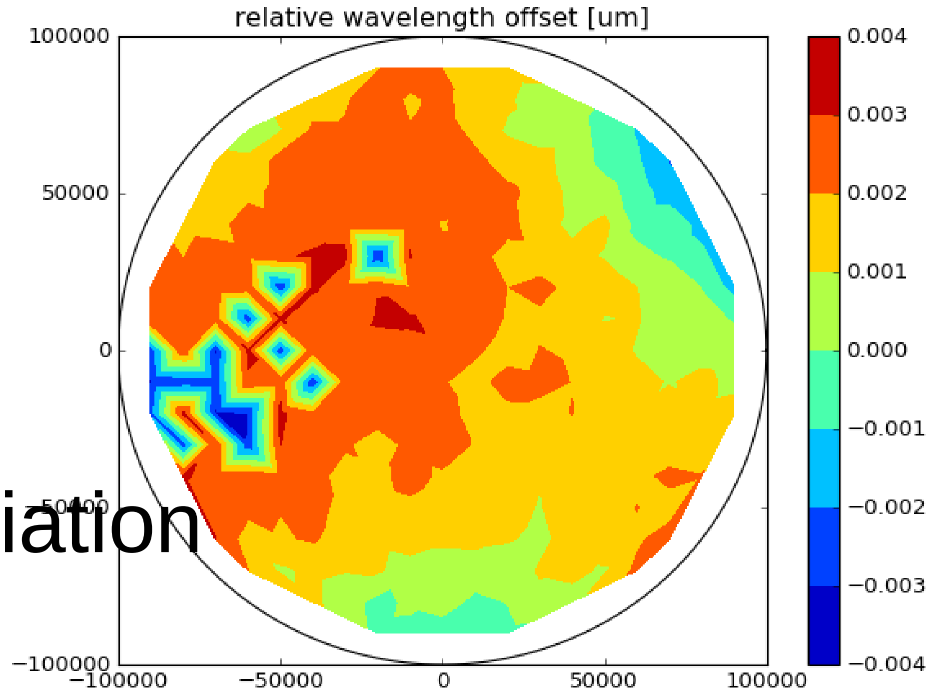


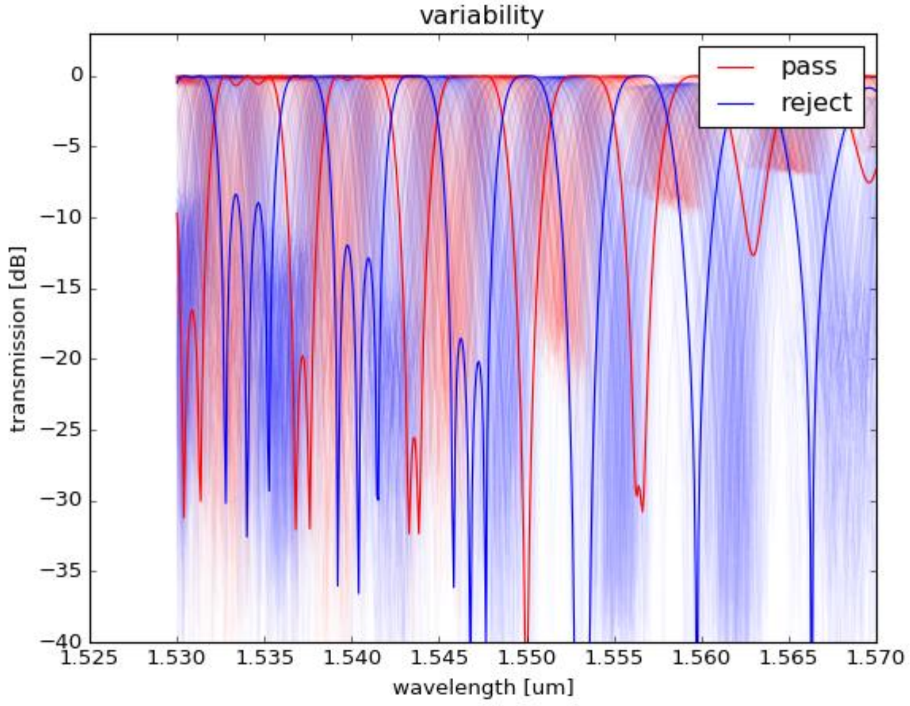
ANALYZE YIELD: PEAK WAVELENGTH

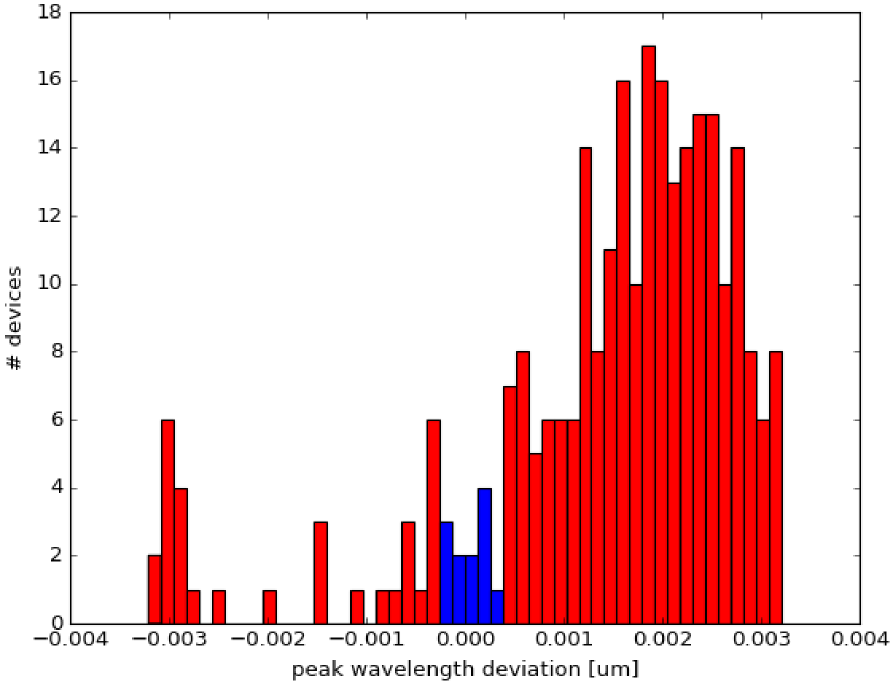
Spec = 1.55µm ± 80 GHz

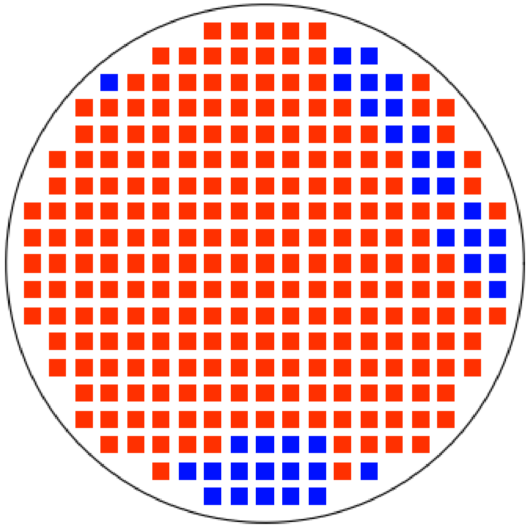
Very poor yield on this spec:

strong shift mostly due to thickness variation









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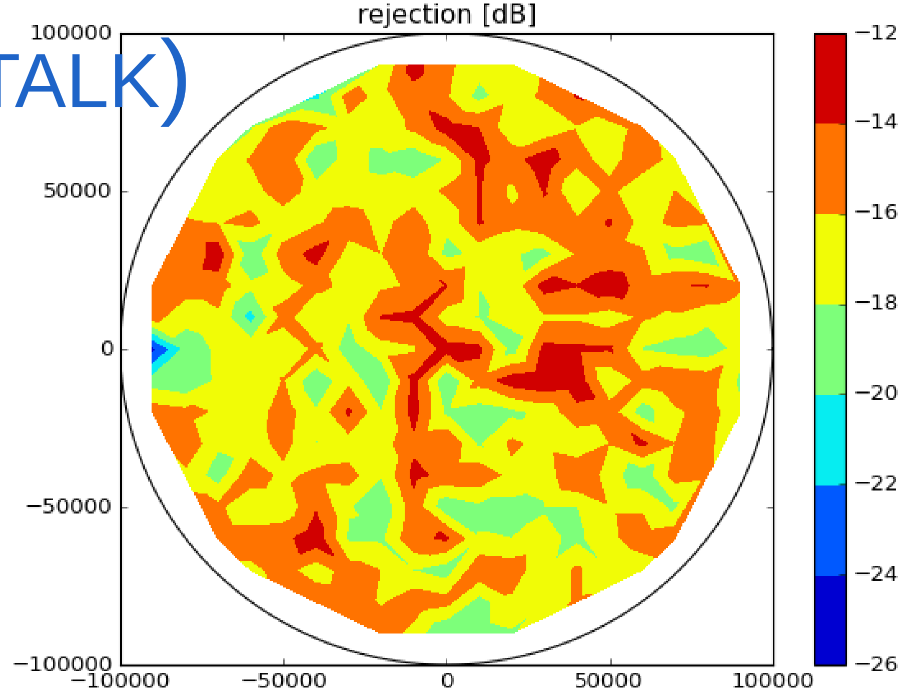
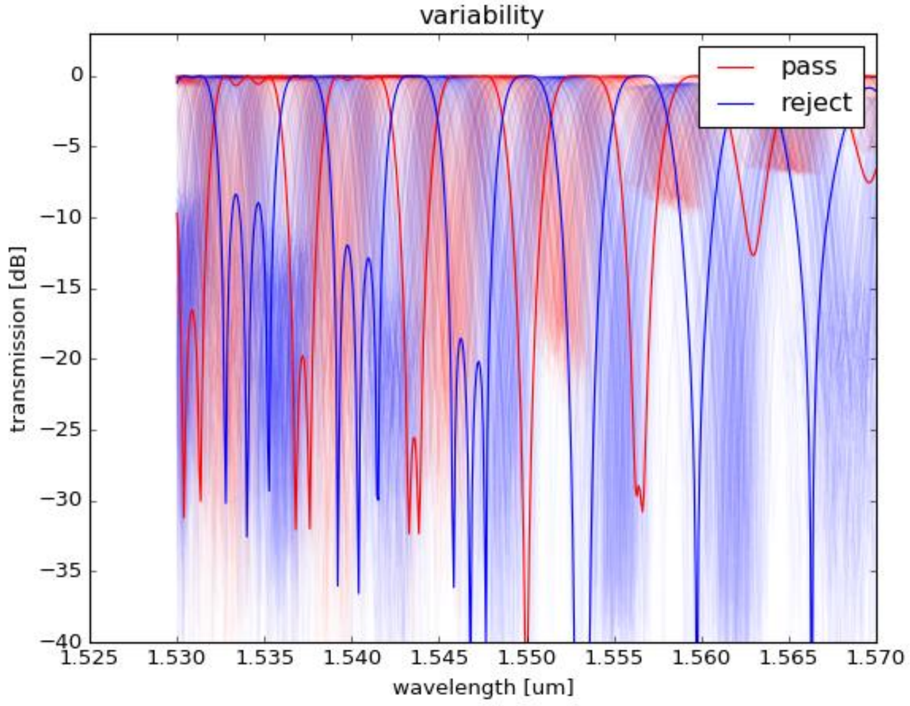
Analyze yield: Rejection (crosstalk)

