SWTEST

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Silicon Photonics - Challenges & Solutions for Wafer-Level Production Tests

FormFactor™

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GLOBALFOUNDRIES

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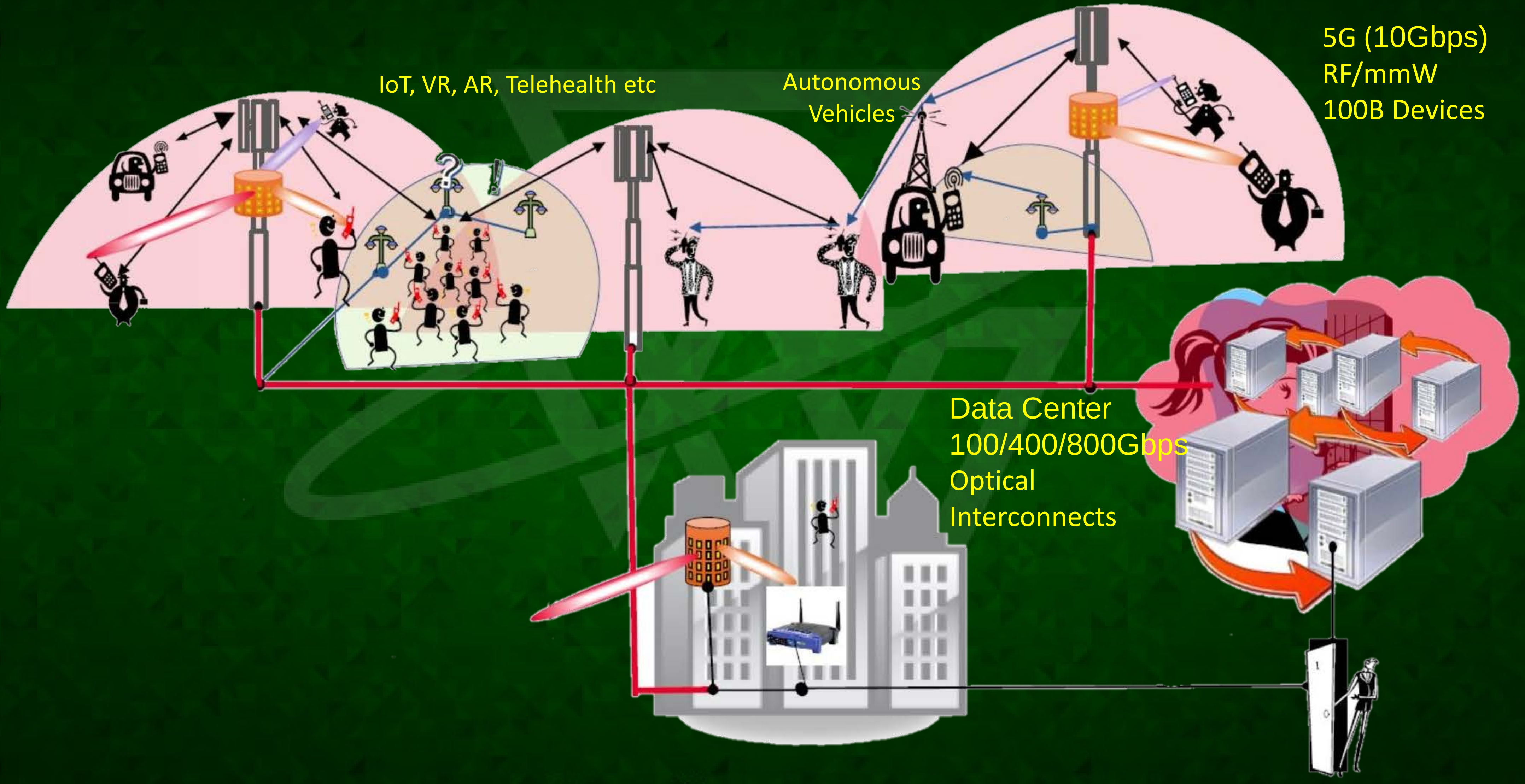
June 2-5, 2019

Overview

- **Why Huge Demands for Silicon Photonics?**
- **Why Wafer-Level Photonics Tests?**
- **What are the Photonics Test Challenges & Possible Solutions?**
  1. How to Optimize Test Setup for Accurate & Repeatable Measurements?
     - How to couple light into a photonics chip (wafer-level)?
     - Optimizing Fiber Height and Incident Angle.
  2. How to Correlate Wafer-Level Test to Final Product test?
  3. How to Achieve Fully Automatic Wafer-Level Production Solution?
- **Summary**

