Solving the Data Center Energy Crisis with Silicon Photonics & Overcoming Photonics Wafer-level Test Challenges

Dr Choon Beng Sia FormFactor

Tiong Leh Yap GLOBALFOUNDRIES

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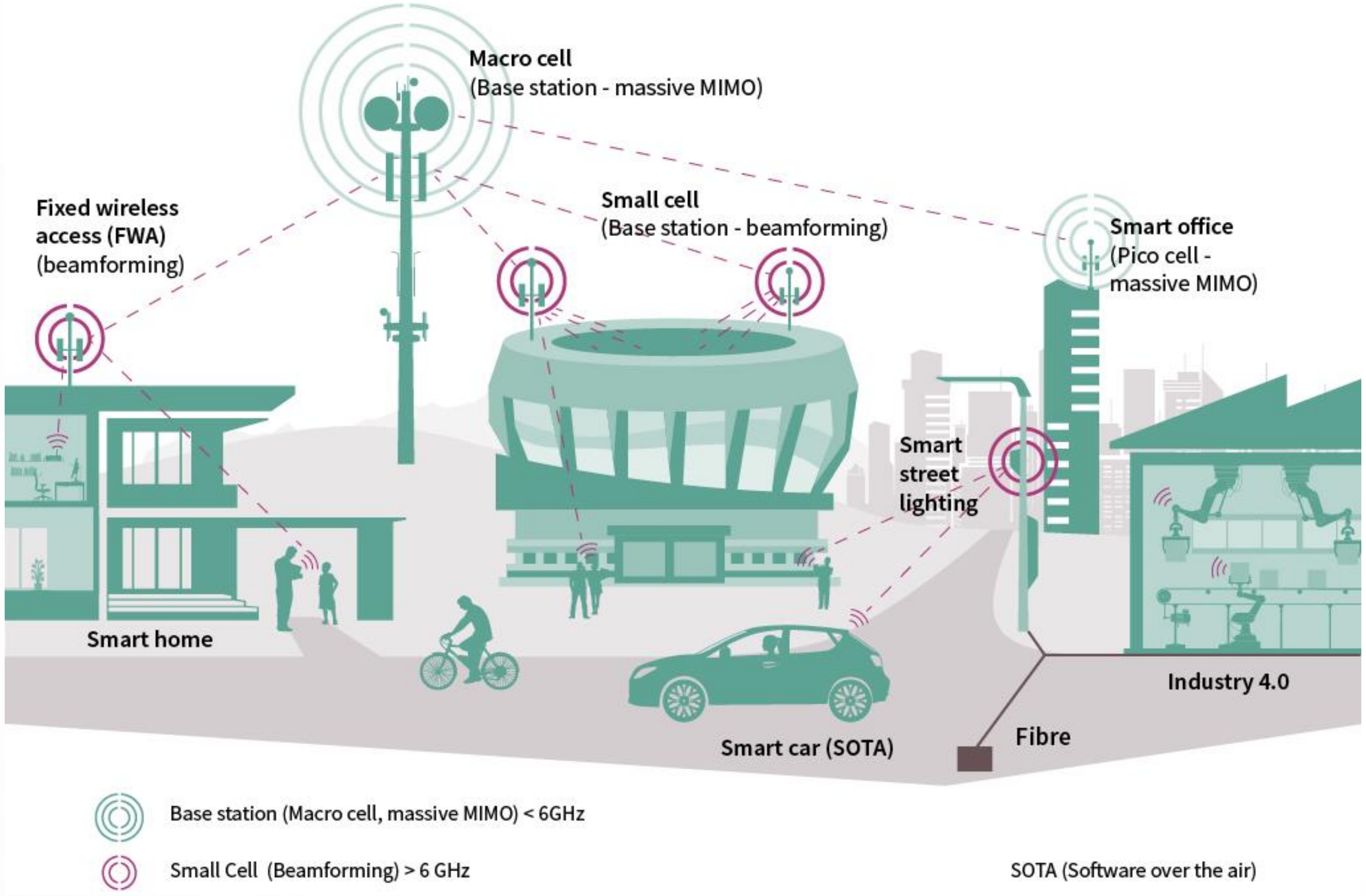
Dr Choon Beng Sia

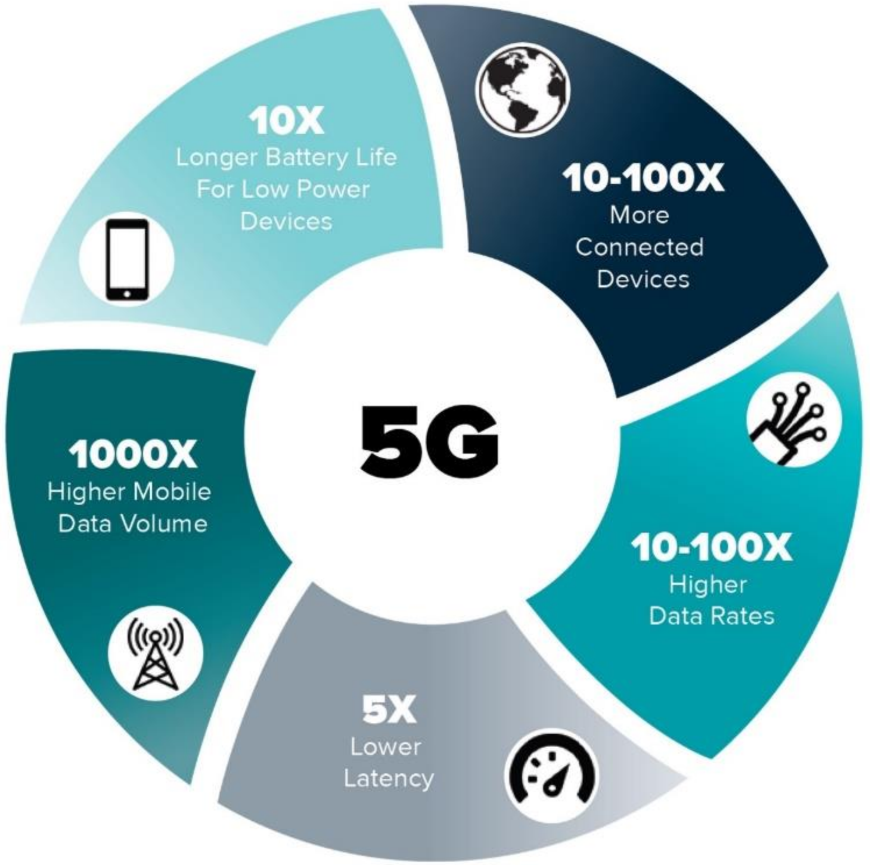
- Test Technologist, FFI Probe System Business Unit
- Ph.D. in RF Device Design and Modelling
  - Nanyang Research Scholar, 5 IEEE Journals for dissertation.
- IEEE Senior Member
- IEEE MTT-3 Microwave Measurement Committee
- IEC TC47 – Technical Expert representing Singapore
- Research Interests:
  - DC, AC, 1/f noise, Power Device Characterization
  - Wafer-Level Optical Measurements, THz Calibration & Characterization of Devices
- 50 Technical Papers, 12 International Patents
- “Best Paper” awards for “5G Production Test” at 2018/2019 SWTest Conf.
- SSG Fellow conferred by President of Singapore

Overview

- Why Huge Demands for Silicon Photonics?
- Why Wafer-Level Photonics Tests?
- What are the Test Challenges & Solutions?
- Summary

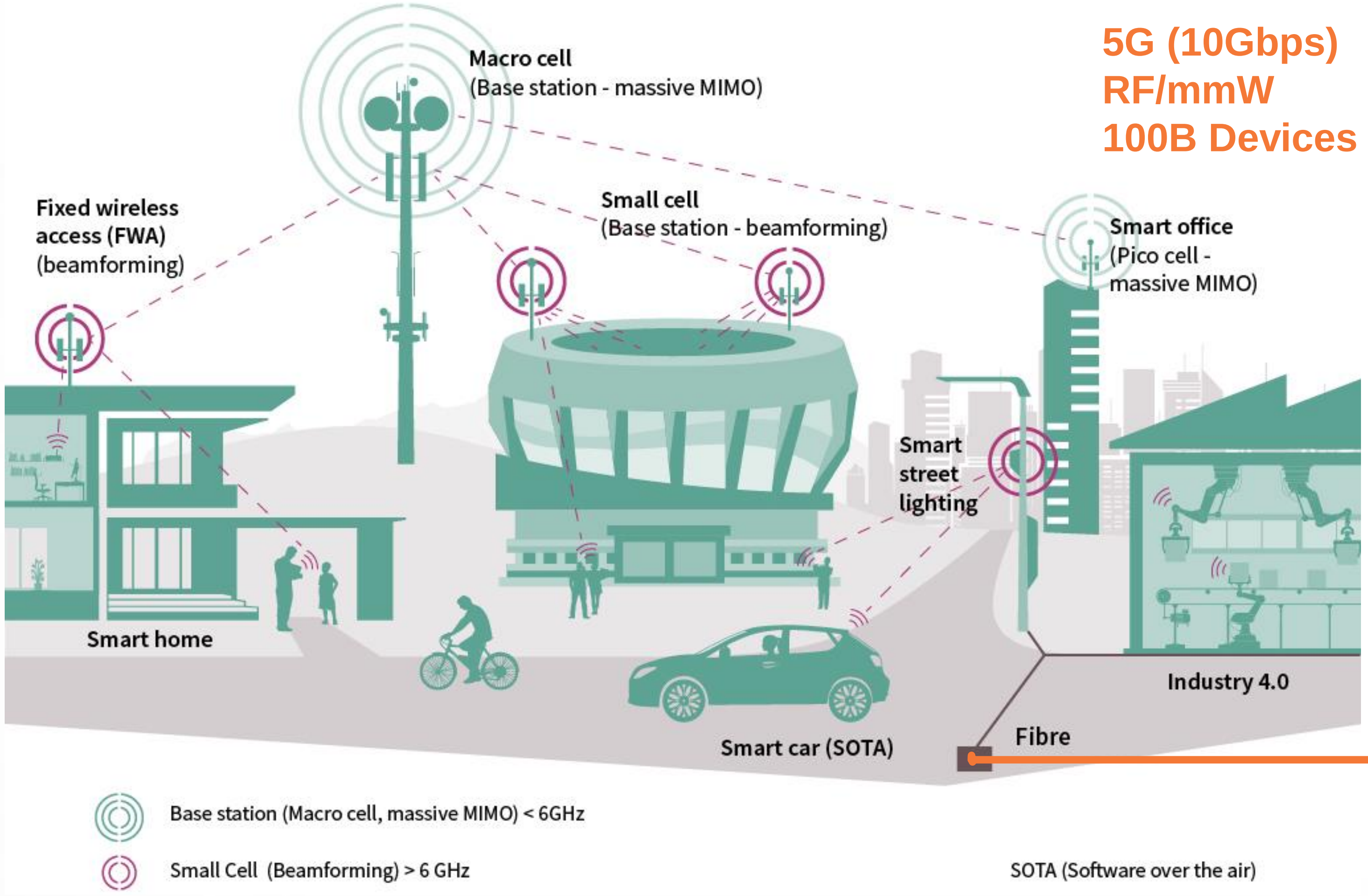
Future Communication Landscape with 5G





https://www.infineon.com/export/sites/default/media/press/Image/press_photo/Infographic-5G-e.png & https://www.sakura.ad.jp/en/corporate/datacenter/

Future Communication Landscape with 5G



5G (10Gbps)
RF/mmW
100B Devices

Data Center
100/400/800Gbps
Optical Interconnects

https://www.infineon.com/export/sites/default/media/press/Image/press_photo/Infographic-5G-e.png & https://www.sakura.ad.jp/en/corporate/datacenter/

The Need for High Performance Network & Data Centers

Big Data Analytics

Artificial Intelligence

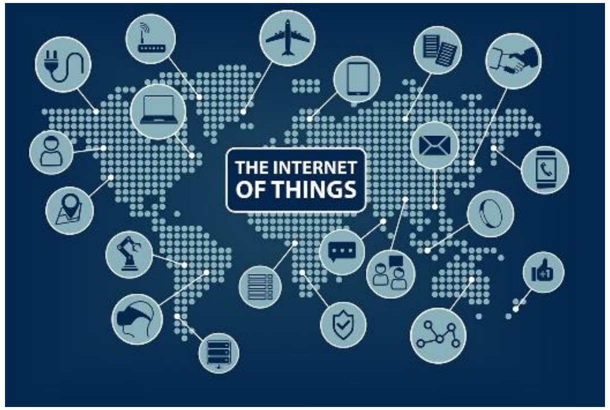
Genomics Revolution

Augmented Reality

Financial Acceleration

Self-Driving Cars

Video Transcoding



Internet of Things

Photo Credits – FIU Honors College, Peshkova/Shutterstock.com, healthskouts.com, Gecko Governance, www.socionext.com, www.gsa.gov.