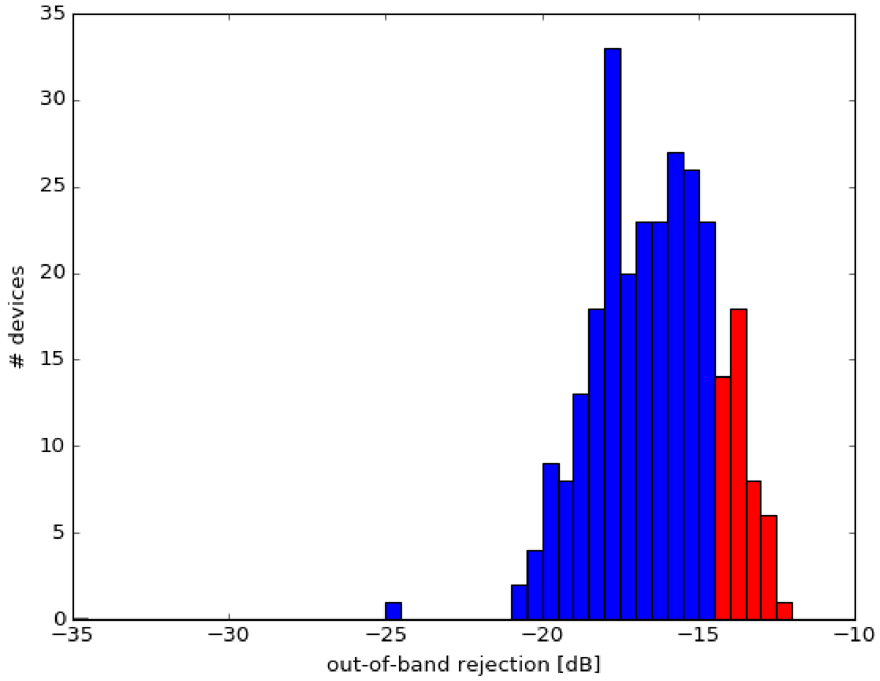
Spec = -15dB

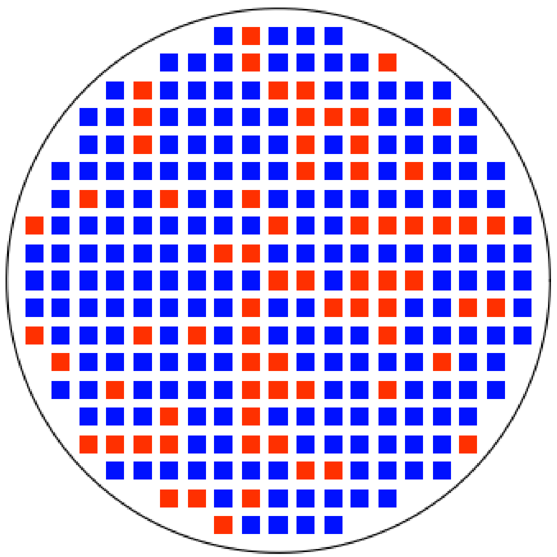
Decent yield on this spec:

Mostly influenced by the couplers





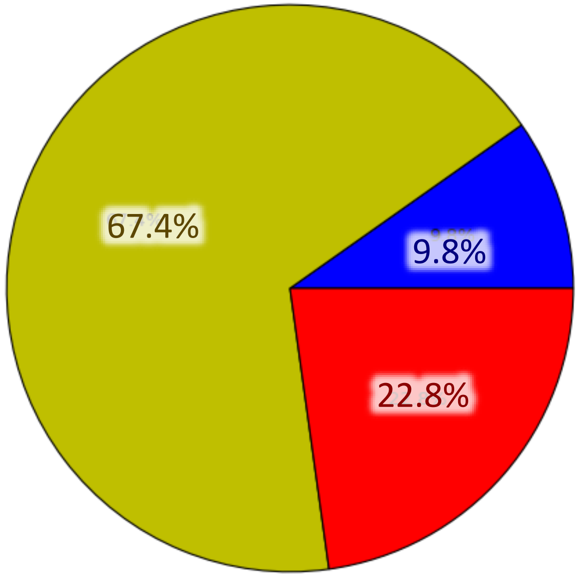


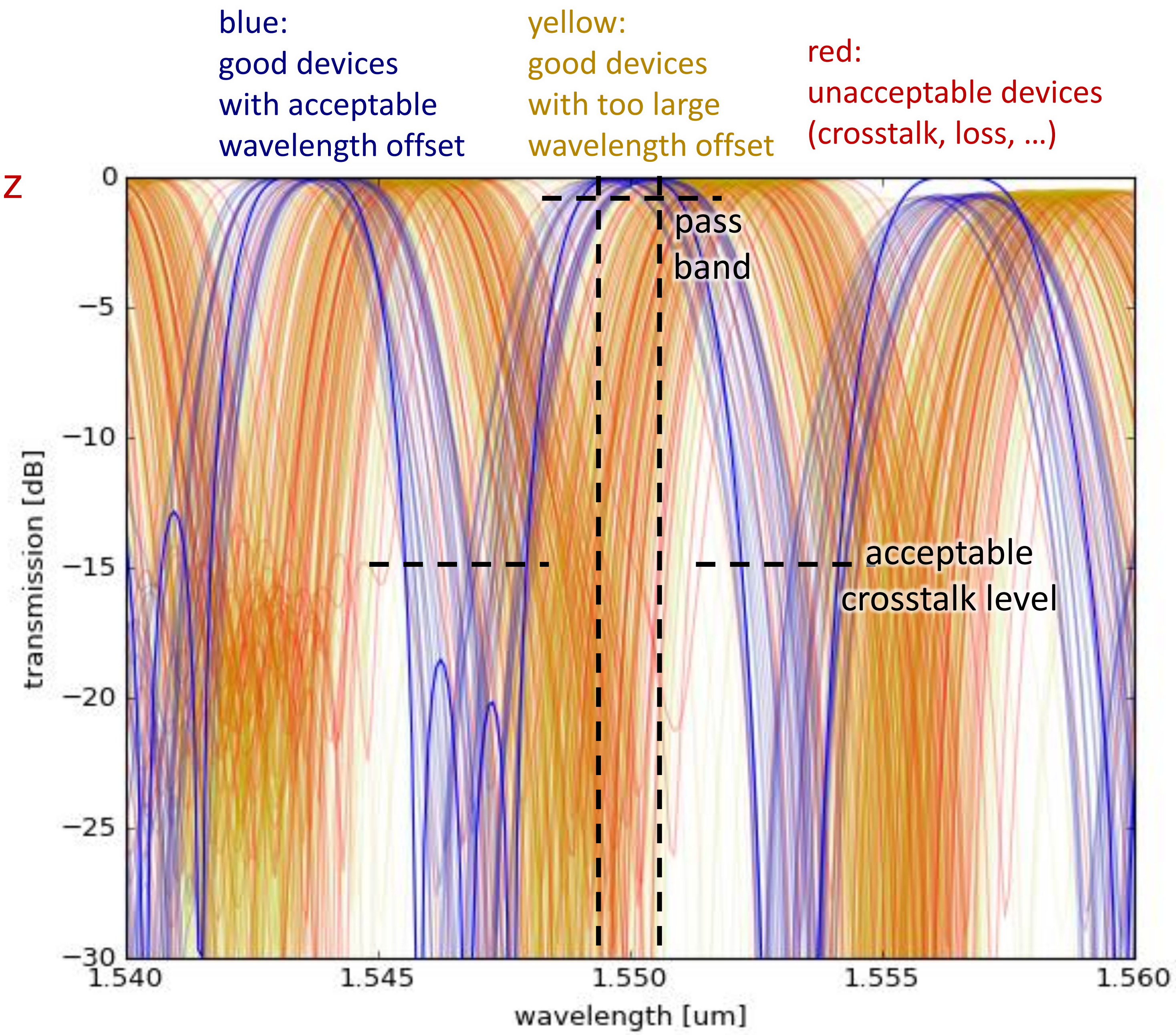


OVERALL YIELD

All specs combined:

- Center wavelength = 1.55µm ± 80 GHz
- Crosstalk (rejection) = -15dB
- Intraband ripple = 1dB
- FSR = 800GHz ± 40GHz
- Peak insertion loss > -1dB