Communication Network for 4th Industrial Revolution



Source: Keysight

The Need for High Performance Network & Data Centers

Big Data Analytics

Artificial Intelligence

Genomics Revolution

Financial Acceleration

Cyber Security

Video Transcoding

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

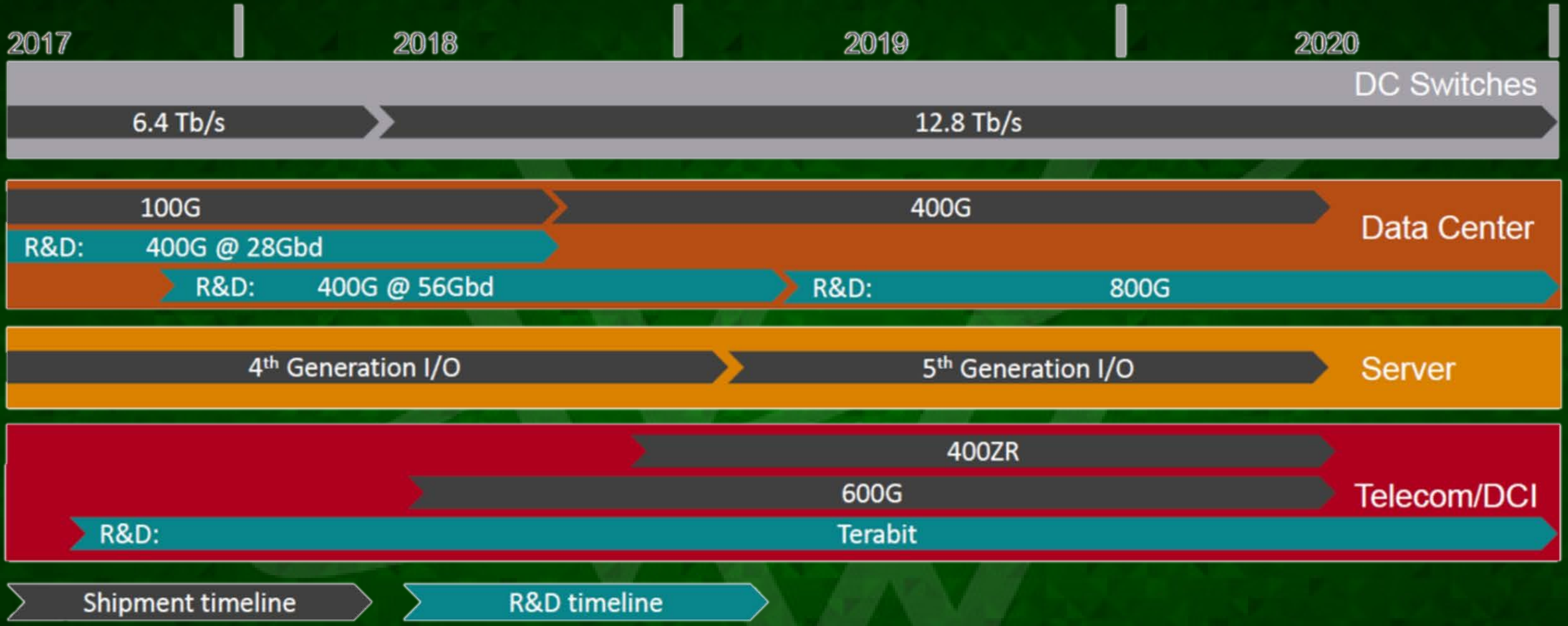
Facebook Invests US$1B HyperScale Data Center in Singapore

- **Facebook's 1st Data Center in Asia (Hub).**
  - IT Talent & Fiber connectivity
  - 170,000 m^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

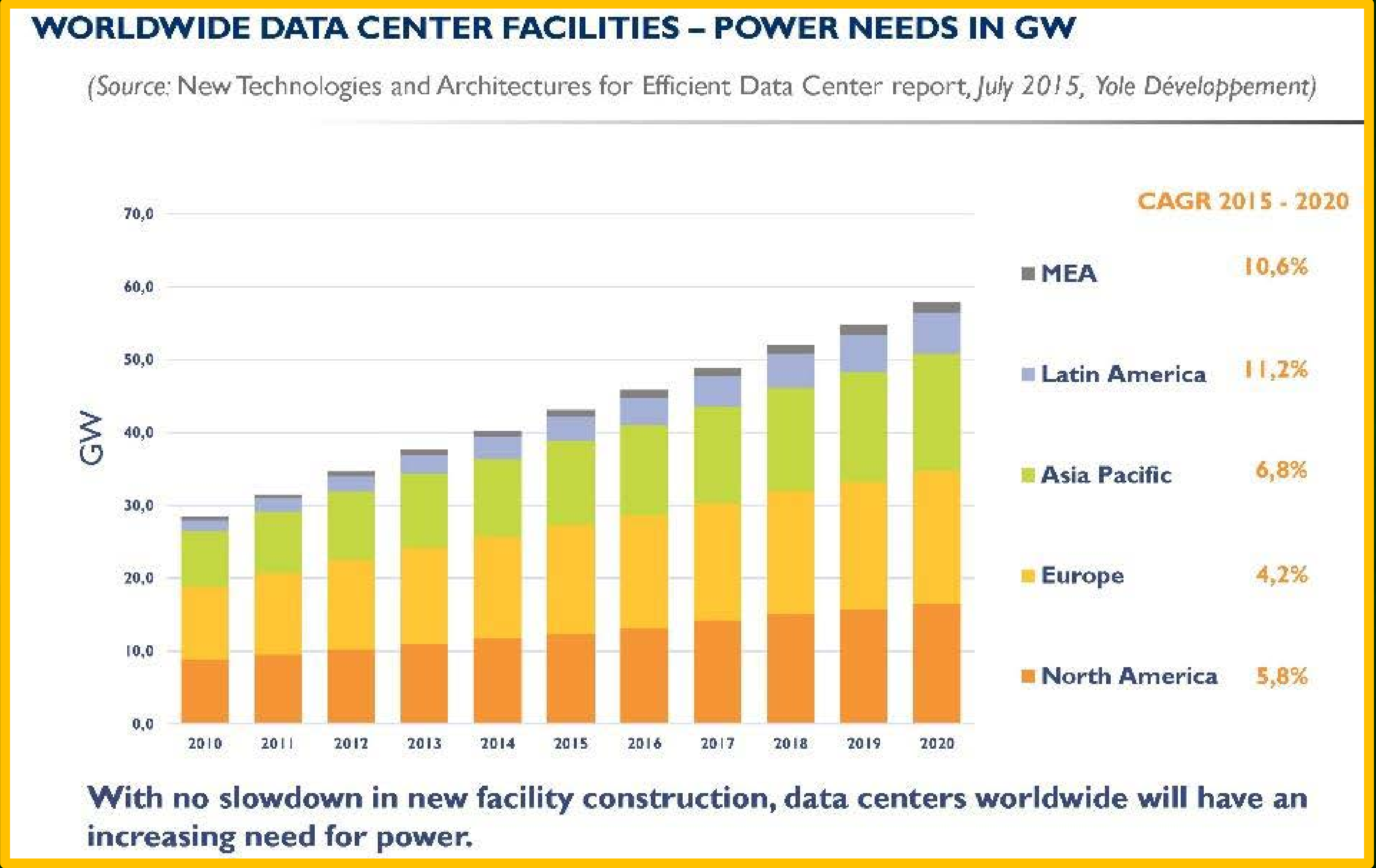
Requirements for Data Center – High Speed Data Rate



- **Wired communication network.**
  - High Speed, High Data Rate, Low Latency requirements.