Facebook's US$1B HyperScale Data Center in Singapore

6th September 2018

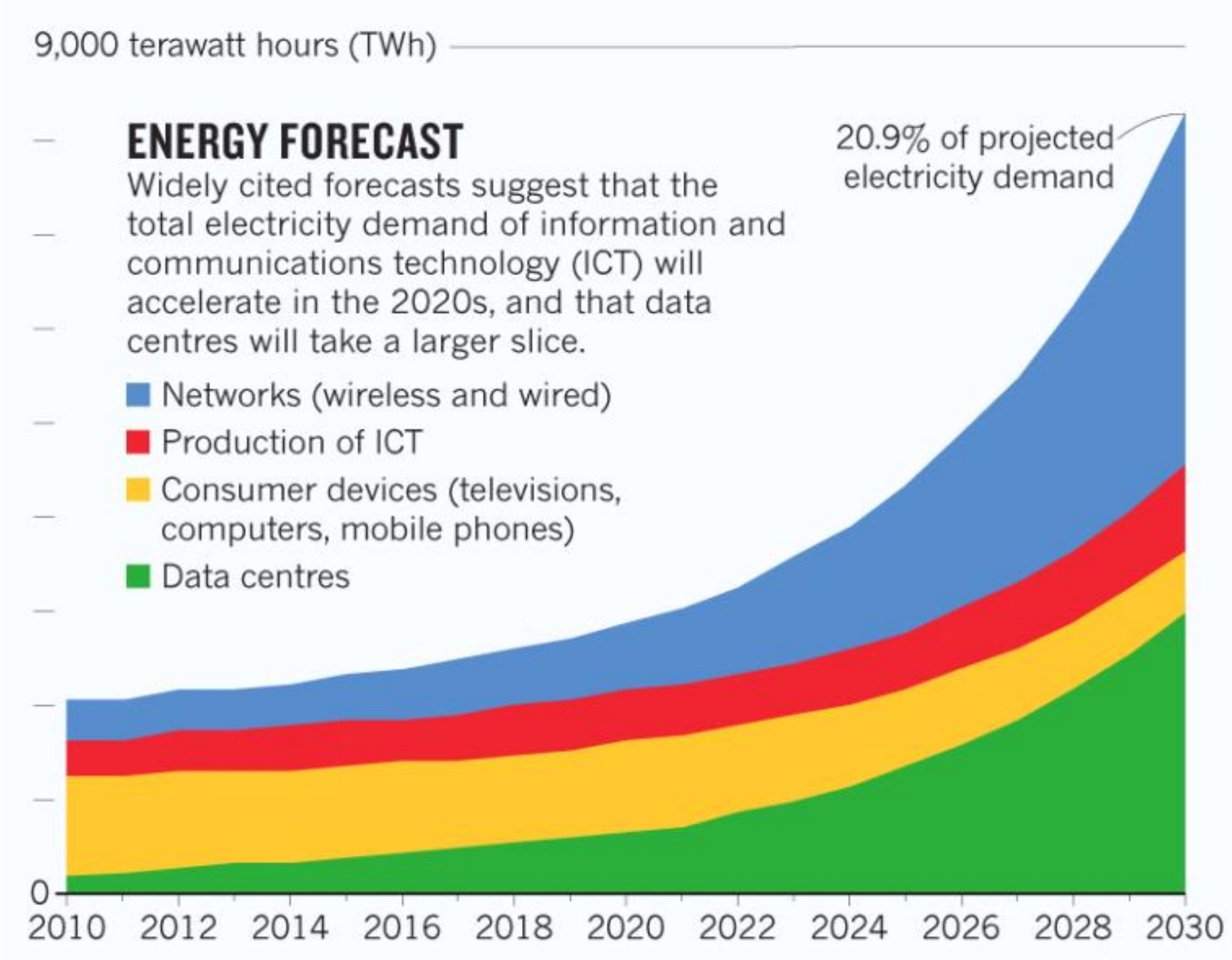
- Facebook's 1st Data Center in Asia (Hub).
  - IT Talent & Fiber connectivity
  - 170,000m^2
  - 150MW
- 5000 servers
  - Each server supports 100 petabytes or 100,000 TB*


Artist Impression of Facebook Data Center in Singapore

*2015 Facebook Video, 1PB=1000TB

Energy Forecast for Information Technology

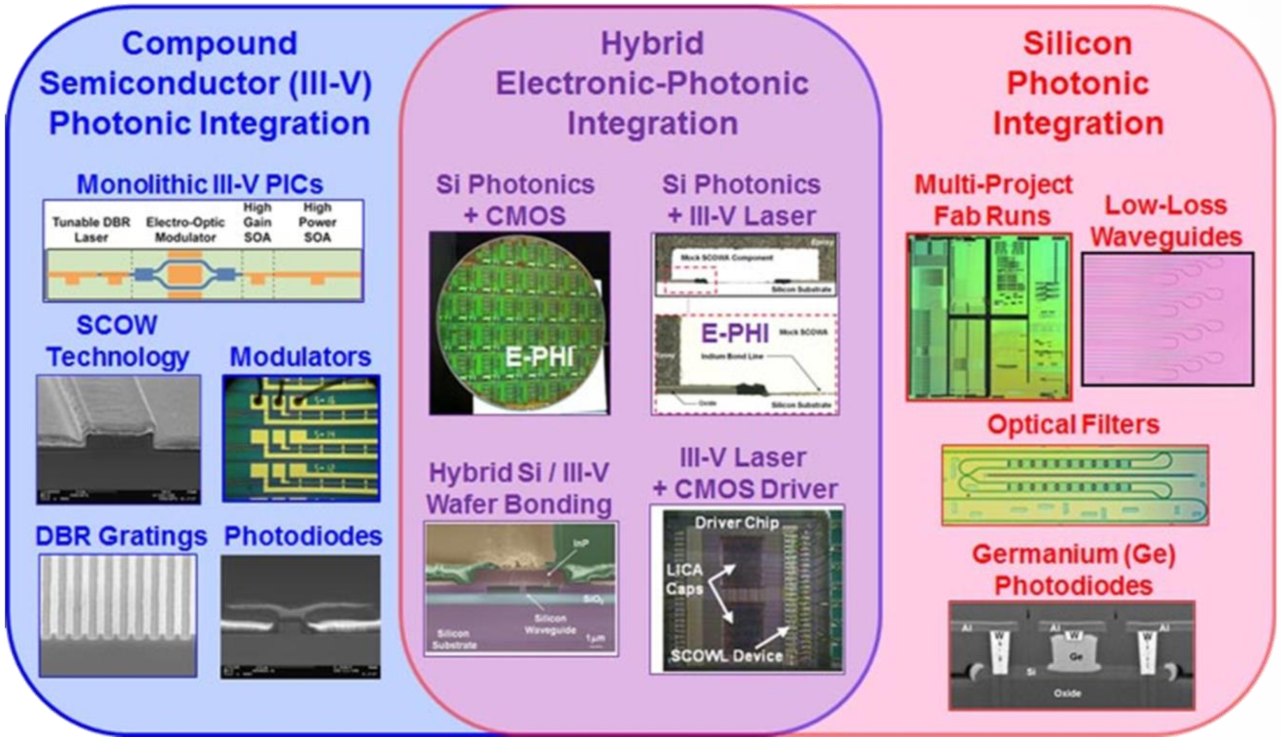
- Speed is not the main Challenge.
  - Reducing Energy Consumption is Key!
  - Data Center Power Usage:-
    - 40% - Server & Switch
    - 40% - Cooling
- By 2030, 20% of World's Energy produced to be consumed by Information Technology?



*A. S. G. Andrae and T. Edler, "On Global Electricity Usage of Communication Technology: Trends to 2030", Challenges, Vol. 6, pp. 117-157, 2015.

Why Silicon Photonics?

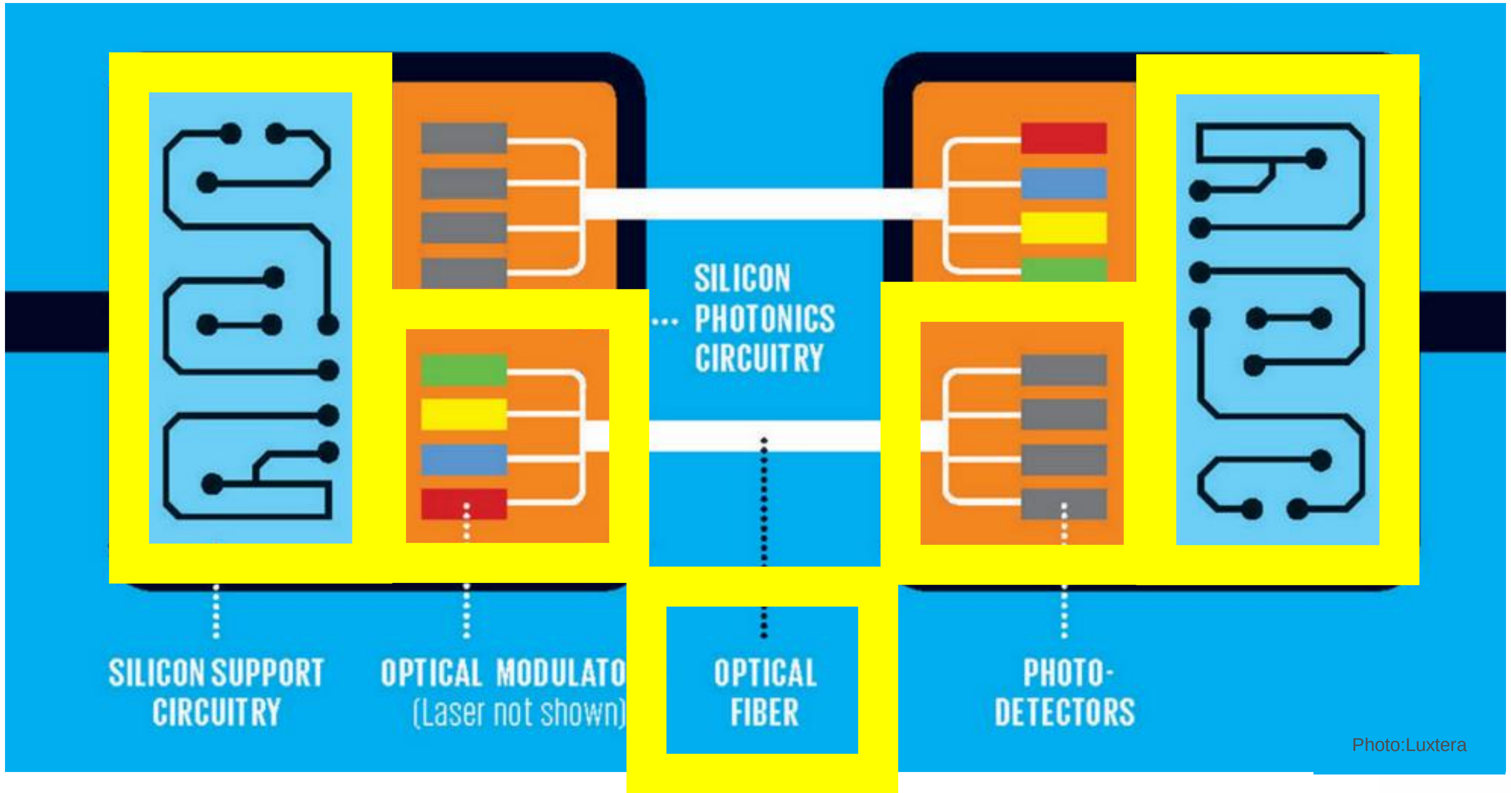
- **Improvements in Thin Film Growth**
  - High Quality Ge on Si
    - Excellent Lattice Matching
    - Hi-Speed Ge-on-Si Photodiodes
- **Exploiting Silicon Technologies**
  - Low-Cost High-Volume Production
  - Low-Power Logic devices
  - High-Speed RFCMOS devices
  - Heterogenous Integration/Packaging



SiPh Optical Transceivers for Data Centers

Components on SiPh Transceivers

1. CMOS Logic Chip
   - Data Encoding (also decoding)
2. Optical Transmitter
   - Optical Modulators - Varying voltage modulate Data onto Light
   - Lasers not implemented on Silicon
3. Optical Receiver
   - Ge Photo detectors
   - Converts Light to Voltage
4. CMOS Logic Chip
   - Data Decoding (also encoding)



For a 10Gb/s Link	Copper Interconnect	Optical Fiber
Power Required	10 W	0.2 W
Range	meters	kilometers

Sources: IEEE Spectrum, Yole - New Technologies & Architectures for Efficient Data Center report – July 2015

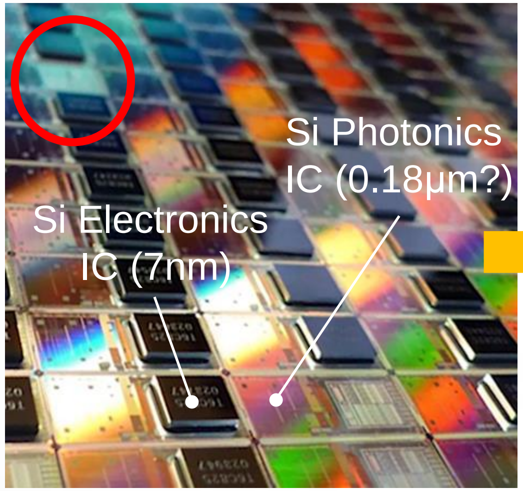
Evolution of Optical Transceivers

CFP	CFP2	CFP4	QSFP28
4 ports/chassis	8-10 ports/chassis	16-18 ports/chassis	18-20 ports/chassis
24W	8W	5W	3.5W

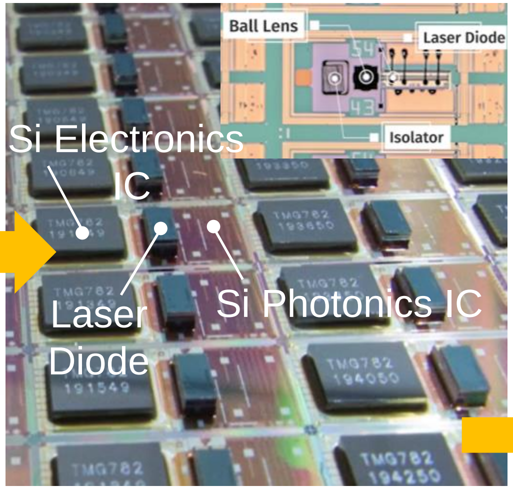
Time

CFP – Centum Form-factor Pluggable ; QSFP28 – Quad Small Form-factor Pluggable 28 Gbit/s
Christian Urricariet, “Latest Trends in Data Center Optics”, 2016.