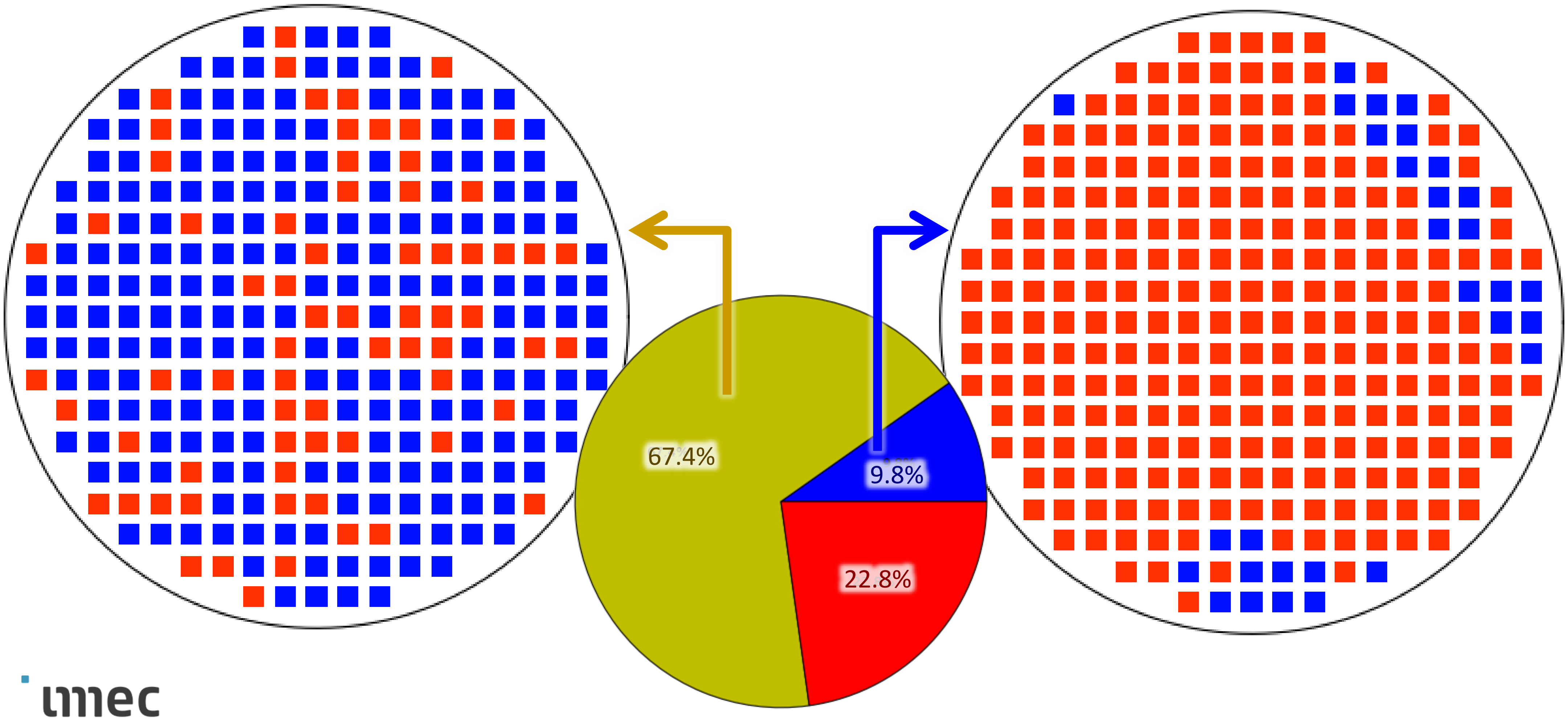




Yield maps

Without absolute wavelength spec

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

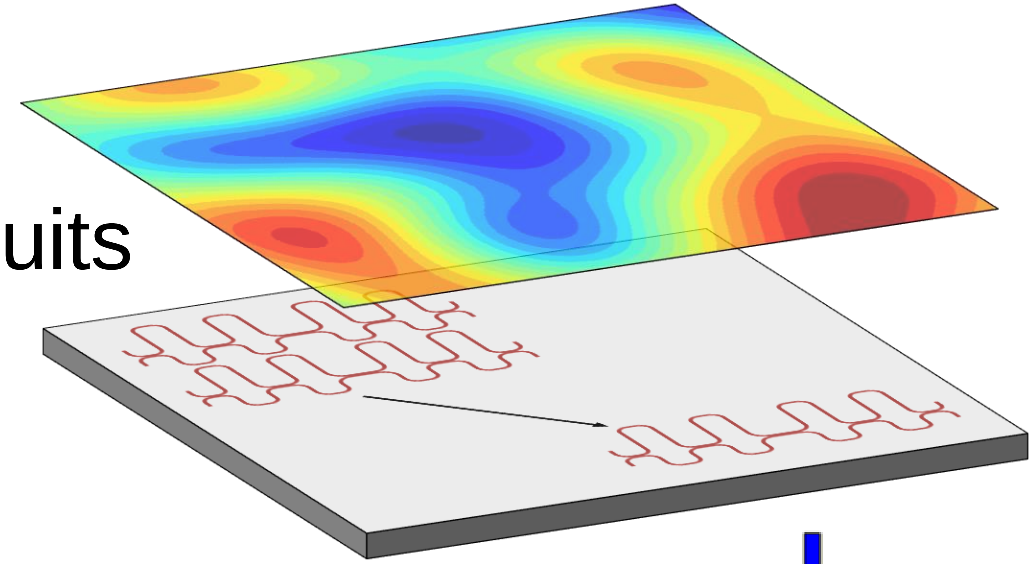


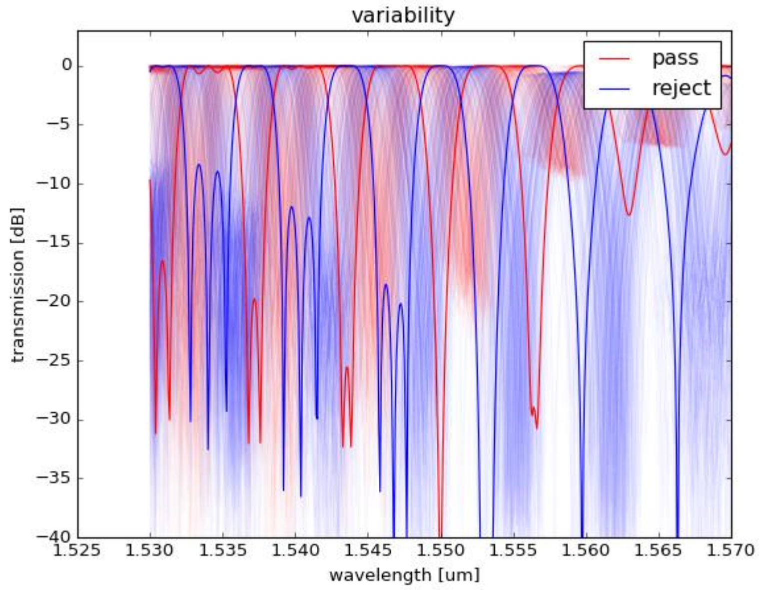
SUMMARY

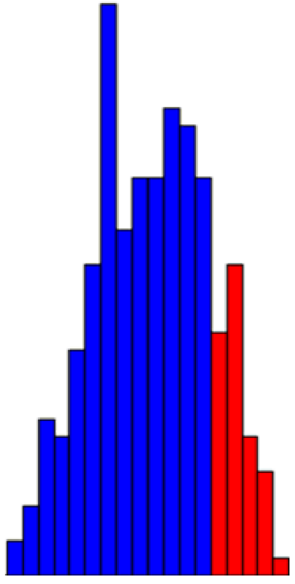
Variability determines the yield of circuits

Need layout-aware yield prediction

- Accurate parameter extraction
- Realistic variation model
- Layout-aware yield prediction







What have we done?

Parameter Extraction

- Extracted of waveguide and DC parameters
- Extracted of linewidth and thickness
- Improved extraction methods to be tolerant to process variations and spectral fringes and noise

Hierarchical spatial variability model

- Established workflow to separate variations
- Found correlation between pattern density and IDS width variation

Yield prediction

- Accelerated variability analysis using stochastic analysis methods
- Generated virtual wafer maps for realistic yield estimation

Many thanks to…

PHOTONICS RESEARCH GROUP

- the FWO project
- the MEPIC project
- Luceda Photonics

- Wim and the complete *photonics*-group
- The people in SUMO group involved in variability analysis

fwo grant G013815N

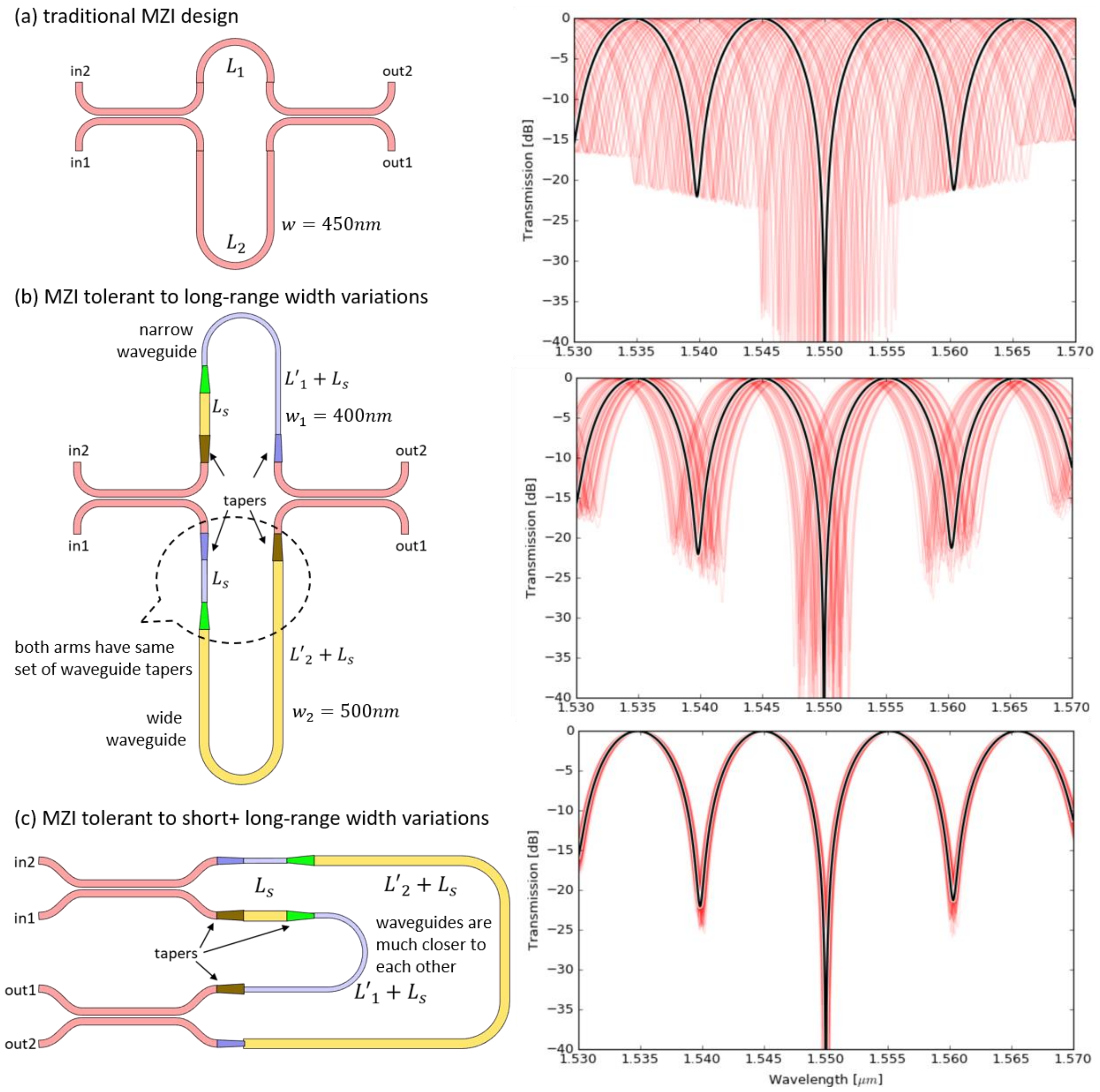
AGENTSCHAP INNOVEREN & ONDERNEMEN MEPIC project