Requirements for Data Center – Energy Efficiency

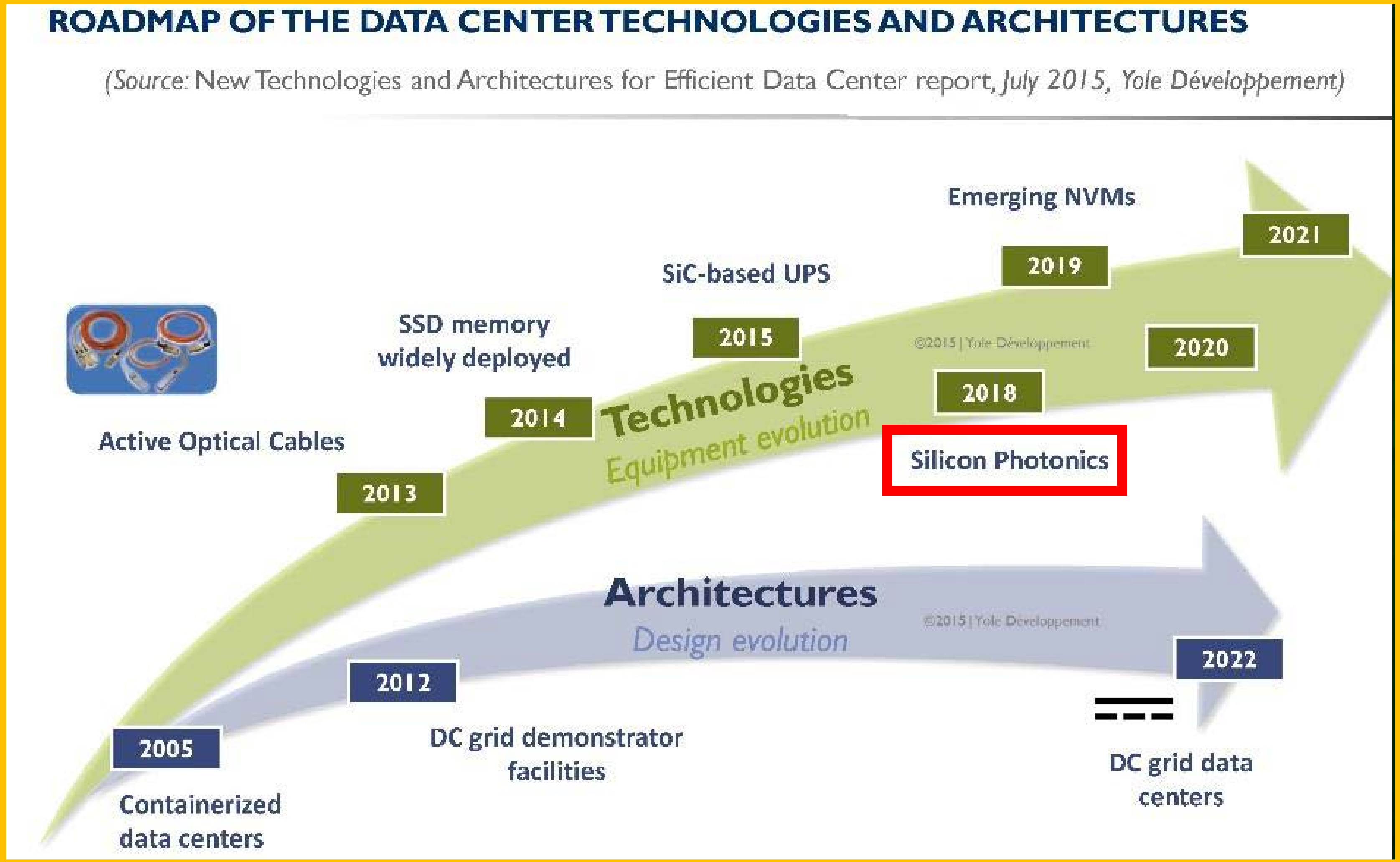
- **Biggest challenge – Not Speed but Reducing power consumption!**
- **Power Usage**
  - 40% - Server & Switch
  - 40% - Cooling
- **Today, Data Centers consume ≈7% of Earth's power**
- ***By 2025, 20%?**



*Data Centres of the world will consume 1/5 of Earth's power by 2025 – João Marques Lima

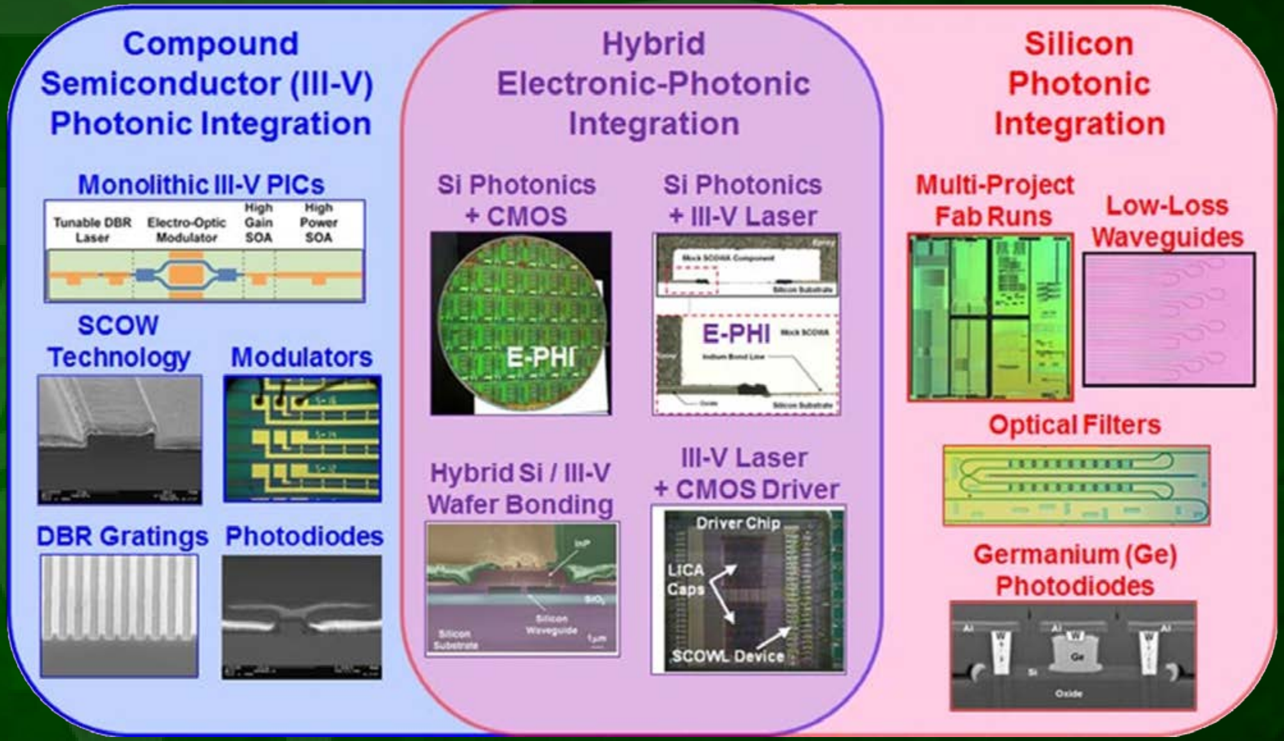
Requirements for Data Center – Energy Efficiency