Why Wafer-level Test? – Heterogenous 3DIC Stacking

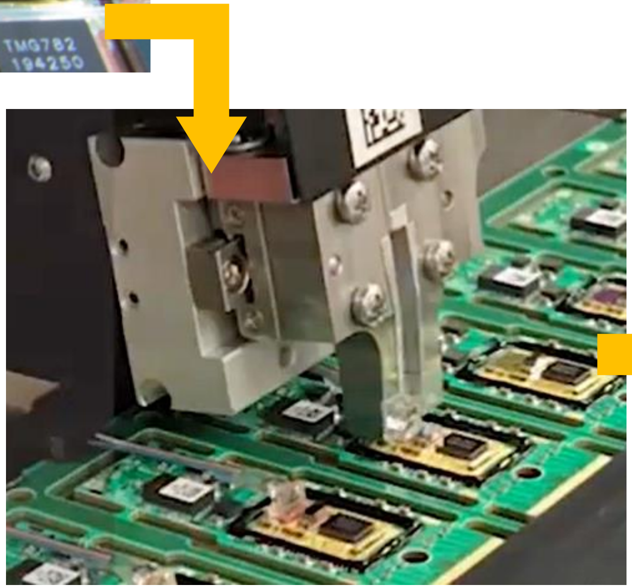


Si Electronics-Die
attach onto
Si Photonics-Die (TSV)

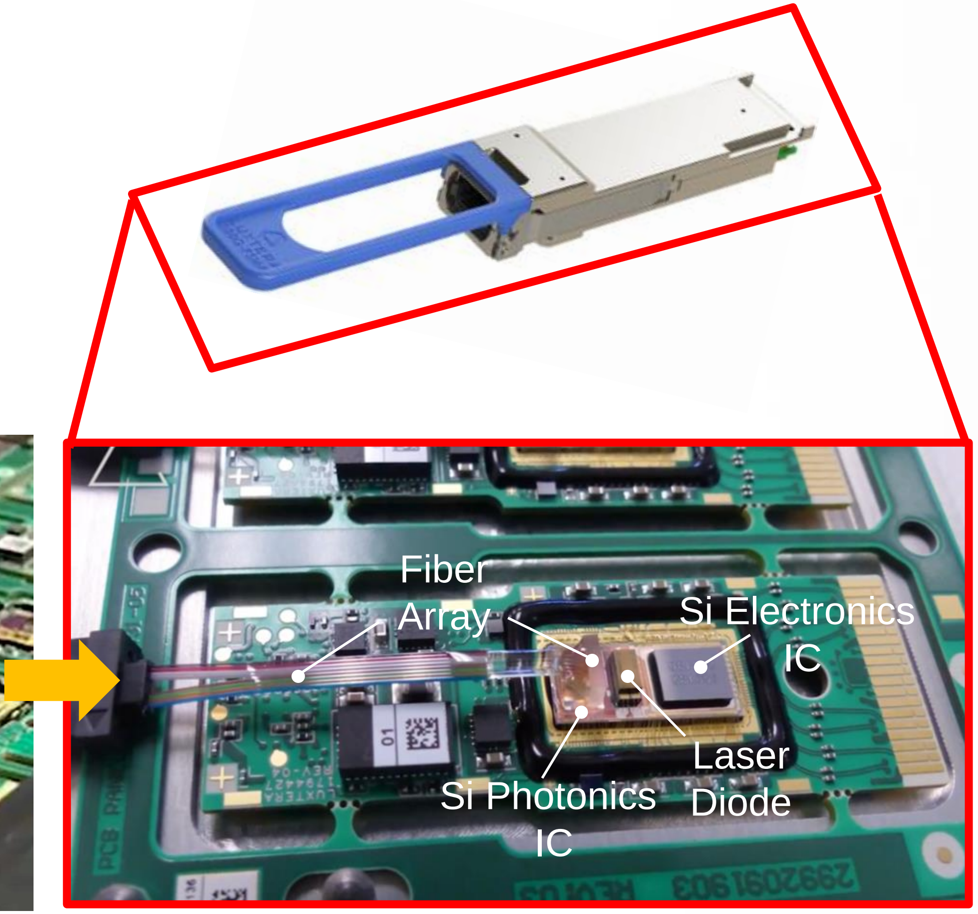


Continuous Wave
Laser Diode on
Si Photonics-Die

Known-Good-Die (KGD) tests needed for 3DIC Heterogenous Integration.



Optical Fiber Array Aligned
& Fused onto Photonics-Die

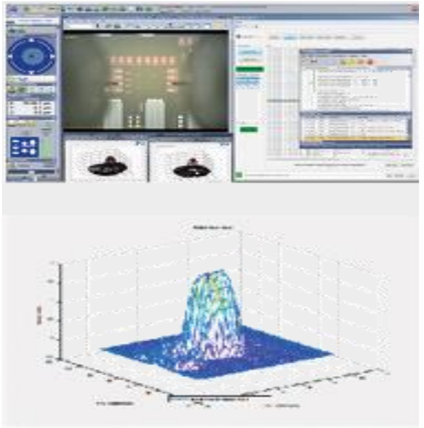


SiP-based Optical Transceiver
Chipset for QSFP28 module

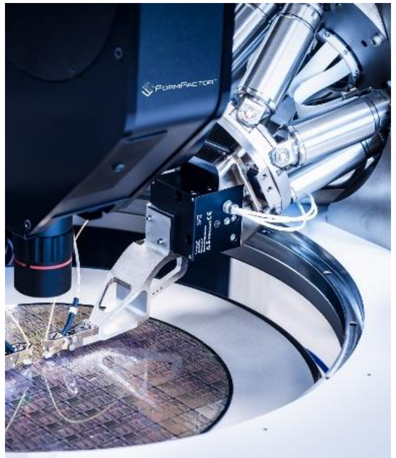
Source: Luxtera's website, Luxtera acquired by CISCO in Dec 2018 for US$660M.

Integrated Wafer-Level Photonics Test Solution

Optical Test Instruments & Software



Software for Optical Positioners & Probe System



6-Axis/Piezoelectric Positioner, Single Fiber/Fiber Array, Displacement Sensors

RF probes, ISS, Cal. Software & DC probes

Fully Automatic Probe System with Wafer Loader

Overview

- Why Huge Demands for Silicon Photonics?
- Why Wafer-Level Photonics Tests?
- What are the Test Challenges & Solutions?
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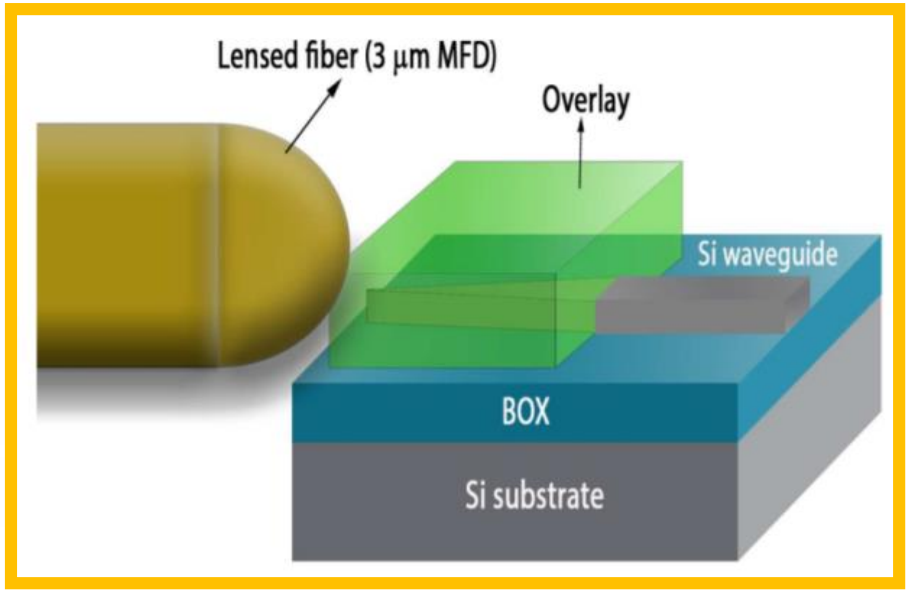
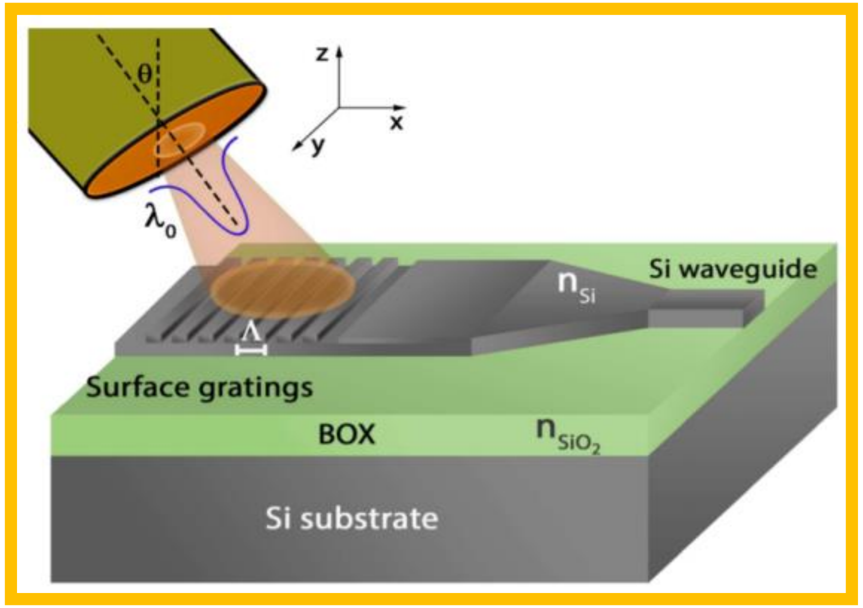
What are the Test Challenges & Solutions?

- How to Optimize Test Setup for Accurate & Repeatable Measurements?
  - How to couple light into a photonics chip (wafer-level)?
  - Achieving Fast and Repeatable Fiber-to-Coupler Alignment
  - Optimizing Fiber Height and Incident Angle.
- How to Correlate Wafer-Level Test to Final Product test?
  - Edge Coupling Optical Tests
- How to Achieve Fully Automatic Wafer-Level Production Solution?

How to Couple Light into a Photonics Chip (Wafer-level)?