LUCEDA PHOTONICS

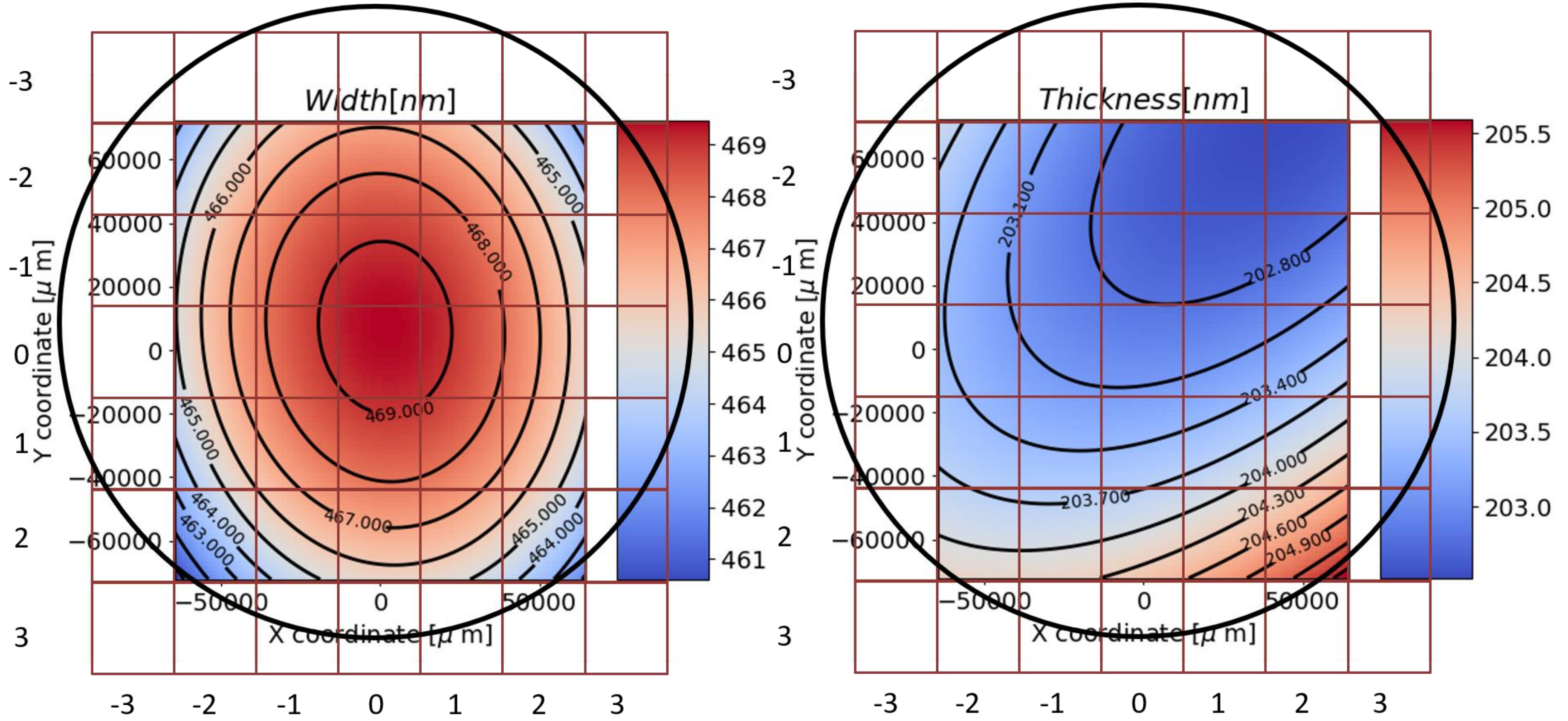
erc European Research Council

ANY QUESTIONS?...