- **Urgent need for Energy-Efficient Data Centers**
- **SiPh technology is rising star in high speed data transfer.**



Why Silicon Photonics?

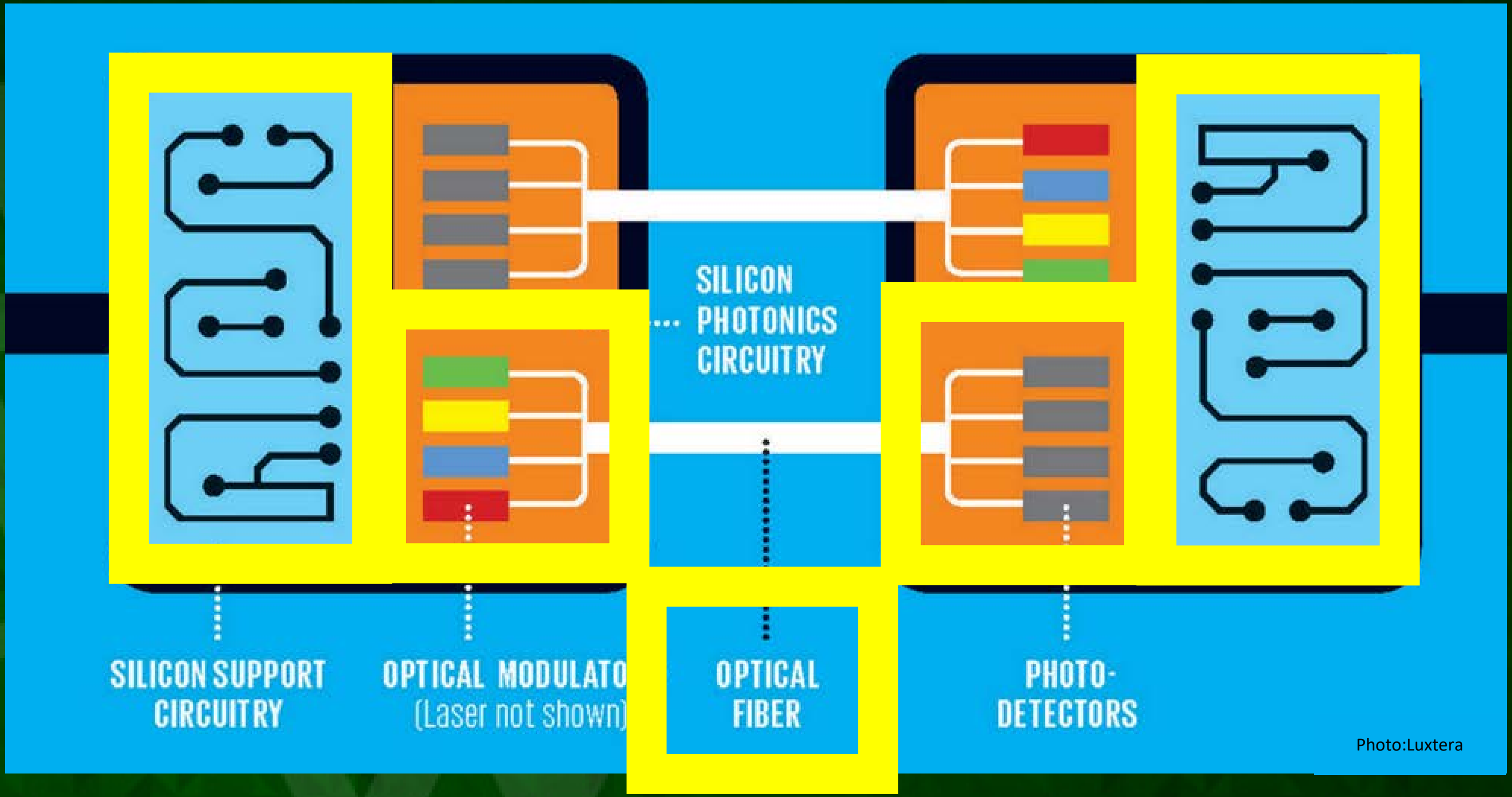
- **Improvements in Thin Film Growth**
  - High Quality Ge on Si
    - Excellent Lattice Matching
    - Hi-Speed Ge-on-Si Photodiodes
- **Exploiting Silicon Technologies**
  - Low-Cost High-Volume Production
  - Low-Power Logic devices
  - High-Speed RFCMOS devices
  - Heterogenous Integration/Packaging