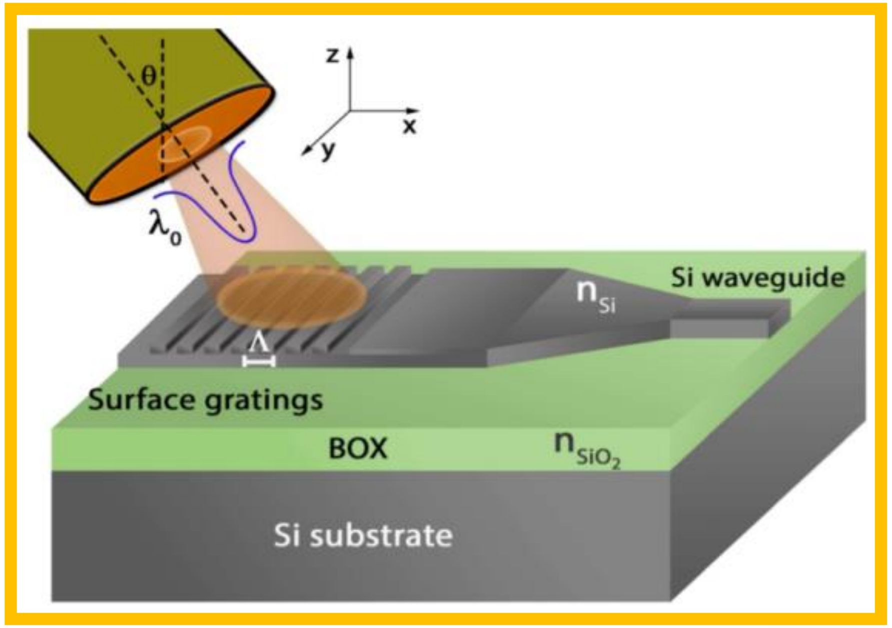
- **Edge Coupling**
  - Final Product (Die Level)
  - Small, Sub-dB Loss Per Facet
  - 200nm – 300nm Bandwidth
  - Low Polarization Sensitivity
  - Harder to Fabricate/Test
  - Fixed Interface (Edge of Chip)
  - Low Fiber-Chip Alignment Tolerance

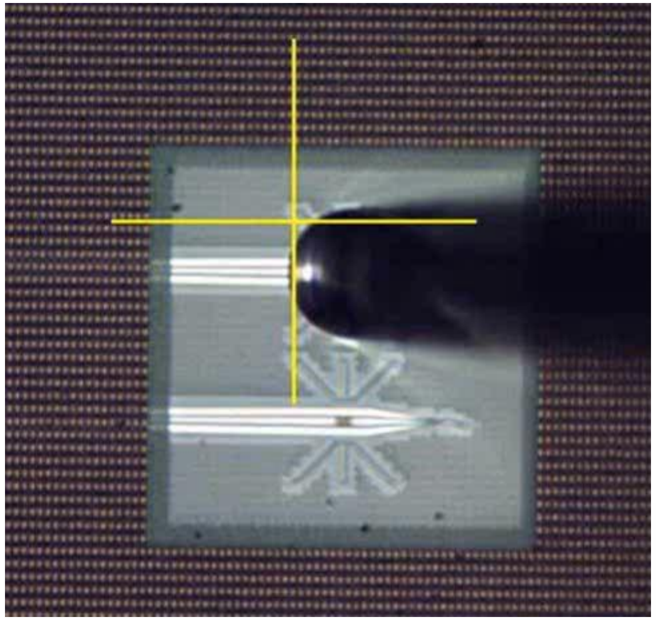
- **Grating Coupling**
  - Process Development & KGD (Wfr Level)
  - Larger, 2 to 4dB Loss per Grating Coupler
  - Typically 60nm Bandwidth
  - Polarization Dependent
  - Easier to Fabricate/Test
  - Flexibility of interface positions
  - High Fiber-Chip Alignment Tolerance

S. Nambiar et al., Appl. Sci., vol. 8, pp. 1142, 2018.

Optimizing Setup – Optical Coupling for Photonics Tests

- **Grating Couplers (Wafer-Level Tests)**
  - Fast & Repeatable Fiber to Grating Coupler Alignment

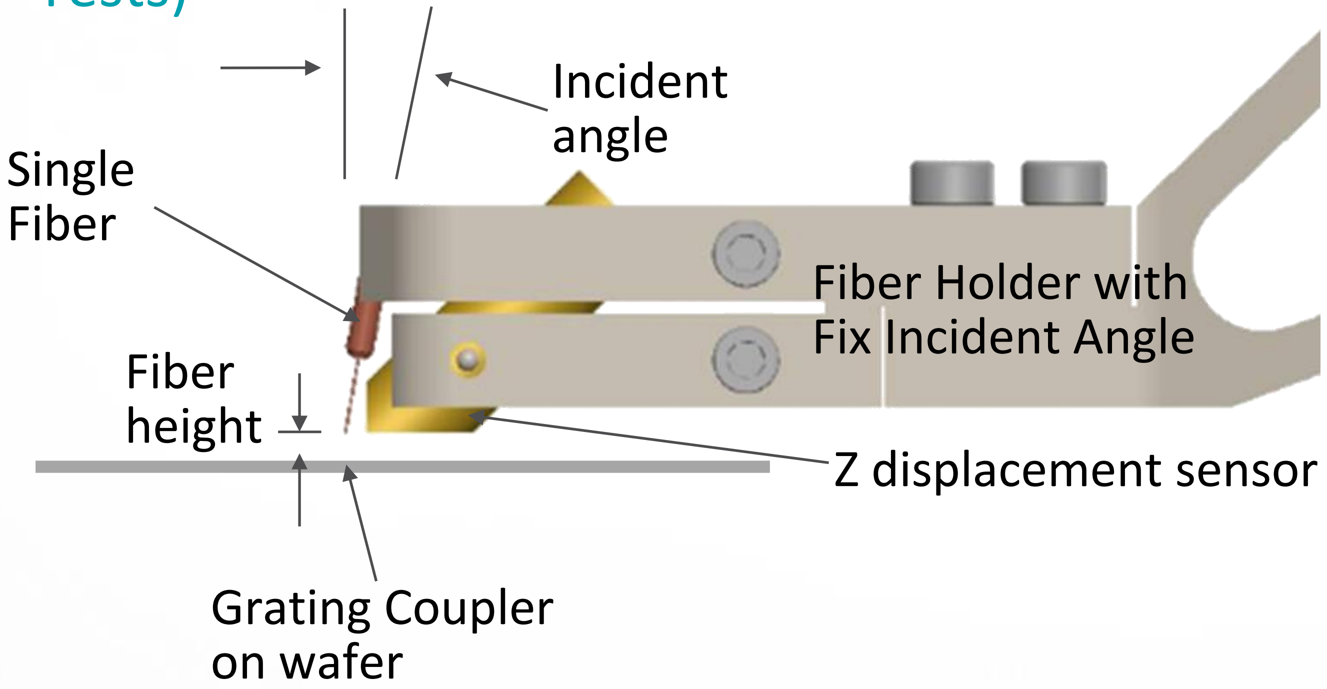


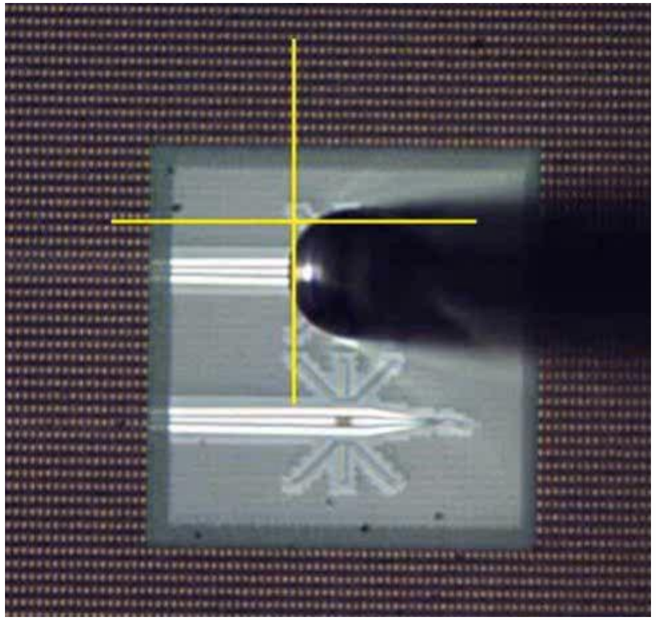


Fiber Alignment with Sinusoidal Scan

Optimizing Setup – Optical Coupling for Photonics Tests

- **Grating Couplers (Wafer-Level Tests)**
  - Fast & Repeatable Fiber to Grating Coupler Alignment
  - Fiber Height (Constant Height to Prevent Damage)
  - Incident Angle (Critical to determine Optimal Incident Angle before Production Tests)

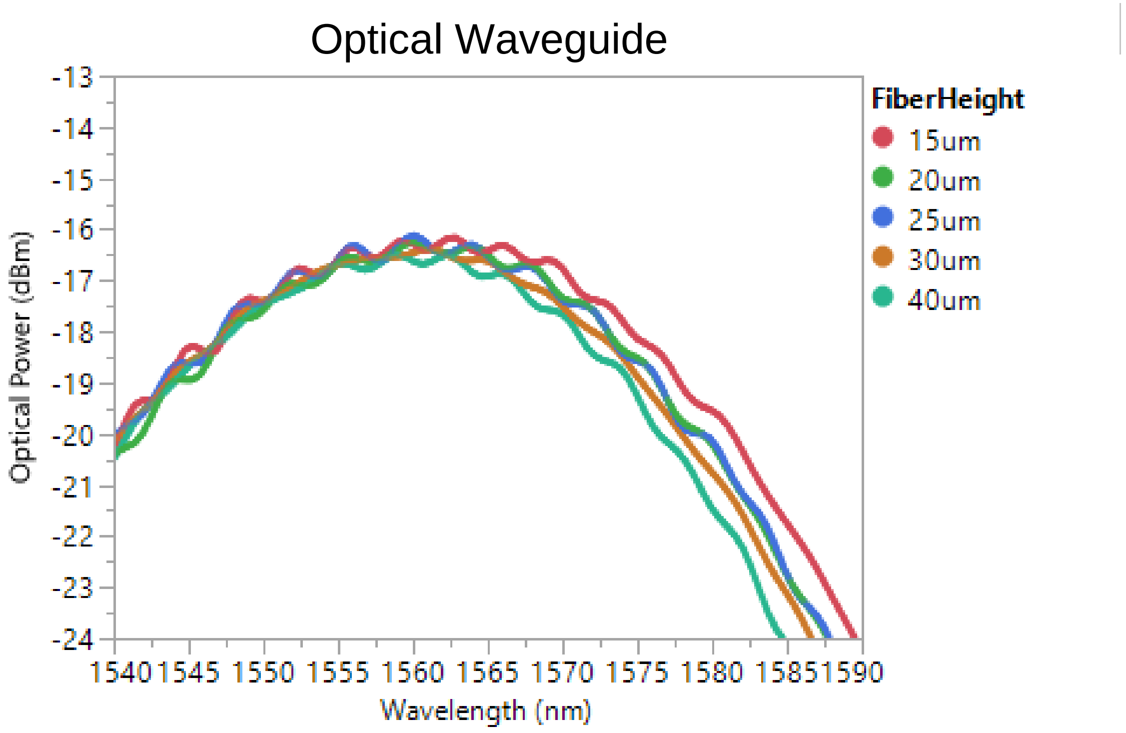


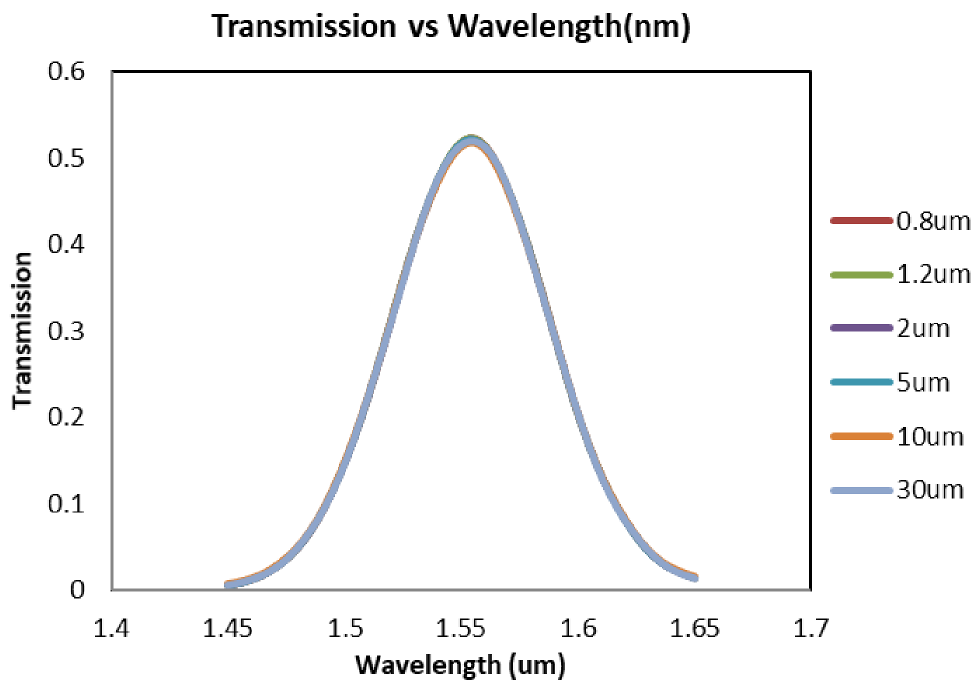


Fiber Alignment with Sinusoidal Scan

Optimizing Setup – Fiber Height (Wafer-Level)