Tolerant MZI design

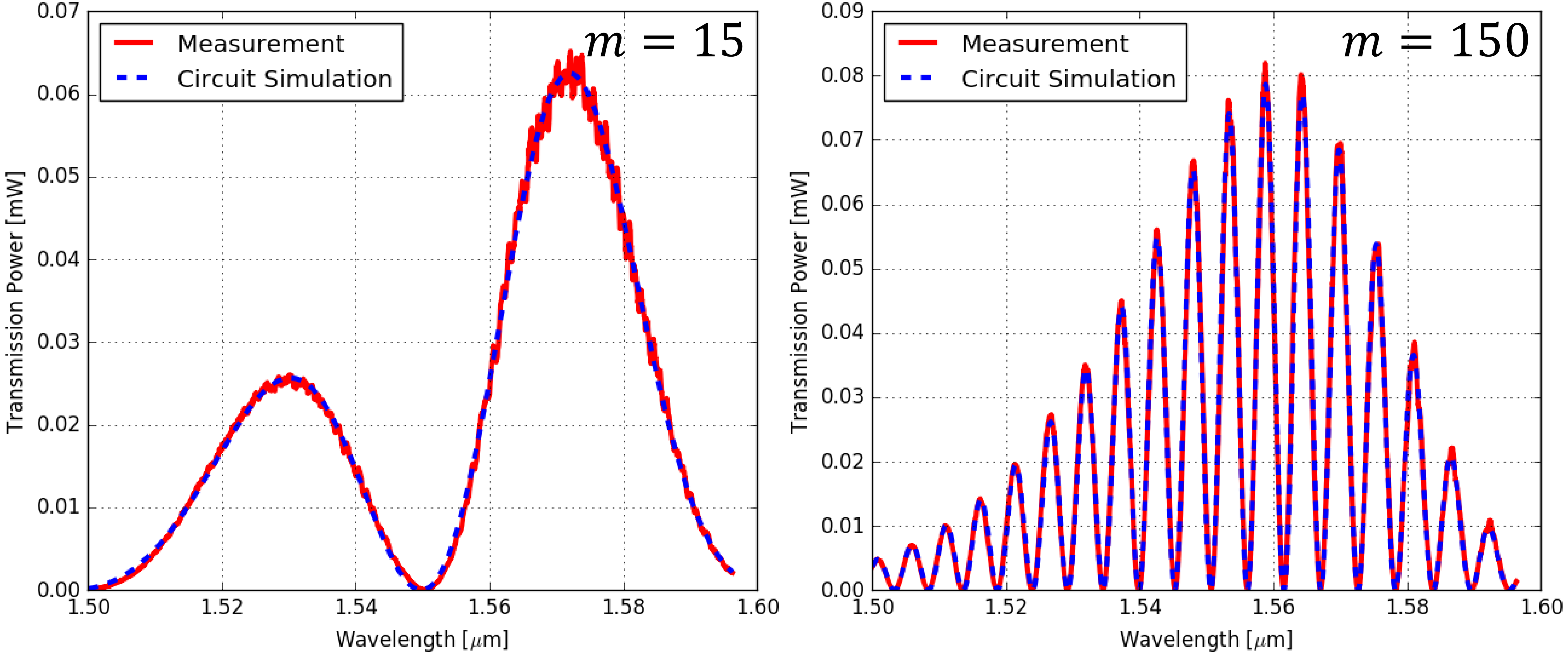


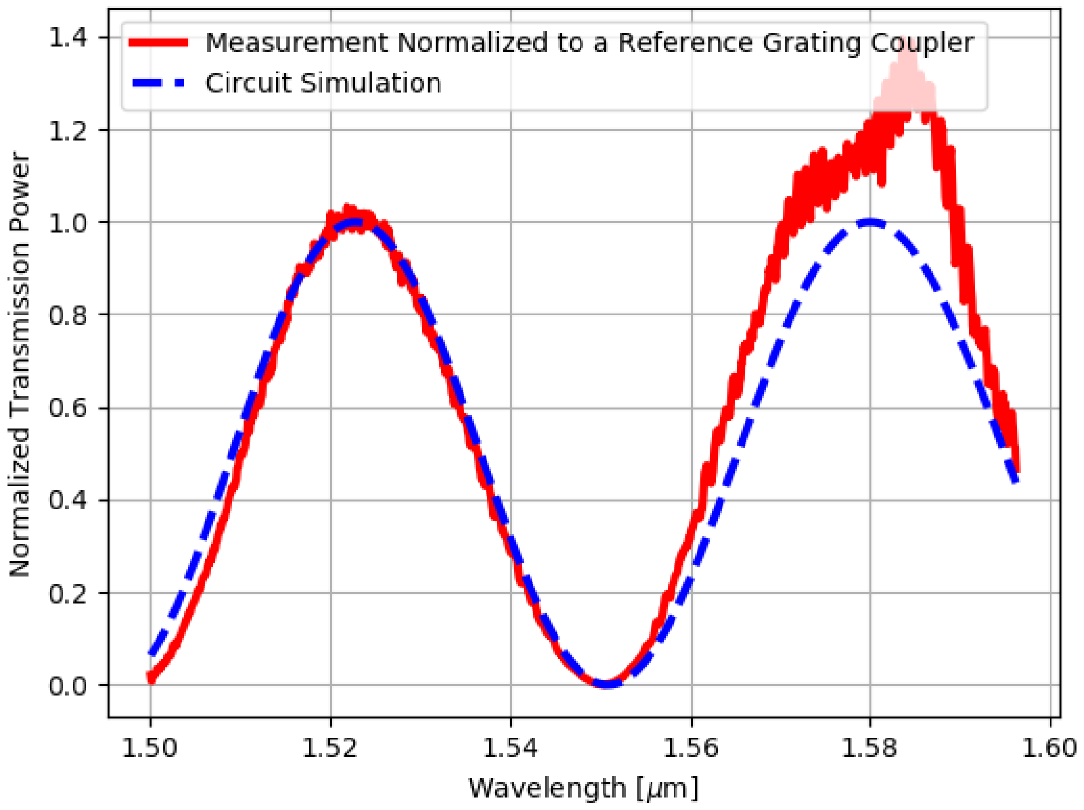
Systematic intra-wafer variation

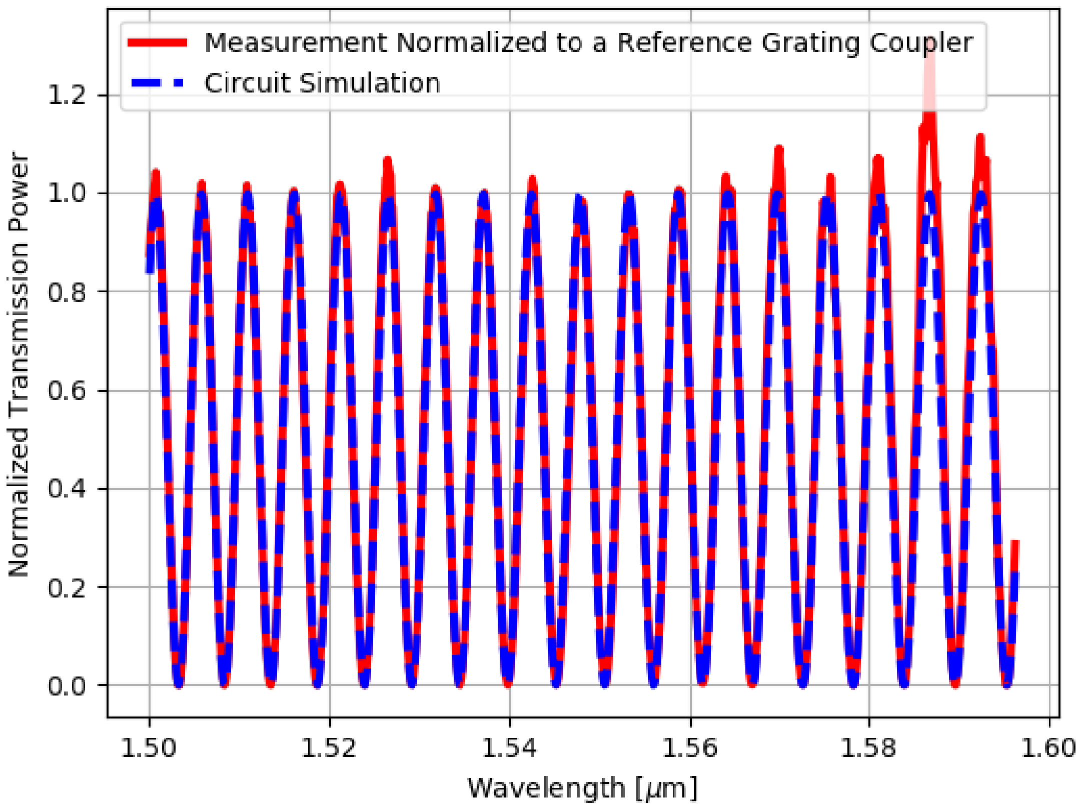


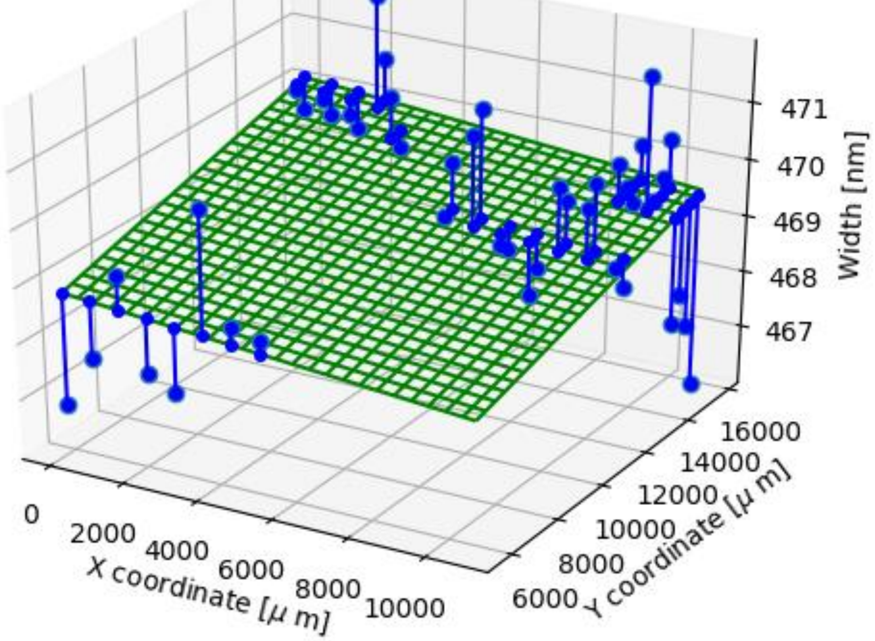
	Systematic intra-wafer (Max-Min)
Linewidth [nm]	8.5
Thickness [nm]	3.0

Xing et al., GFP 2018


Measurement
Circuit Simulation
$m = 15$
Transmission Power [mW]
Wavelength [μm]
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
1.50
1.52
1.54
1.56
1.58
1.60
Measurement
Circuit Simulation
$m = 150$
Transmission Power [mW]
Wavelength [μm]
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
1.50
1.52
1.54
1.56
1.58
1.60

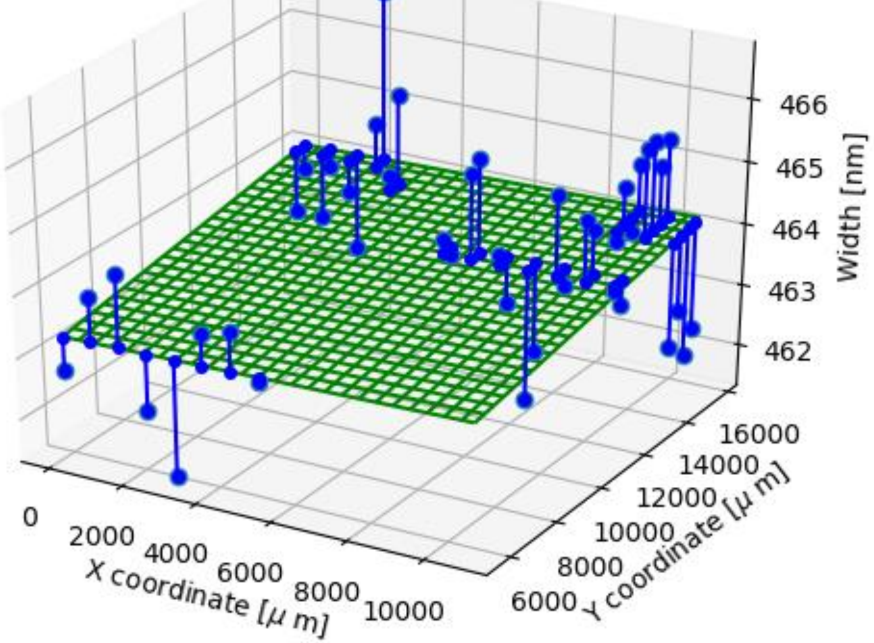

Measurement Normalized to a Reference Grating Coupler
Circuit Simulation
Normalized Transmission Power
Wavelength [μm]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.50
1.52
1.54
1.56
1.58
1.60


Measurement Normalized to a Reference Grating Coupler
Circuit Simulation
Normalized Transmission Power
Wavelength [μm]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.50
1.52
1.54
1.56
1.58
1.60



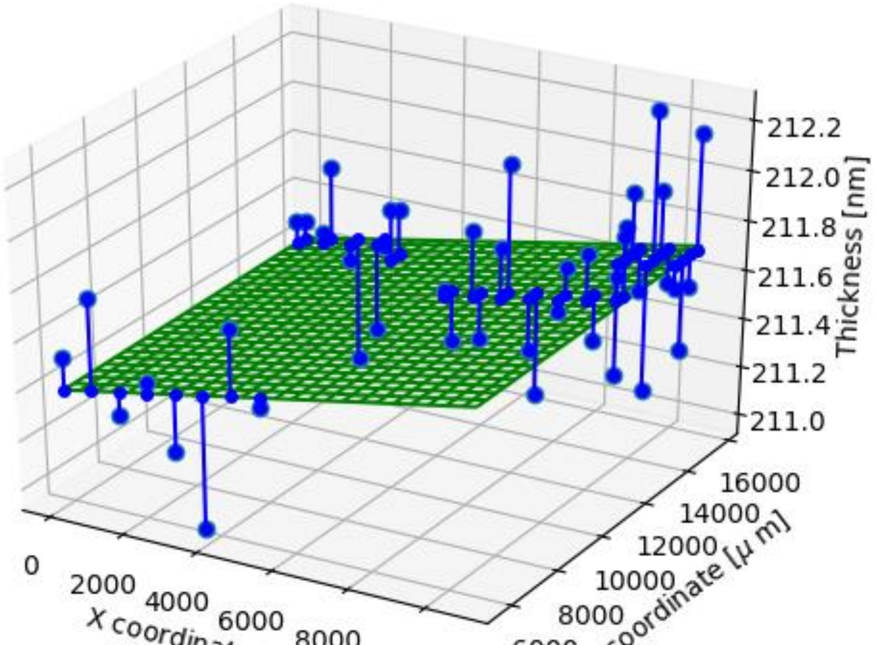
471
470
469
468
467
Width [nm]
16000
14000
12000
10000
8000
6000
Y coordinate [μ m]
0
2000
4000
6000
8000
10000
X coordinate [μ m]

(a)

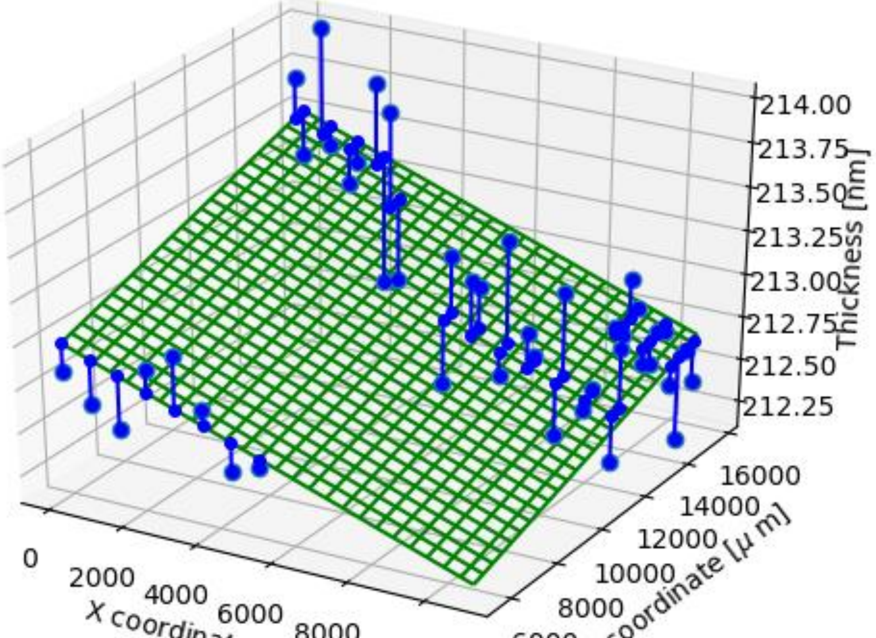


466
465
464
463
462
Width [nm]
16000
14000
12000
10000
8000
6000
Y coordinate [μ m]
0
2000
4000
6000
8000
10000
X coordinate [μ m]