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

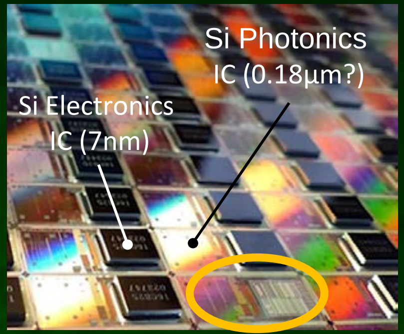
Evolution of Optical Transceivers

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

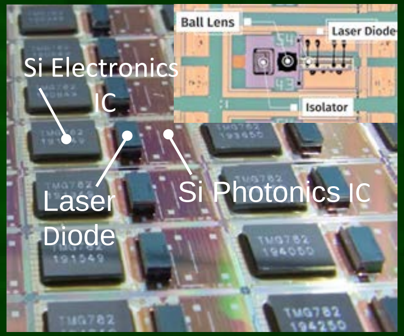
Time

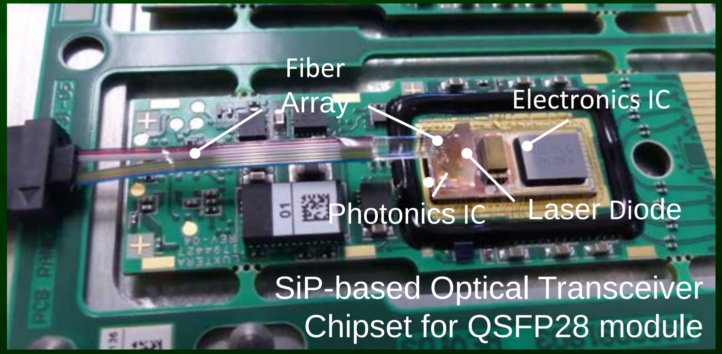
Why Wafer-level Tests?

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



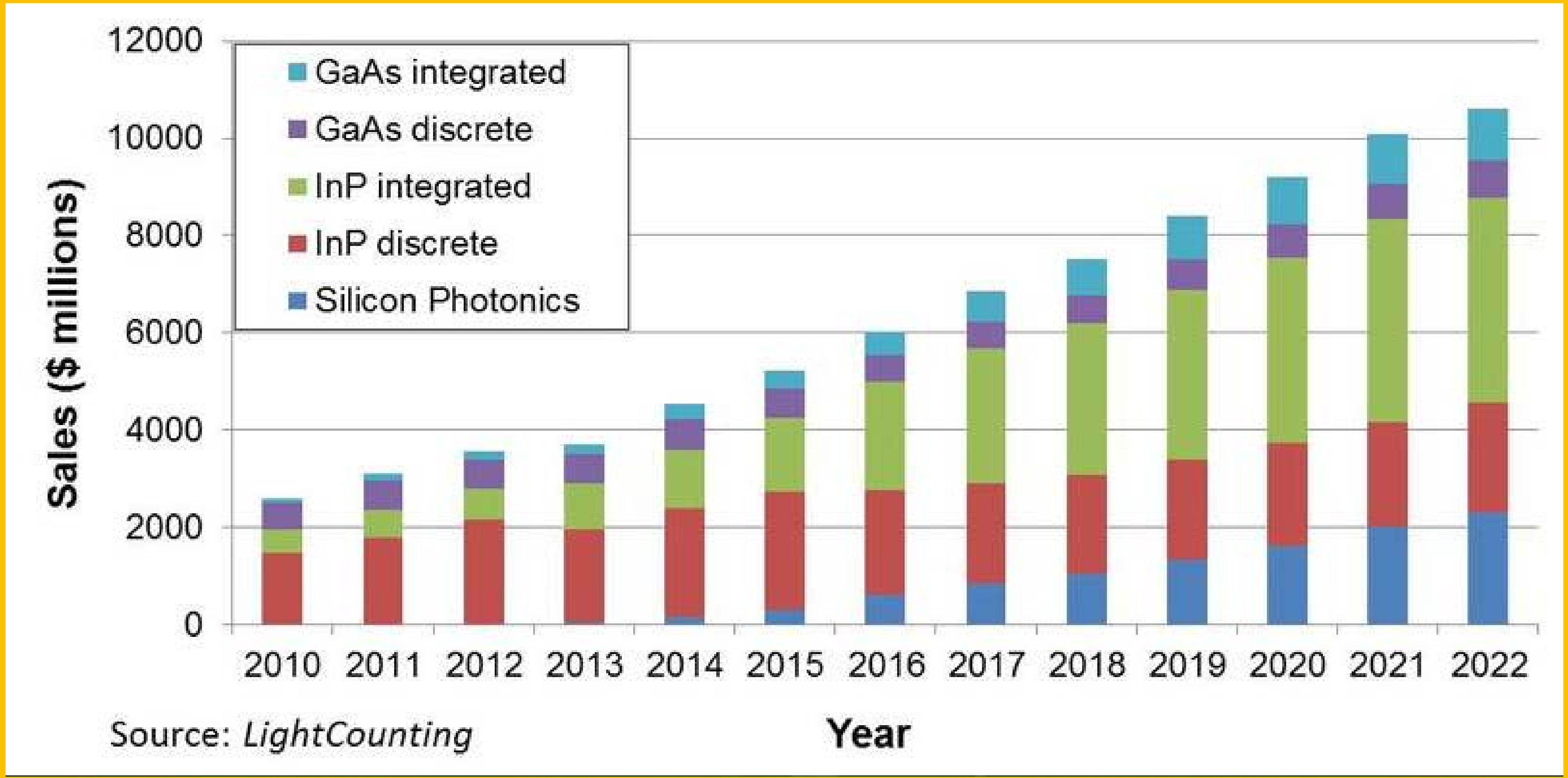
Continuous Wave Laser Diode on SiPh-Die





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

Integrated Optical Transceiver Market

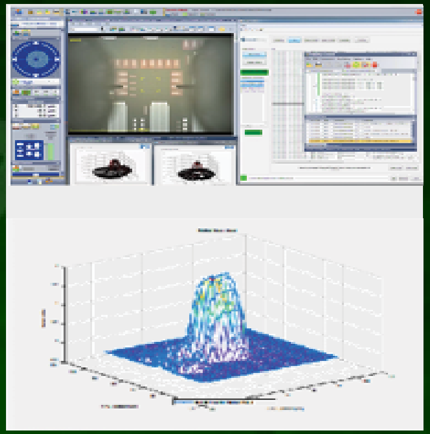


SiPh
US$2.3B
(US$1.6B)