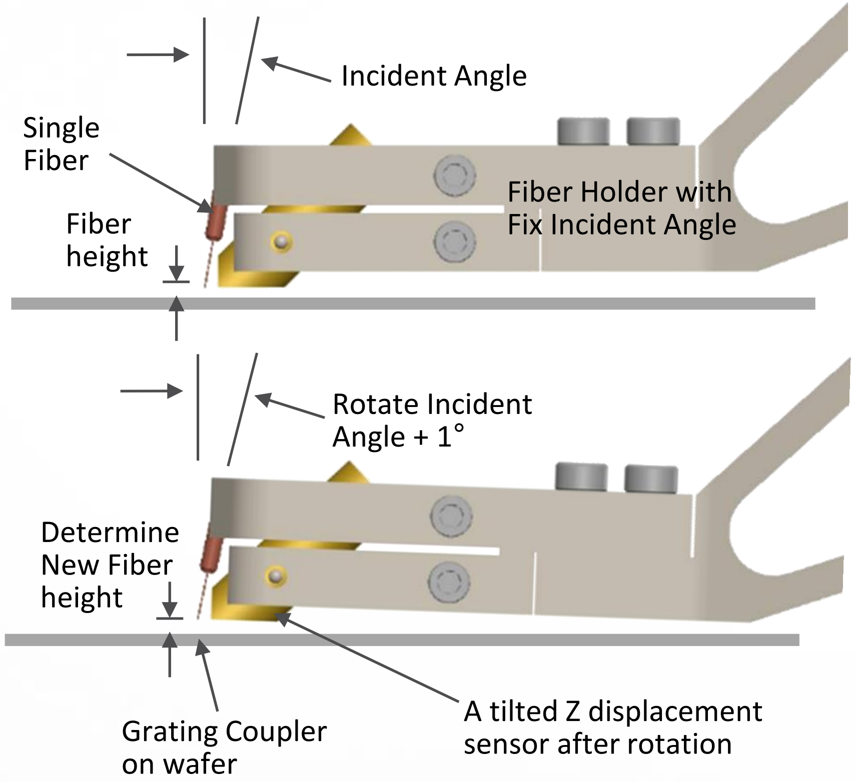
- 1. Set Fiber Height, 2. Peak Search, 3. Make Measurements → Repeat diff. Height
- No Significant Effect on Coupling Efficiency, Peak Wavelength & Bandwidth.
- Good Agreement with Simulation Data.

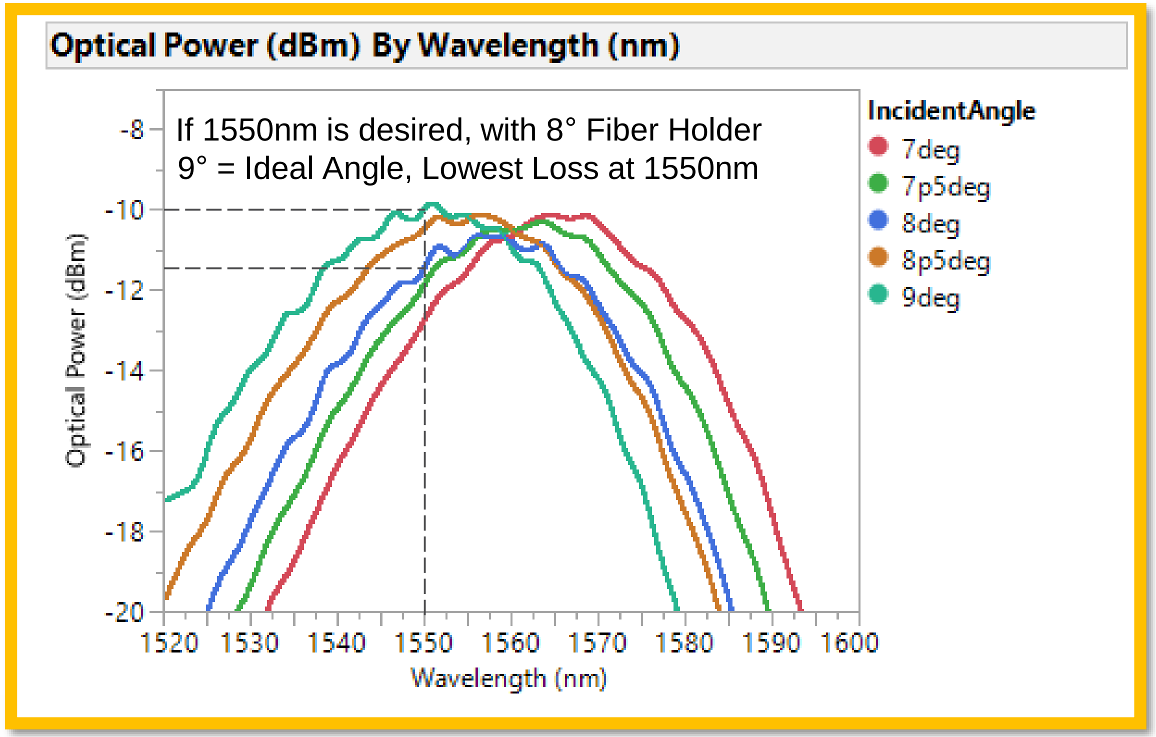




Optimizing Setup – Incident Angle (Wafer-Level)

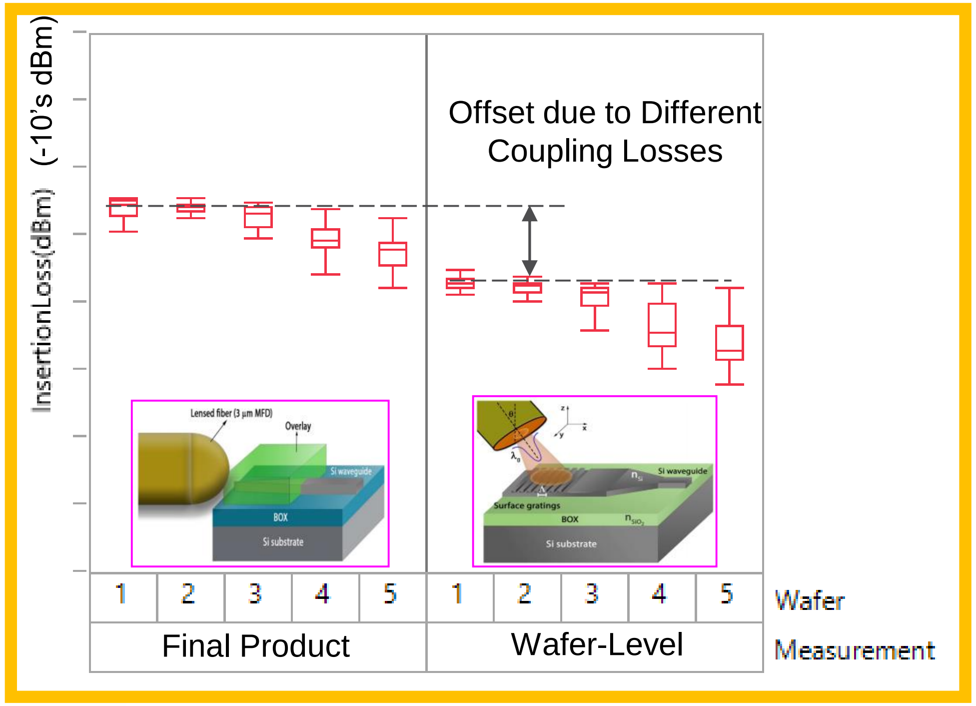
- 1. Set Incident Angle, 2. Peak Search, 3. Make Measurements → Repeat diff. Angle
  - Use 6-axis positioner to vary incident angle ±1° ; Fiber height set with Z sensor (Pivot Cal needed).
- Critical to determine Optimal Incident Angle before Production Tests (1.5dB improvement).





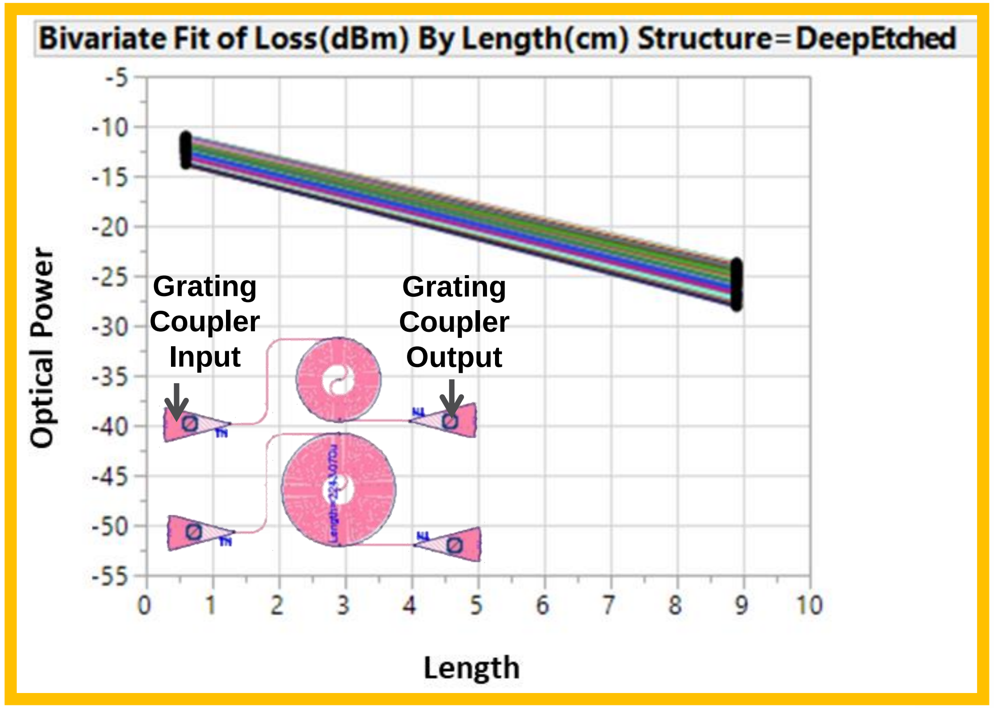
Wafer-Level vs Final Product Tests (Passive Device)

Offset bet wfr-level & final product



- Critical to correlate Wafer-Level & Final product Tests
- Using Optical Waveguides as Test Structures
  - Different Insertion Losses observed

Obtaining Coupling Losses



- Edge Coupling & Grating Coupling losses are obtained by Cut Back method.
  - Comparing output intensity of waveguides with different length

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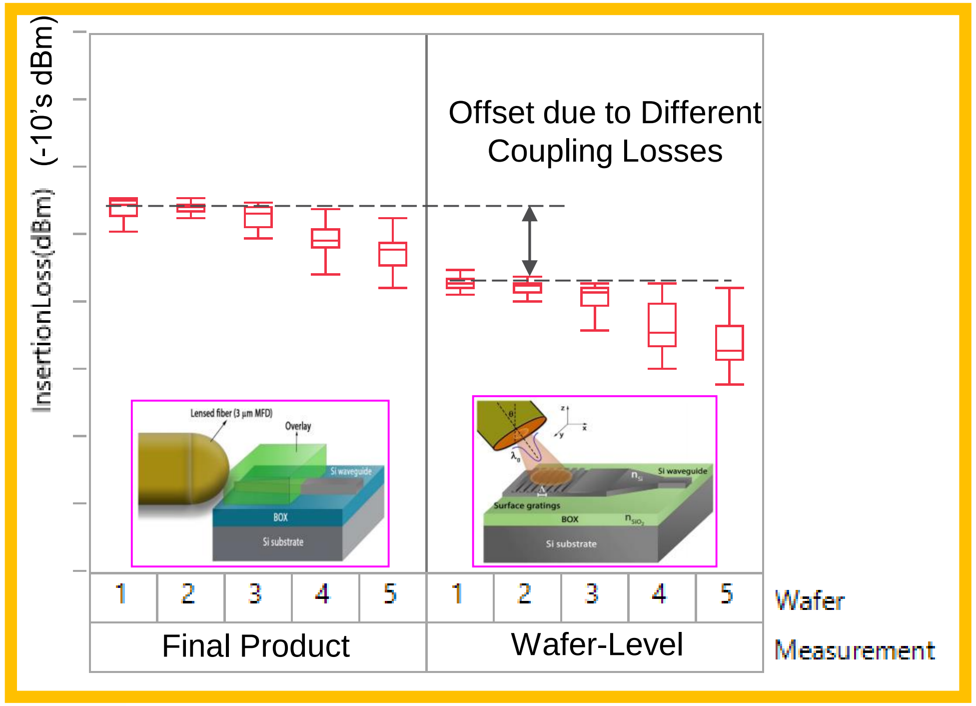
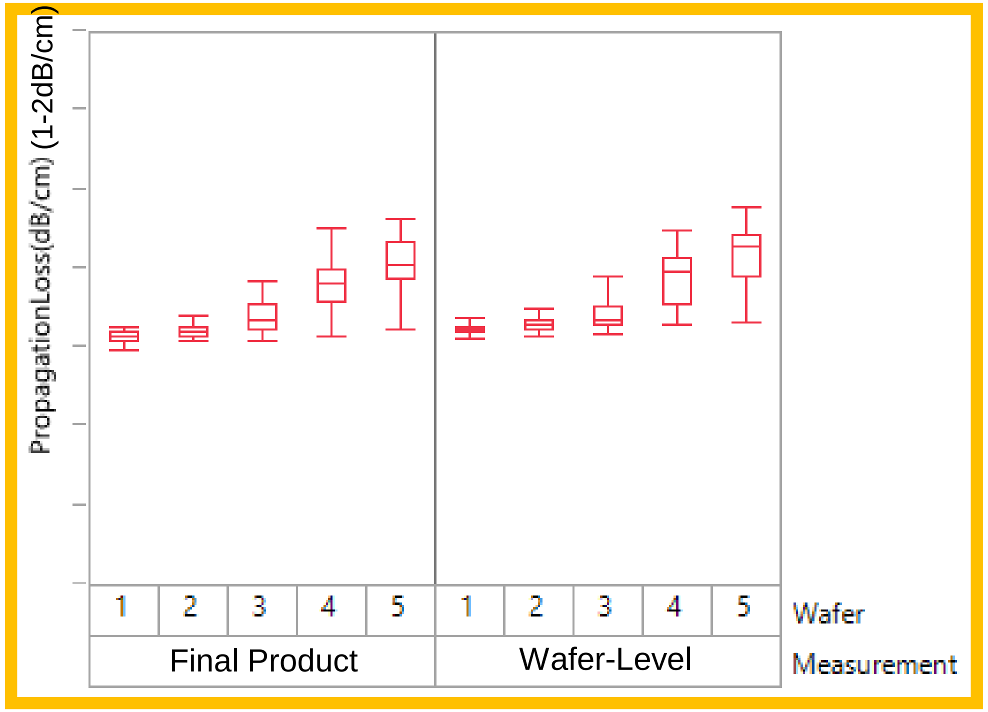
Wafer-Level vs Final Product Tests (Passive Device)