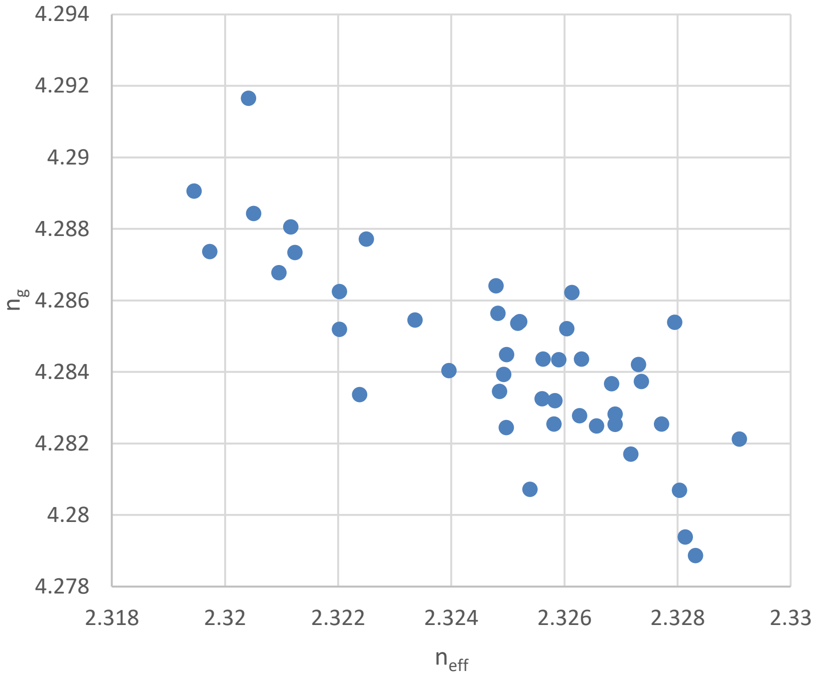
(c)



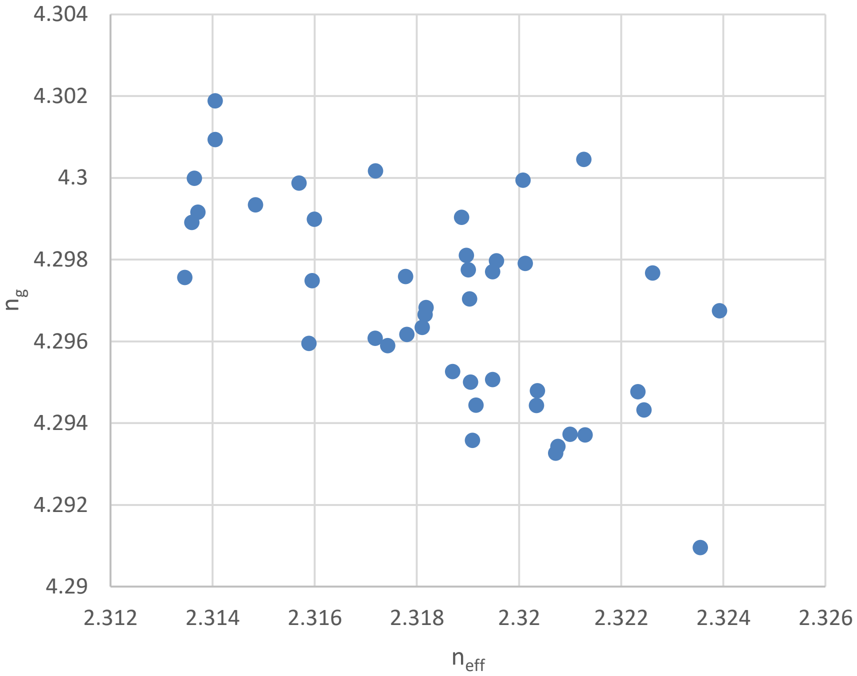
212.2
212.0
211.8
211.6
211.4
211.2
211.0
Thickness [nm]
16000
14000
12000
10000
8000
0
2000
4000
6000
8000



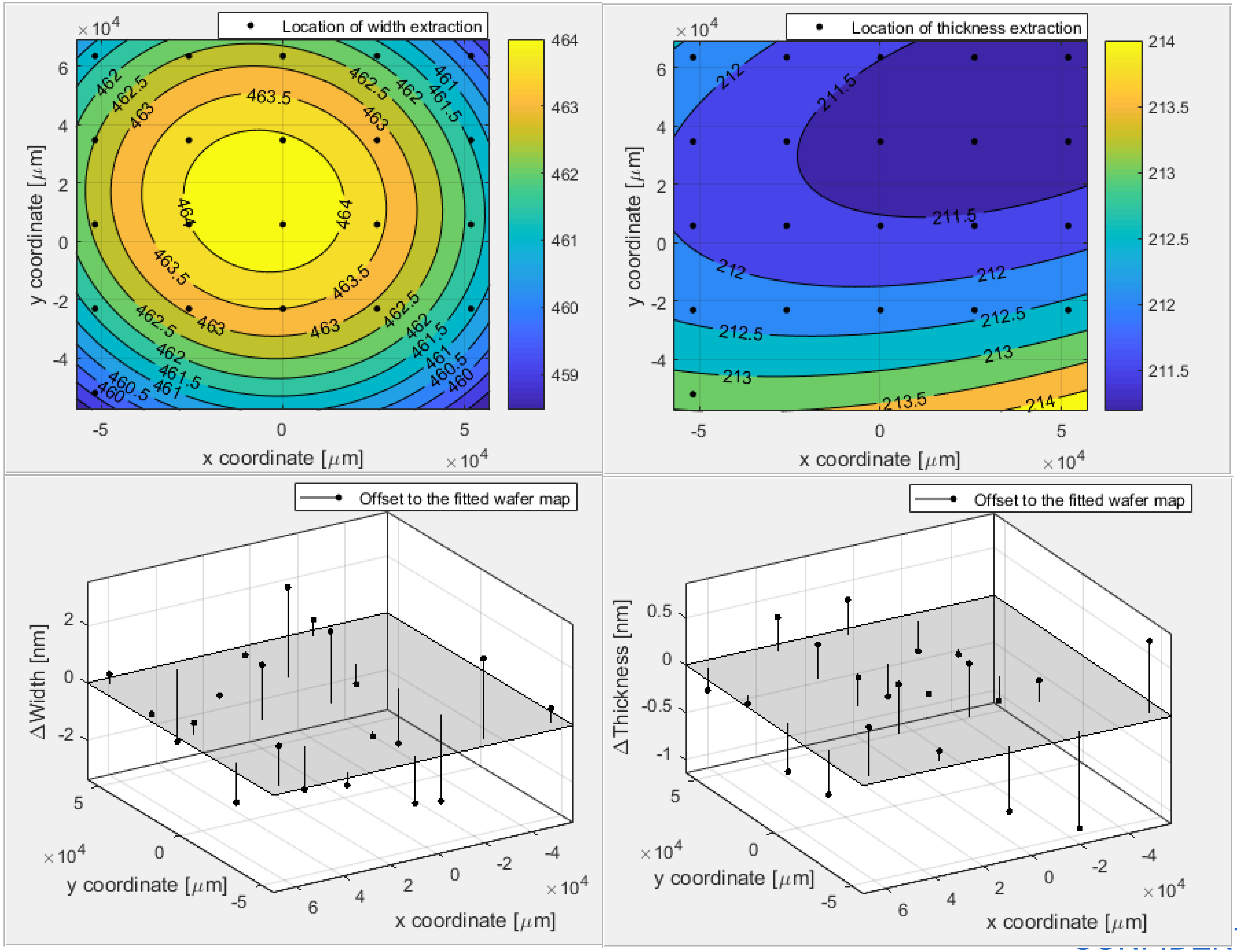
214.00
213.75
213.50
213.25
213.00
212.75
212.50
212.25
Thickness [nm]
16000
14000
12000
10000
8000
0
2000
4000
6000
8000

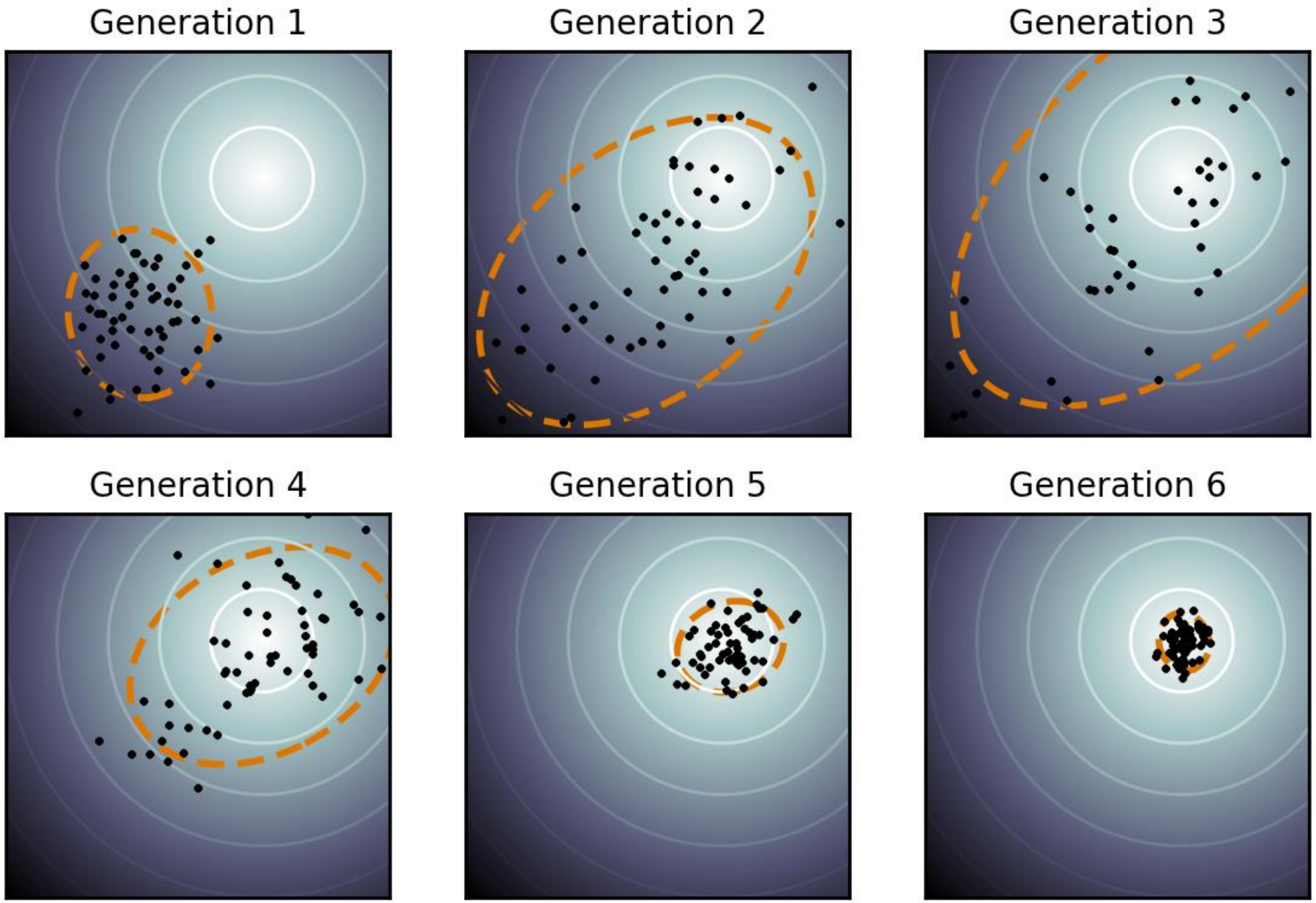


4.294
4.292
4.29
4.288
4.286
4.284
4.282
4.28
4.278
n_g
2.318
2.32
2.322
2.324
2.326
2.328
2.33
n_{eff}