- **SiPh Transceivers - US$2.3B, CAGR >35% (2022).**
- **Demonstrate using SiPh in Switches for Data Centers.**

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

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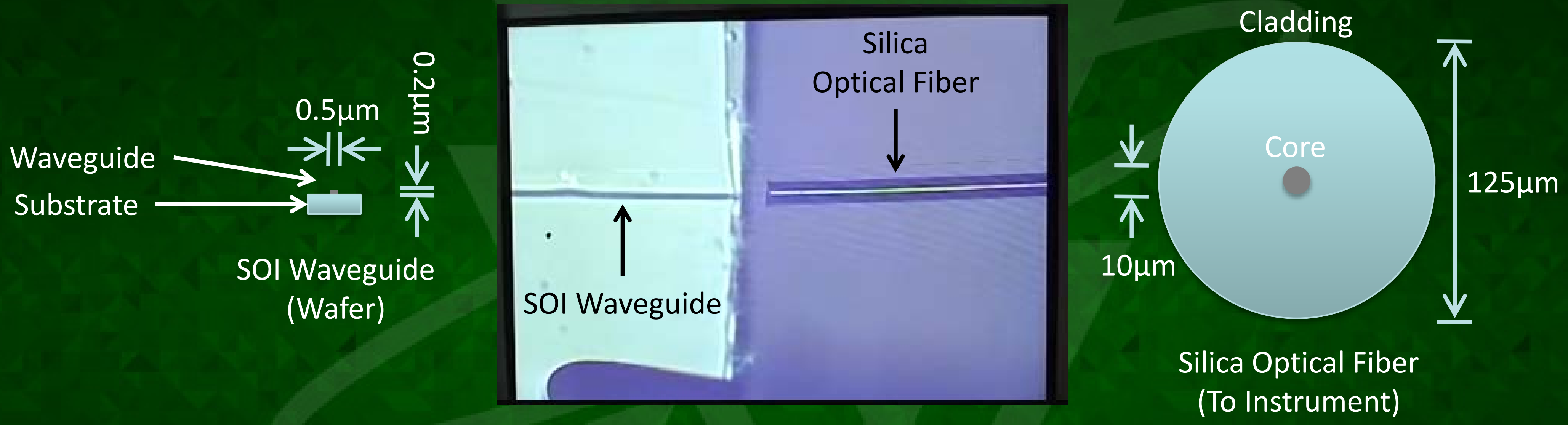
- **Why Wafer-Level Photonics Tests?**
- **What are the Photonics Test Challenges & Possible Solutions?**
  1. How to Optimize Test Setup for Accurate & Repeatable Measurements?
     - How to couple light into a photonics chip (wafer-level)?
     - Optimizing Fiber Height and Incident Angle.
  2. How to correlate wafer level test to final product test?
  3. How to Achieve Fully Automatic Wafer-Level Production Solution?
- **Summary**

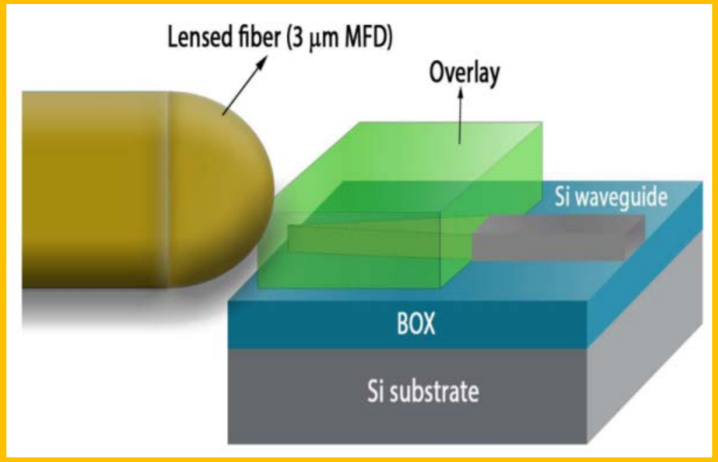
1.1. How to Couple Light into a Photonics Chip (Wafer-level)?

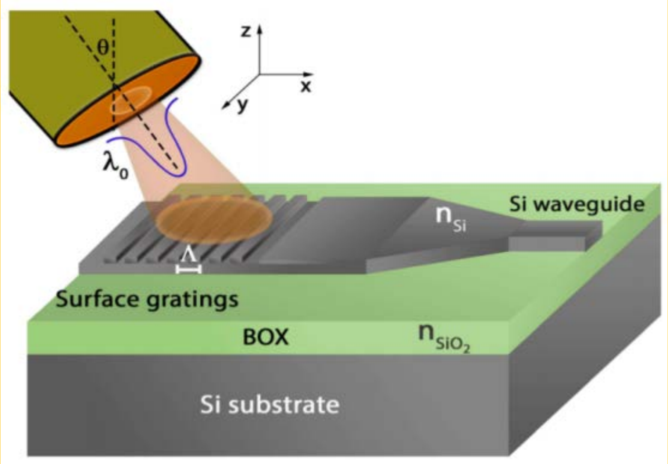


- **Fiber vs SOI Waveguide – 2 order mag difference in Size**
- **Direct Coupling ≈ >96% Insertion Loss***

*CMDITR (Center on Materials and Devices for Information Technology Research) Science and Technology Center