Offset bet wfr-level & final product



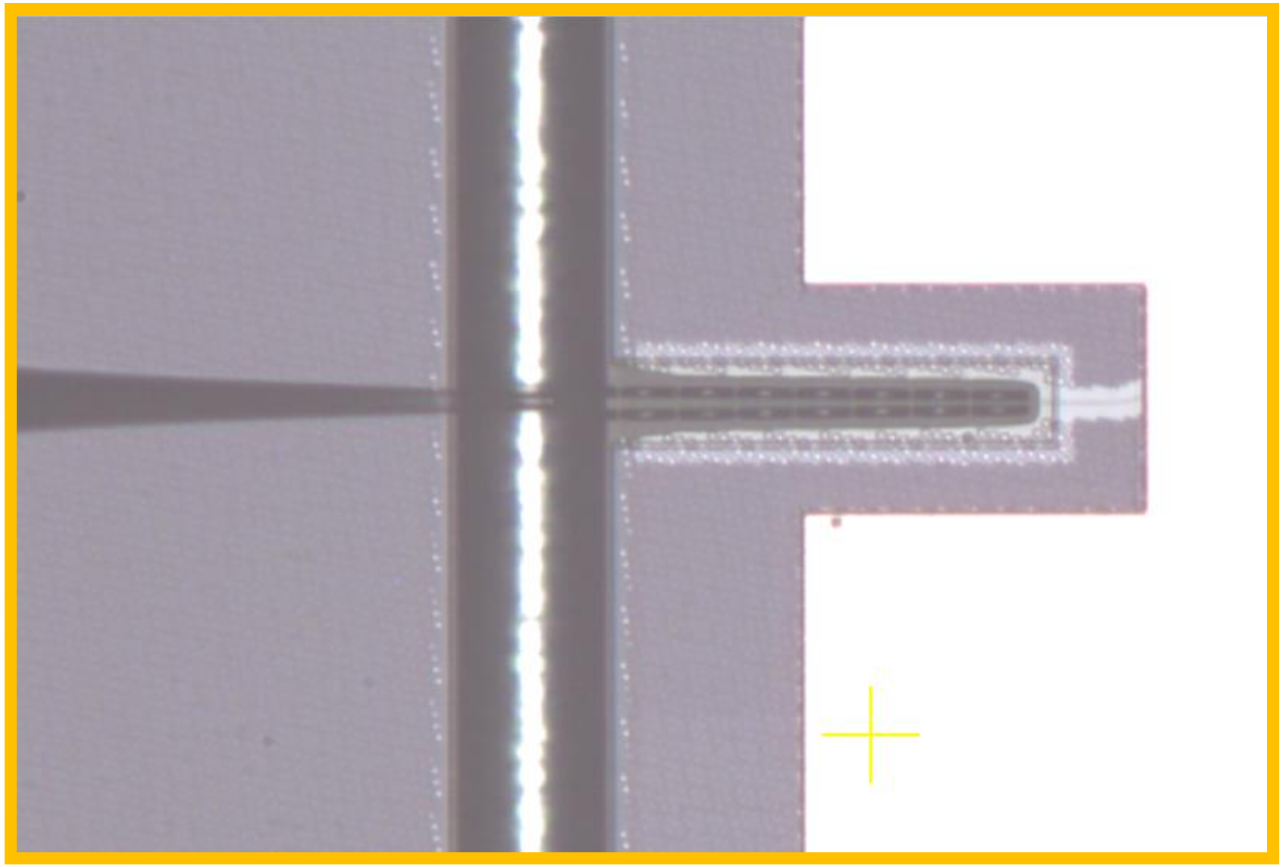
- Critical to correlate Wafer-Level & Final product Tests
- Using Optical Waveguides as Test Structures
  - Different Insertion Losses observed

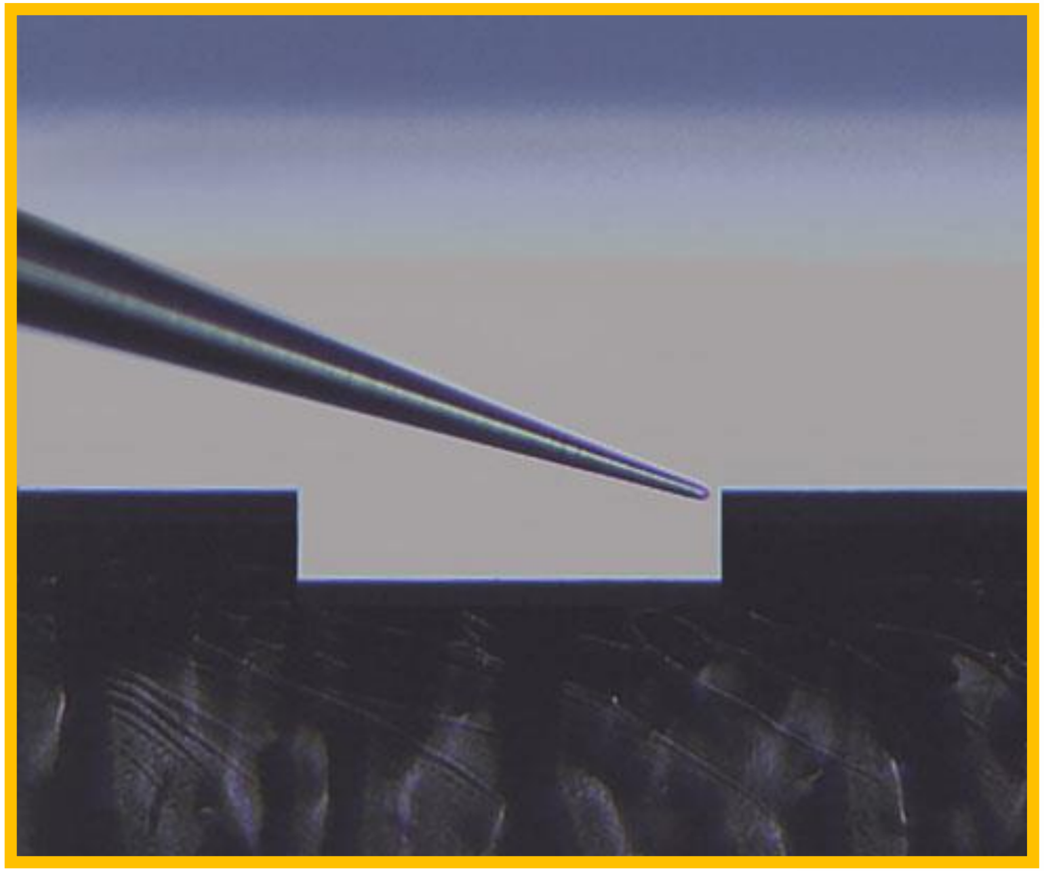
After Coupling Losses Correction



- Remove Coupling Loss
- Comparable Propagation Loss per unit Length.
- Establish Good Correlations between Wfr-level and Final product Tests!

Wafer-Level Edge Coupling





Achieving Automatic Production Photonics Tests

- **Challenging for one Test Setup to handle…**
  - Passive vs Active Device
  - Single Photonics Device & Complex Photonics Integrated Circuit Tests
  - Endless Permutations of Test Layouts
  - Establish Design Rules, Standardize Layout (Design-for-Testability)
  - Implement Automatic Testing Architecture

Parameter	Unit	Probes Needed
Photodiode Dark Current	nA	DC probes
N/P-doped Modulator Resistance	ohm	
Heater Resistance	ohm	
Waveguide Propagation Loss	dB/cm	Optical Fiber Probes
Y-splitter splitting ratio	%	
Tap Coupler Coupling Strength	%	
Modulator Extinction Ratio	dB	Optical Fiber Probe(s) + DC Probes
Photodiode Responsivity	A/W	
Modulator Bandwidth	GHz	Optical Fiber Probe(s) + RF Probes
Photodiode Bandwidth	GHz	

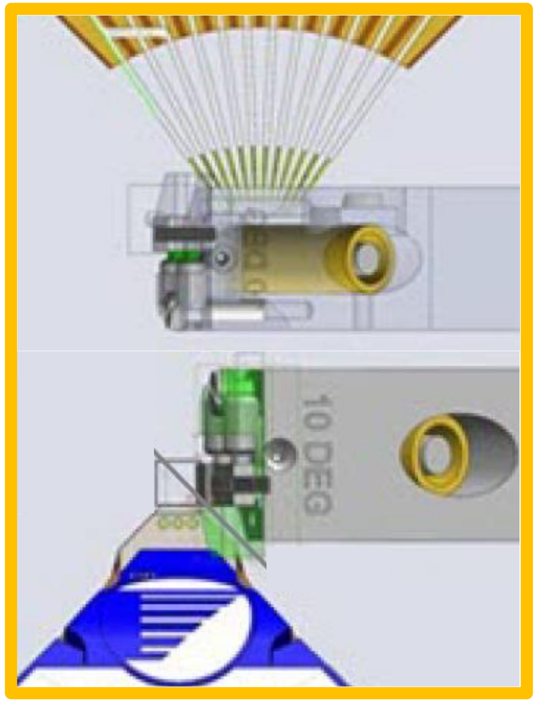
Photonics Device Tests

Photonics IC Tests

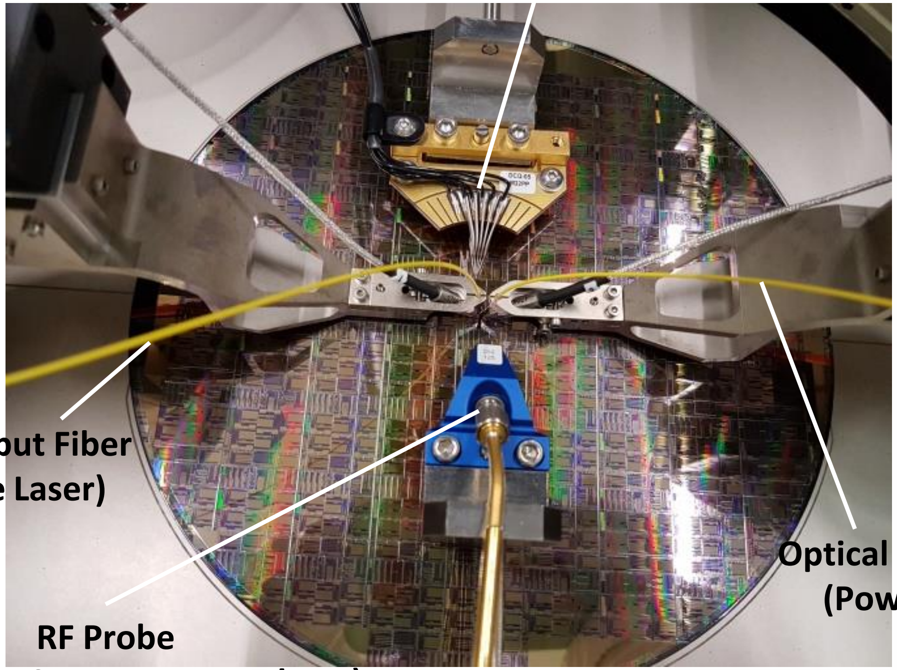
Achieving Automatic Production Photonics Tests

- **Layout Design Rules & I/O Standardization**
  - Establish Test Pads vs Grating Couplers Layout Design Rules.
  - Fix DC @North, RF @South, Optical I/Os @East&West side of the DUT.