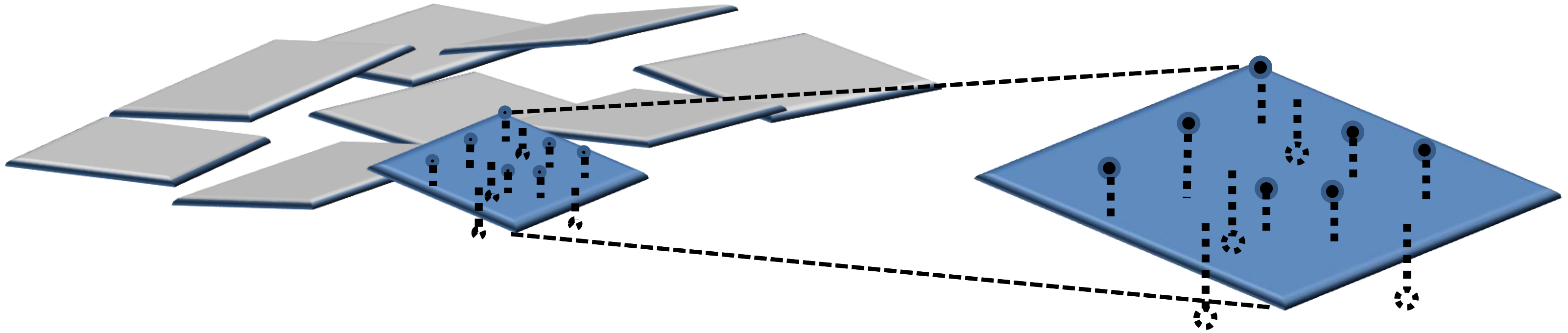


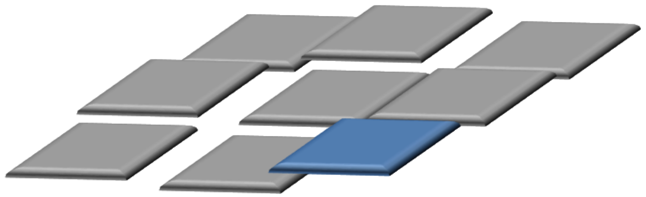
4.304
4.302
4.3
4.298
4.296
4.294
4.292
4.29
n_g
2.312
2.314
2.316
2.318
2.32
2.322
2.324
2.326
n_{eff}


Location of width extraction
Location of thickness extraction
y coordinate [μm]
x coordinate [μm]
Offset to the fitted wafer map
Offset to the fitted wafer map
ΔWidth [nm]
ΔThickness [nm]
y coordinate [μm]
x coordinate [μm]