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





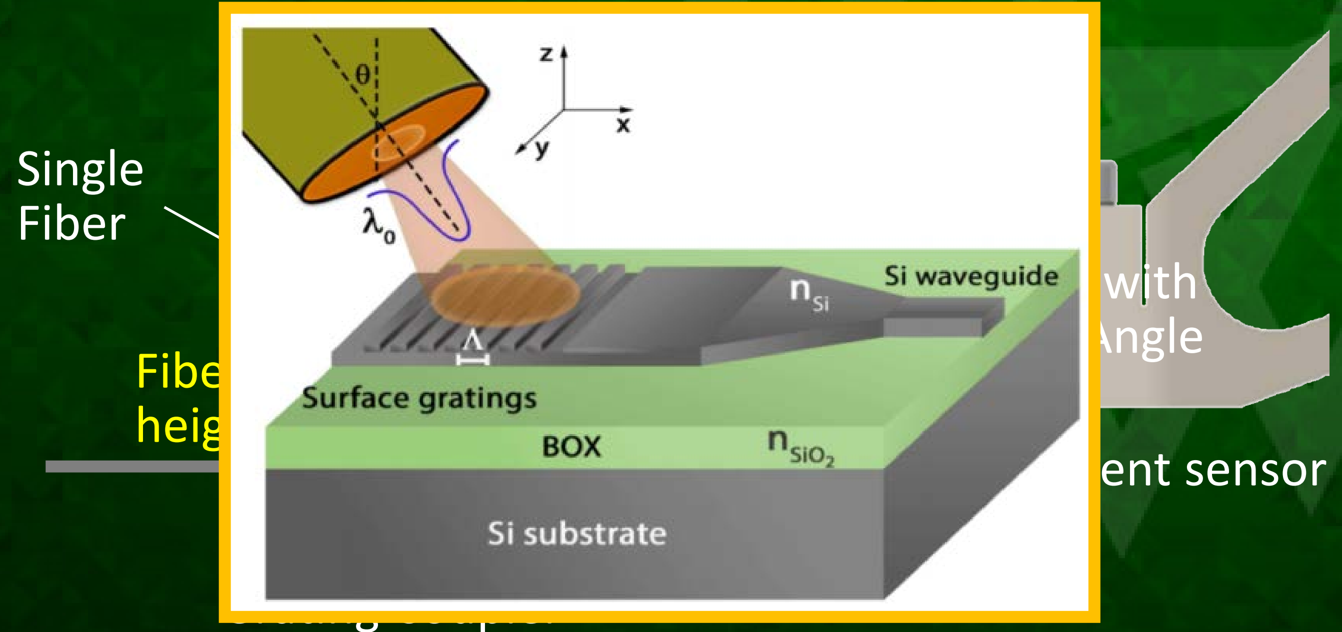
- **Edge Coupling**
  - Final Product (Die Level)
  - Sub-dB Loss Per Facet
  - 200nm – 300nm Bandwidth
  - Low Polarization Sensitivity
  - Harder to Fabricate/Test
  - Fixed Interface (Edge of Chip)
  - Low Fiber-Chip Alignment Tolerance

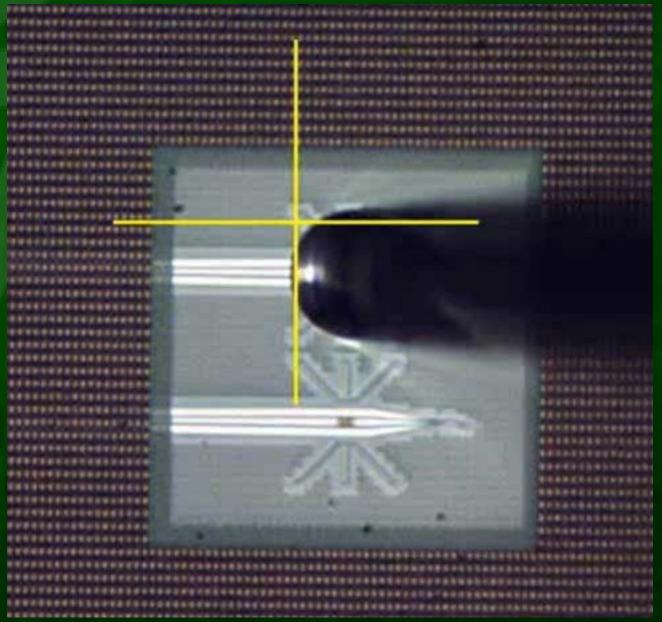
- **Grating Coupling**
  - Process Development & KGD (Wfr Level)
  - -2dB → -4dB Loss per Grating Coupler
  - Typically 60nm Bandwidth
  - Polarization Dependent
  - Easier to Fabricate/Test
  - Flexibility of interface positions
  - High Fiber-Chip Alignment Tolerance