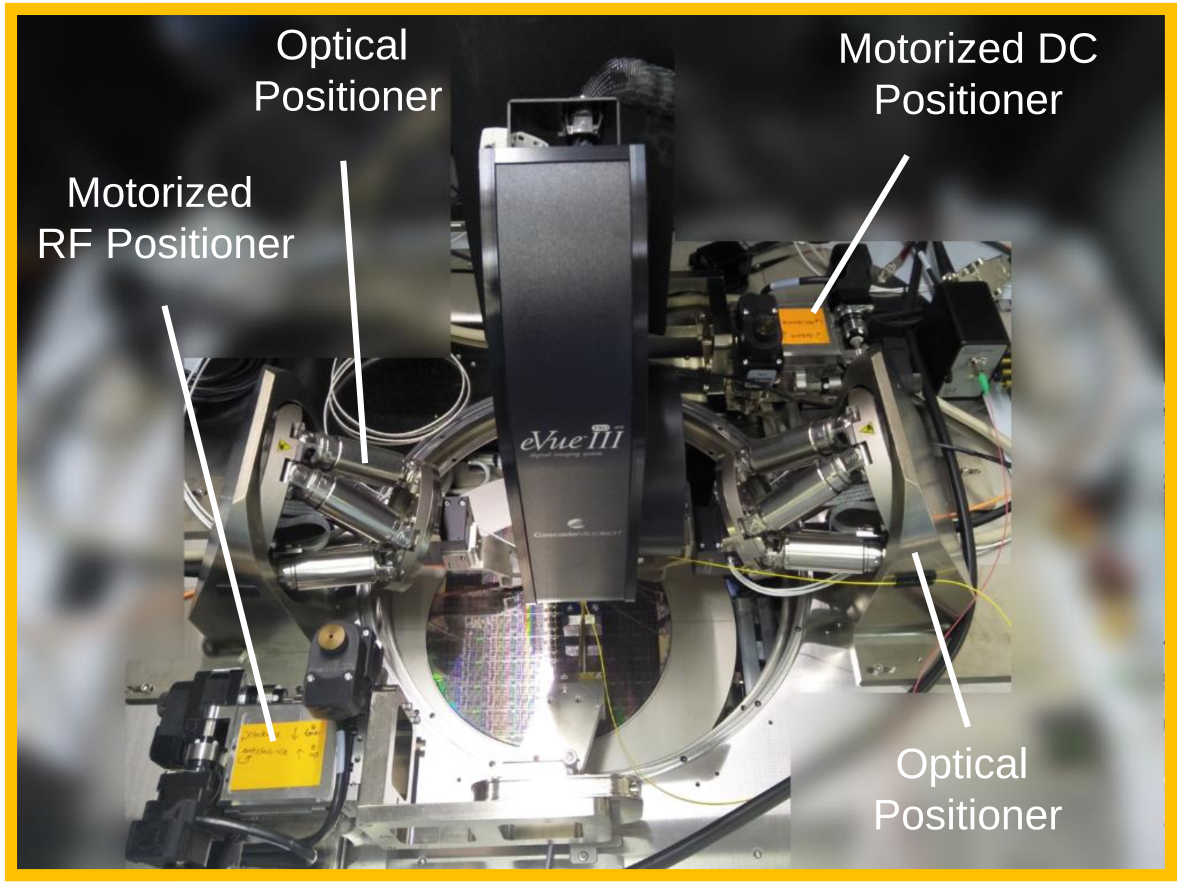
Design Rules for Single Fiber



Design Rules for Fiber Array



Achieving Automatic Production Photonics Tests

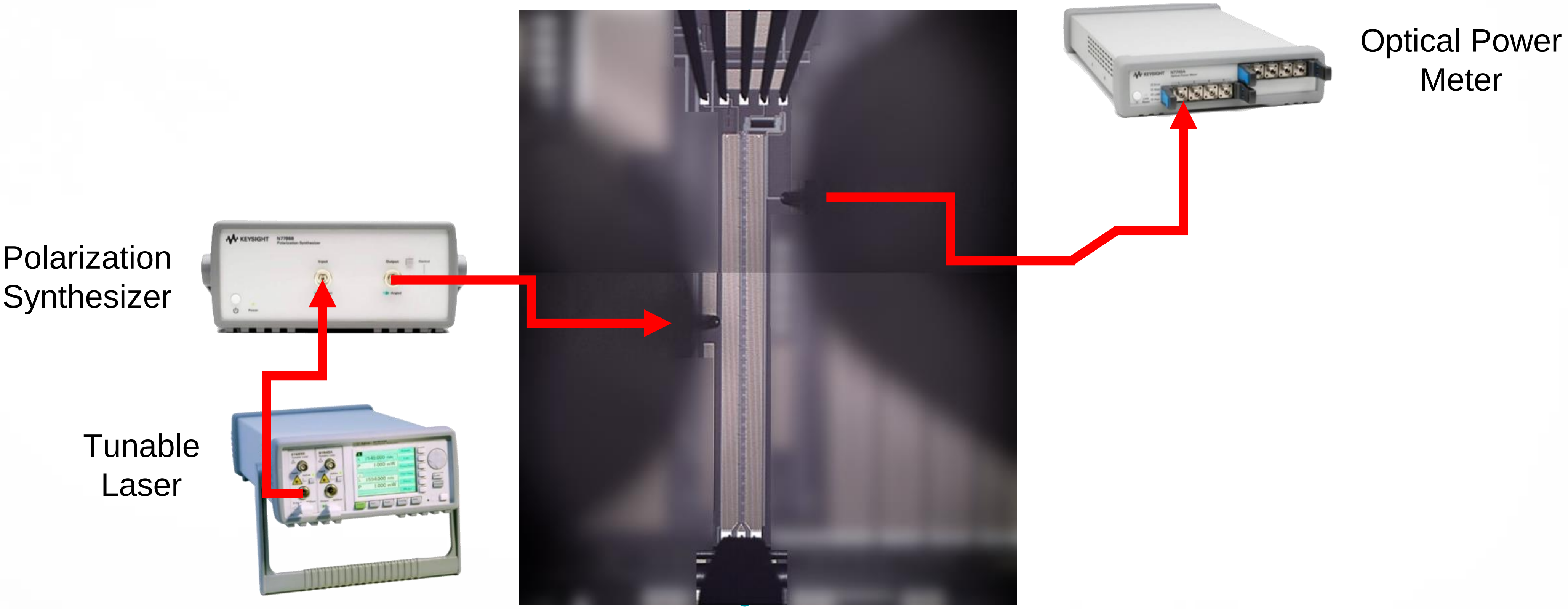


- 2 Optical & 2 Motorized DC/RF positioners
- Handle diff. layout with remote commands

- Fully Automatic 300mm Probe System
- Automatic Wafer Loading/Unloading

Achieving Automatic Production Photonics Tests

- Implement Automatic Testing Architecture - Modulator as Example
  - Peak Search; Optimizing Polarization → Setup optical path



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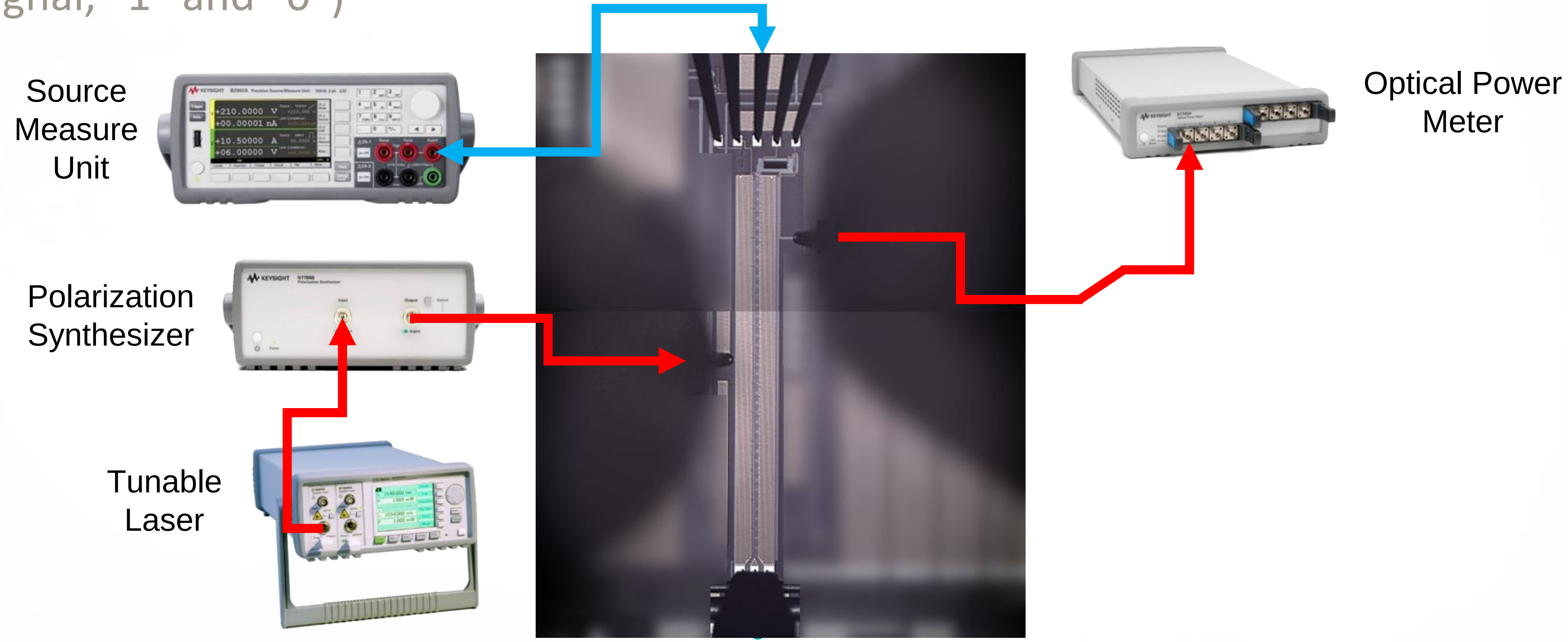
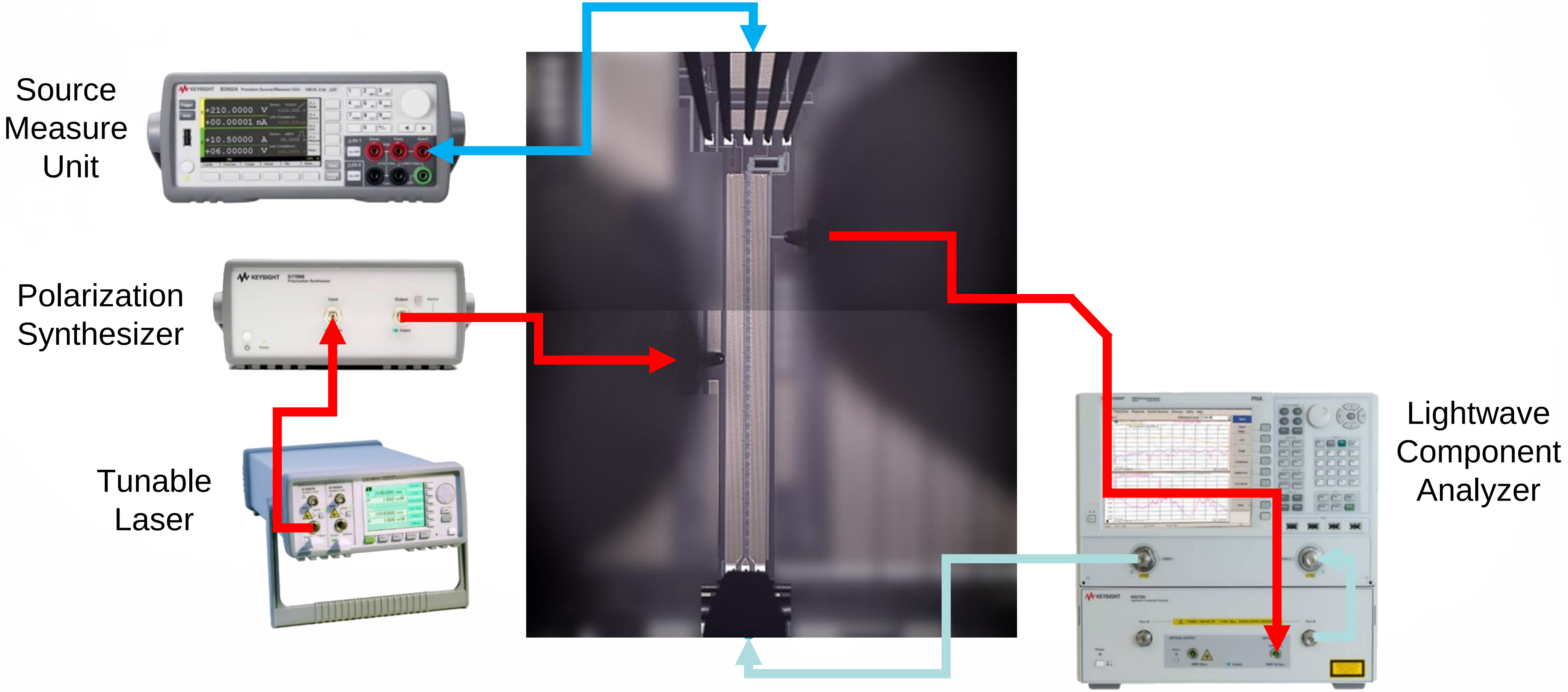
Achieving Automatic Production Photonics Tests