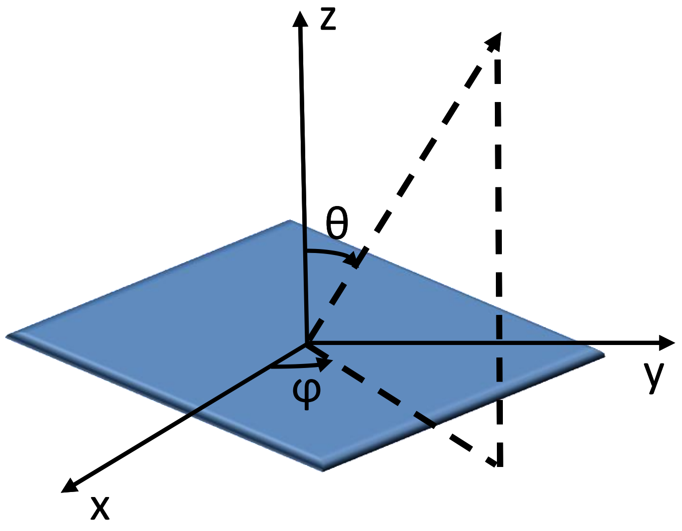


Generation 1
Generation 2
Generation 3
Generation 4
Generation 5
Generation 6

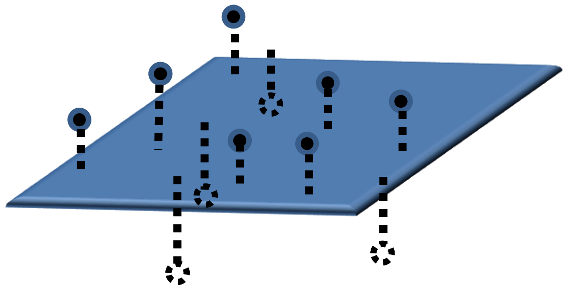




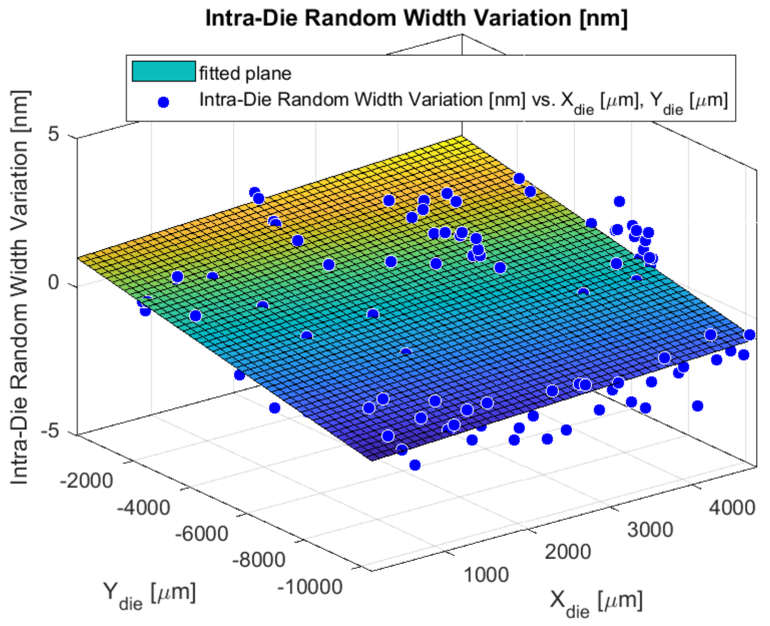
IWR

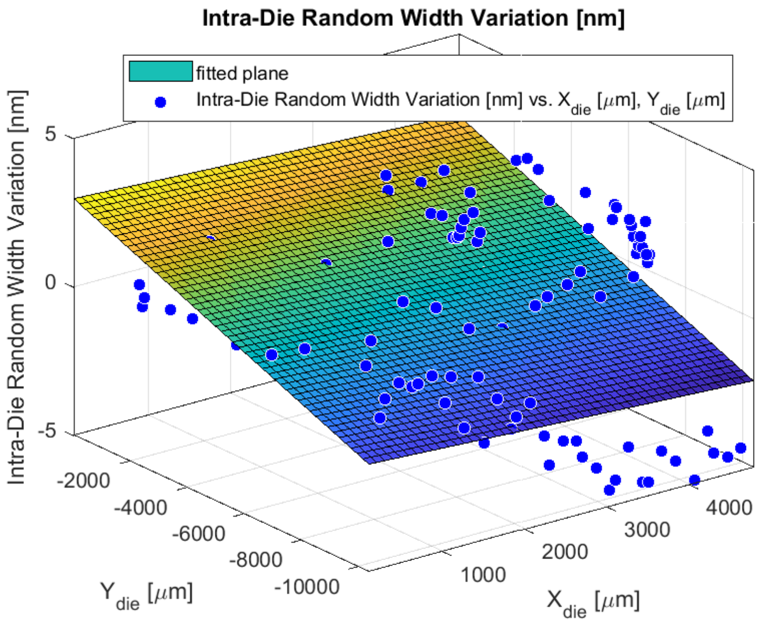


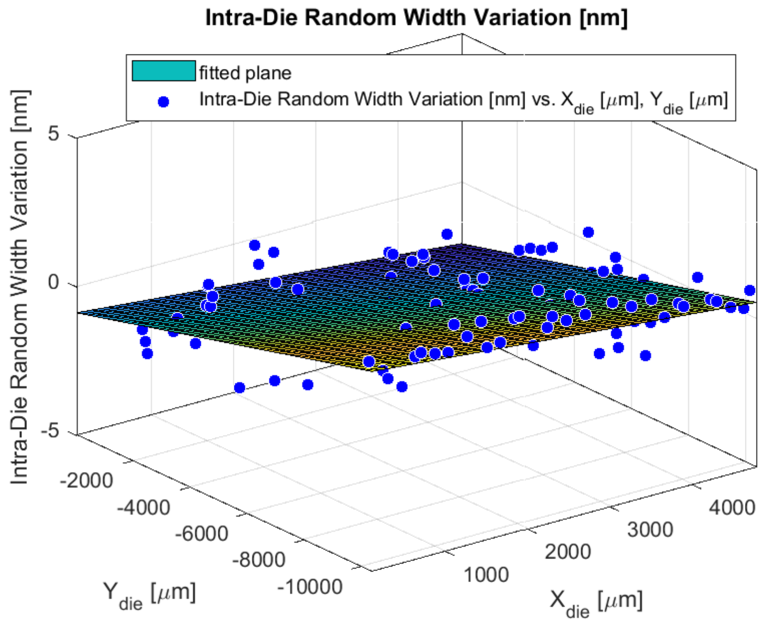
WDI

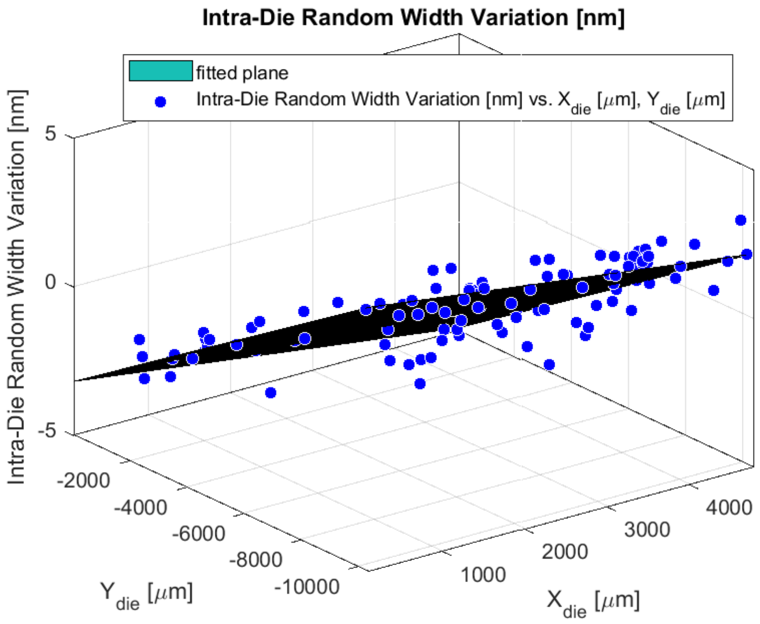


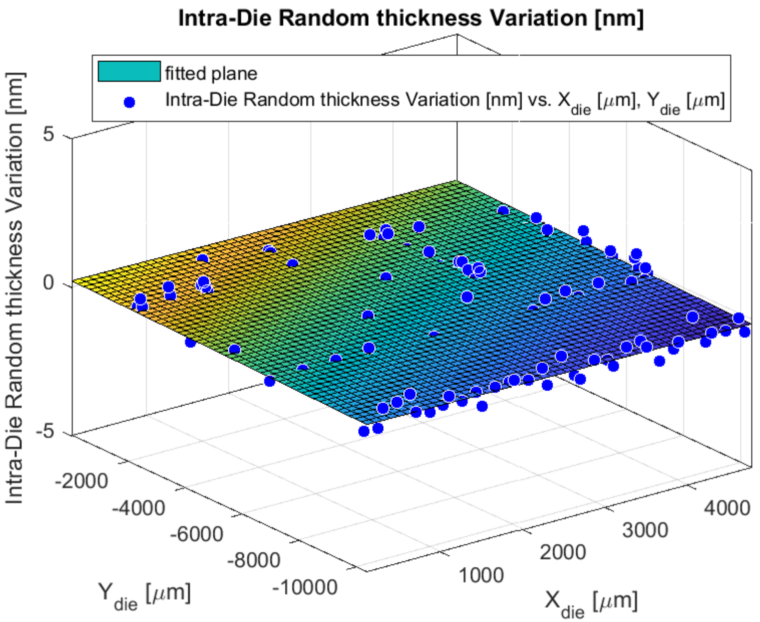
IDR

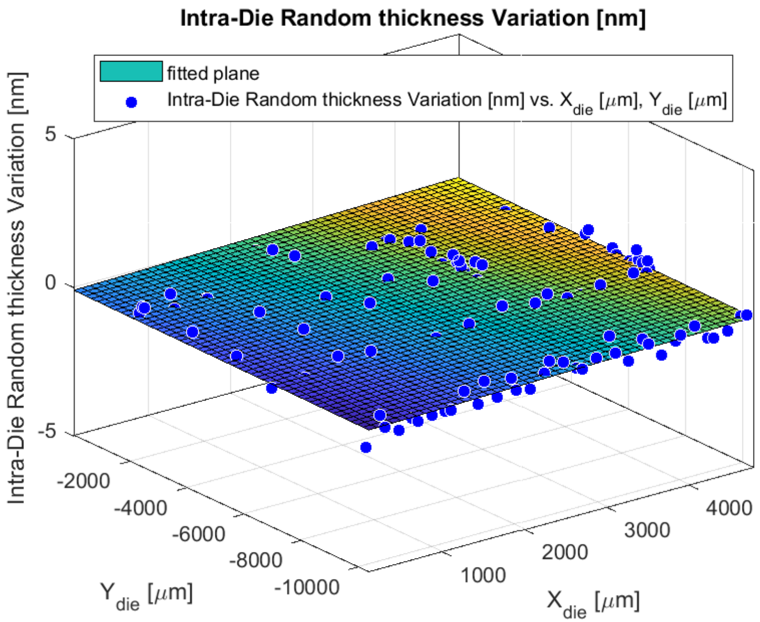

Intra-Die Random Width Variation [nm]
fitted plane
Intra-Die Random Width Variation [nm] vs. X_{die} [μm], Y_{die} [μm]
Intra-Die Random Width Variation [nm]
5
0
-5
-2000
-4000
-6000
-8000
-10000
Y_{die} [μm]
1000
2000
3000
4000
X_{die} [μm]

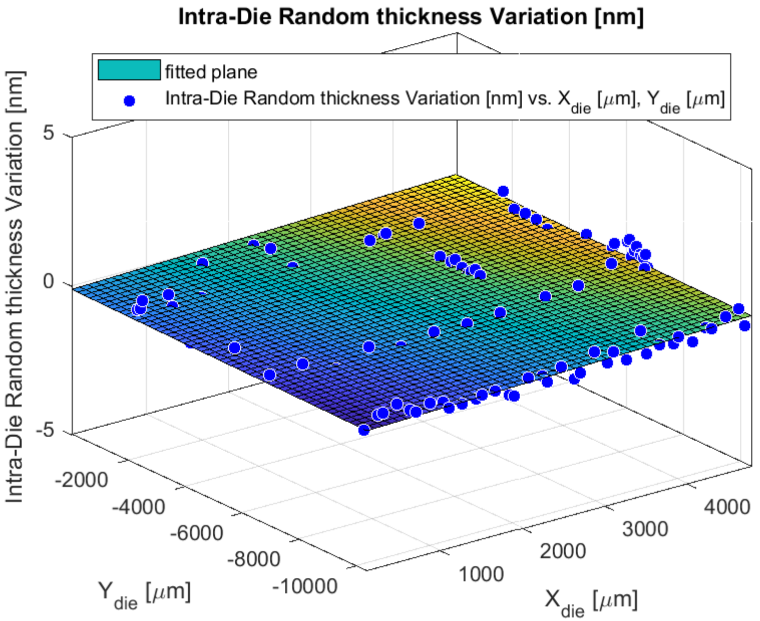

Intra-Die Random Width Variation [nm]
fitted plane
Intra-Die Random Width Variation [nm] vs. X_{die} [μm], Y_{die} [μm]
Intra-Die Random Width Variation [nm]
5
0
-5
-2000
-4000
-6000
-8000
-10000
Y_{die} [μm]
1000
2000
3000
4000
X_{die} [μm]

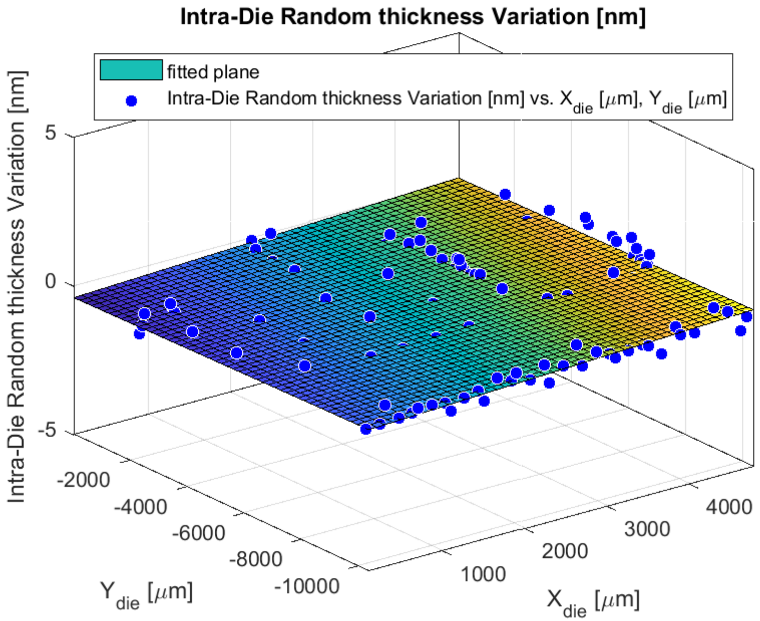

Intra-Die Random Width Variation [nm]
fitted plane
Intra-Die Random Width Variation [nm] vs. X_{die} [μm], Y_{die} [μm]
Intra-Die Random Width Variation [nm]
5
0
-5
-2000
-4000
-6000
-8000
-10000
Y_{die} [μm]
1000
2000
3000
4000
X_{die} [μm]


Intra-Die Random Width Variation [nm]
fitted plane
Intra-Die Random Width Variation [nm] vs. X_{die} [μm], Y_{die} [μm]
Intra-Die Random Width Variation [nm]
5
0
-5
-2000
-4000
-6000
-8000
-10000
Y_{die} [μm]
1000
2000
3000
4000
X_{die} [μm]


Intra-Die Random thickness Variation [nm]
fitted plane
Intra-Die Random thickness Variation [nm] vs. X_die [μm], Y_die [μm]
Intra-Die Random thickness Variation [nm]
5
0
-5
-2000
-4000
-6000
-8000
-10000
Y_die [μm]
1000
2000
3000
4000
X_die [μm]


Intra-Die Random thickness Variation [nm]
fitted plane
Intra-Die Random thickness Variation [nm] vs. X_die [μm], Y_die [μm]
Intra-Die Random thickness Variation [nm]
5
0
-5
-2000
-4000
-6000
-8000
-10000
Y_die [μm]
1000
2000
3000
4000
X_die [μm]

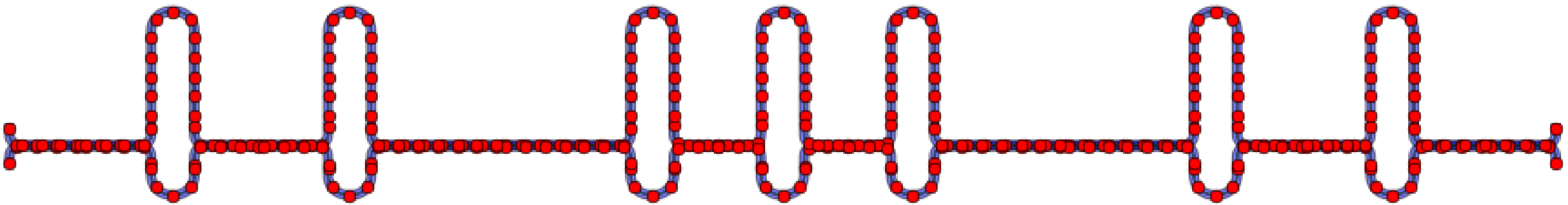

Intra-Die Random thickness Variation [nm]
fitted plane
Intra-Die Random thickness Variation [nm] vs. X_die [μm], Y_die [μm]
Intra-Die Random thickness Variation [nm]
5
0
-5
-2000
-4000
-6000
-8000
-10000
Y_die [μm]
1000
2000
3000
4000
X_die [μm]


Intra-Die Random thickness Variation [nm]
fitted plane
Intra-Die Random thickness Variation [nm] vs. X_die [μm], Y_die [μm]
Intra-Die Random thickness Variation [nm]
5
0
-5
-2000
-4000
-6000
-8000
-10000
Y_die [μm]
1000
2000
3000
4000
X_die [μm]

Sampling points in the Layout

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

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



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

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