- Implement Automatic Testing Architecture - Modulator as Example
  - Bias Tuning to Measure Extinction Ratio (ratio of optical power levels of a digital signal, “1” and “0”)



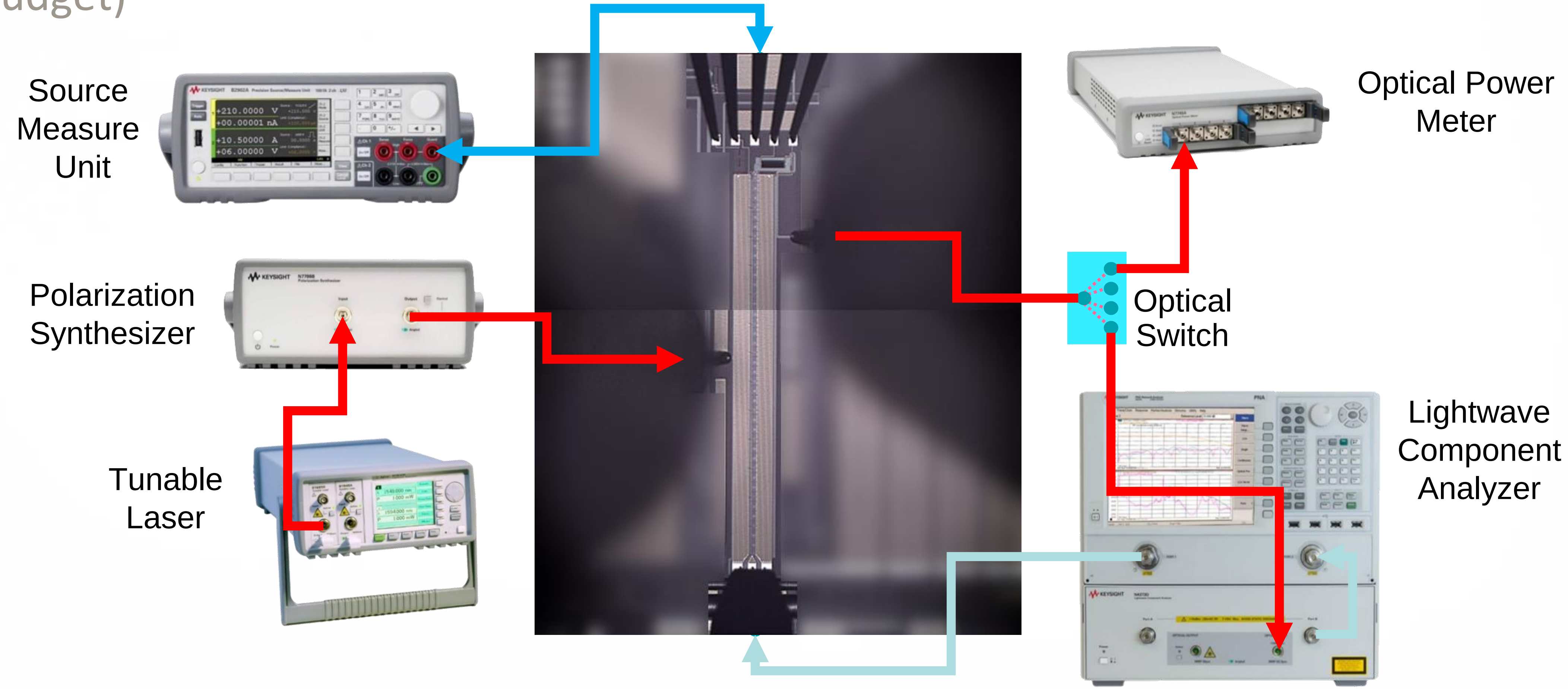
Achieving Automatic Production Photonics Tests

- Implement Automatic Testing Architecture - Modulator as Example
  - Connect to LCA for RF Frequency Sweep to Measure Modulator Bandwidth

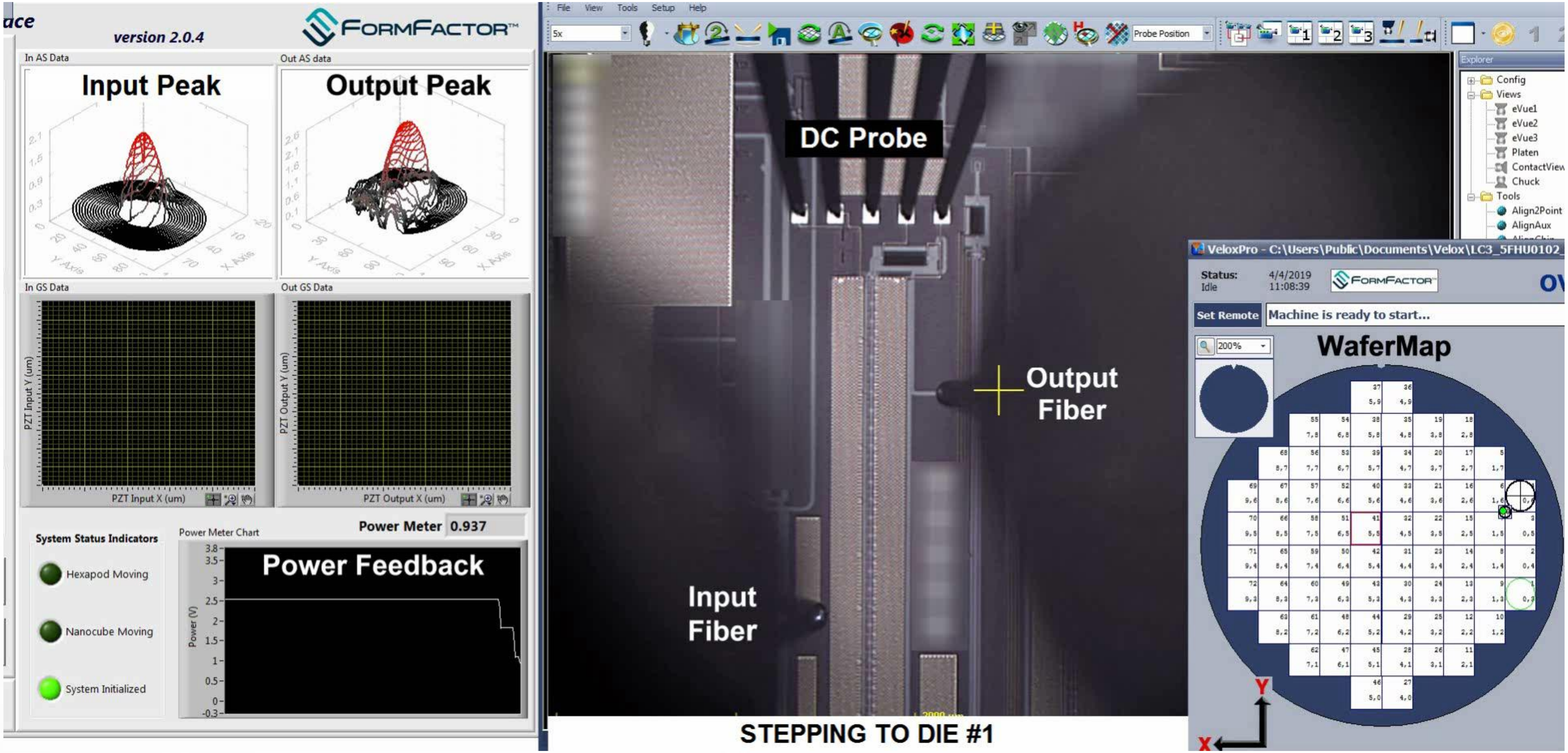


Achieving Automatic Production Photonics Tests

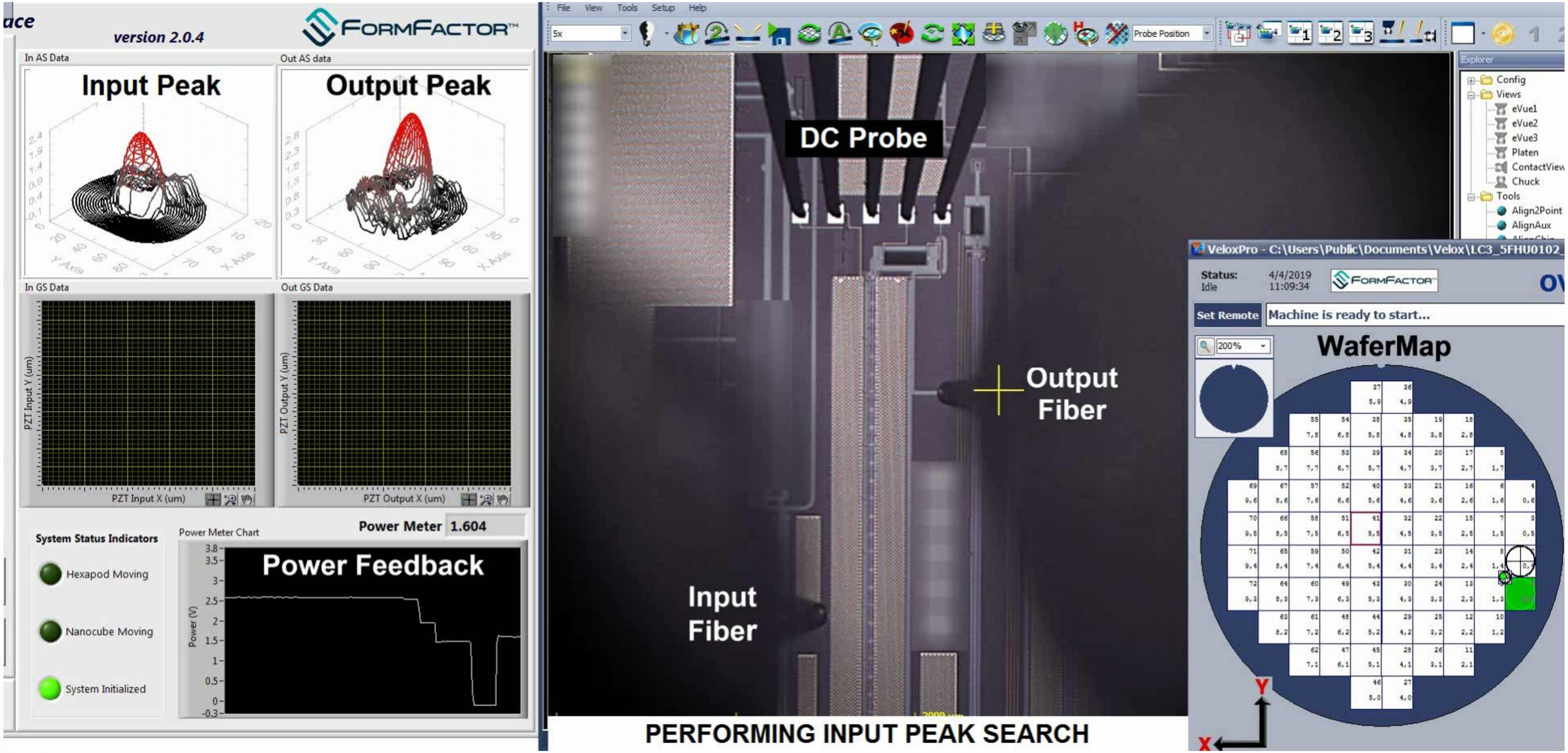
- Implement Automatic Testing Architecture - Modulator as Example
  - Instrument Automation implemented with an Optical Switch. (automation vs power budget)



Achieving Automatic Production Photonics Tests



Achieving Automatic Production Photonics Tests



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Summary

- Why Huge Demands for Silicon Photonics?
  - Need for Energy-Efficient Data Centers is driving huge demands for SiPh.
- Why Wafer-Level Photonics Tests?
  - Determine Known-Good-Dies & Shorten Product Time to Market.
- What are the Test Challenges & Possible Solutions?
  - Fast and Repeatable Fiber-to-Coupler Alignment
  - Must Optimize the Incident Angle for Production Tests.
  - Achieve Good Correlations between Wafer-level & Final Product Tests.
  - Establish Design Rules, Standardize Layout & Implement Automatic Testing Architecture = Fully Automatic Photonics Tests.

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FFI

Thank You!

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