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

1.2. Optimizing Setup – Optical Coupling for Photonics Tests

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

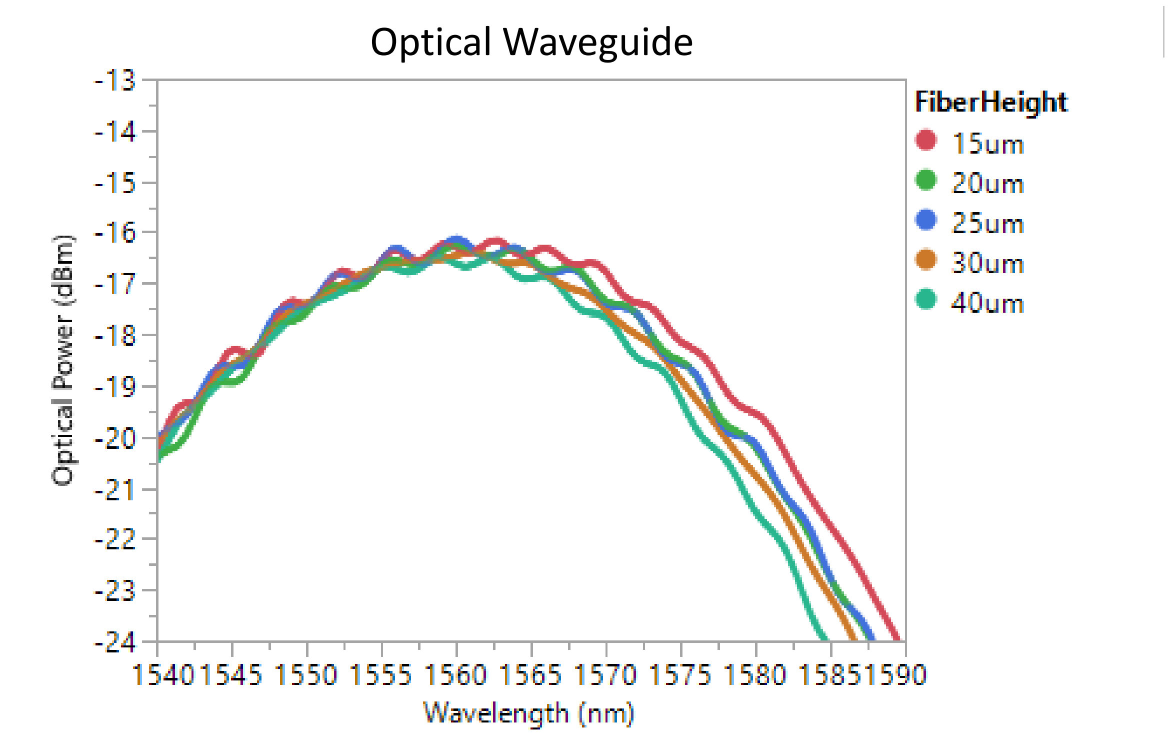


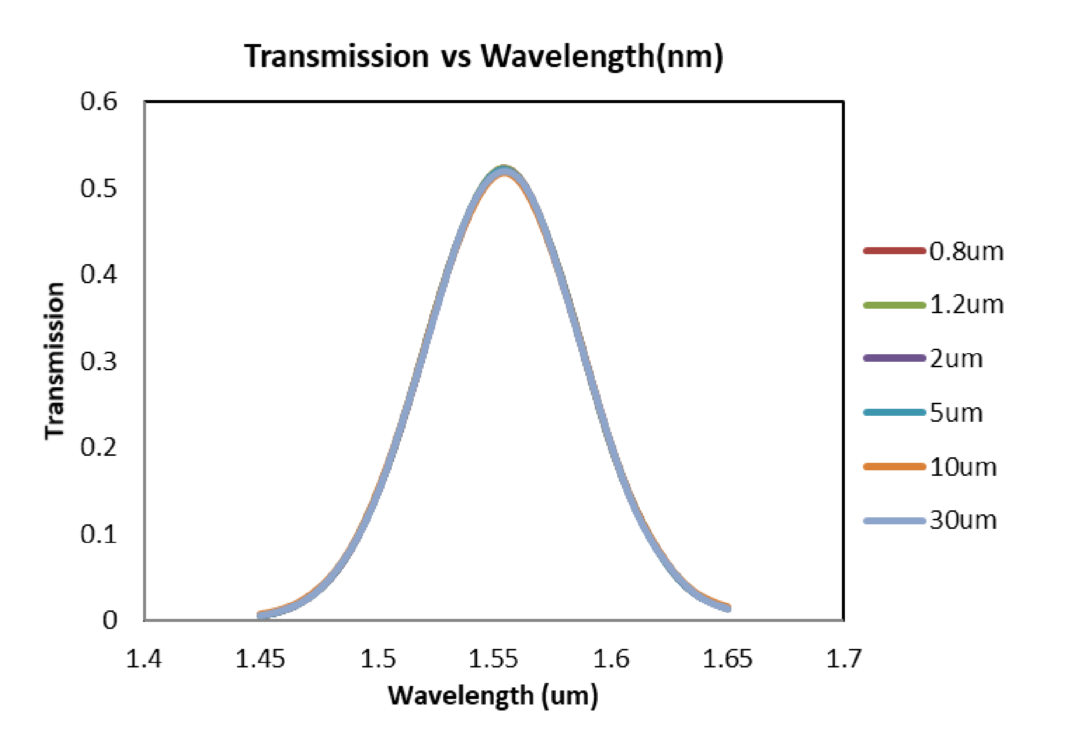


Fiber Alignment with Sinusoidal Scan

1.2.1. 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.

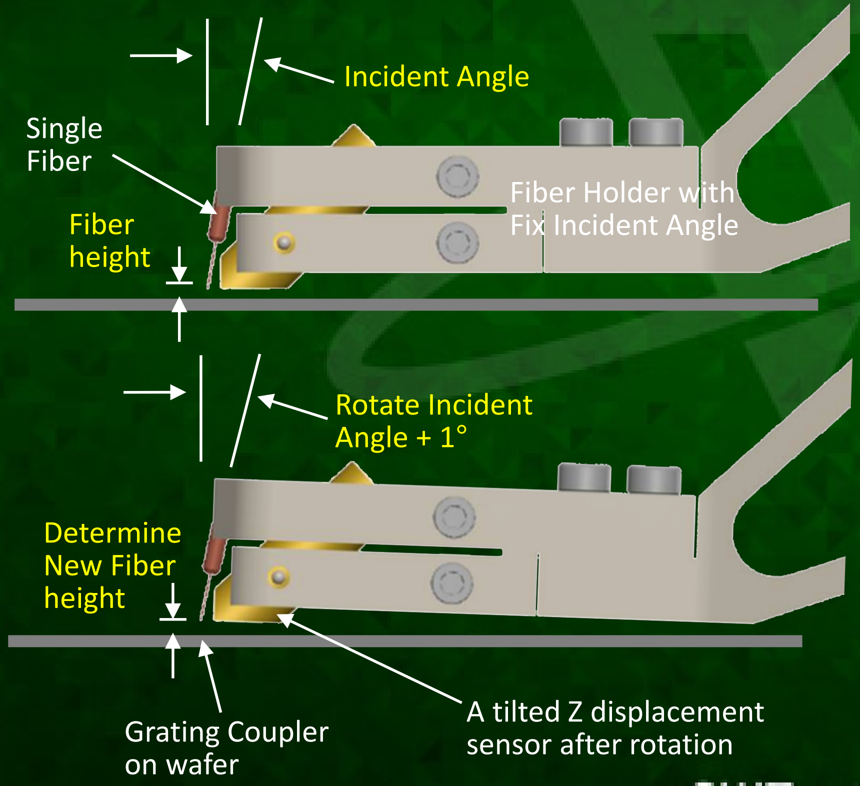


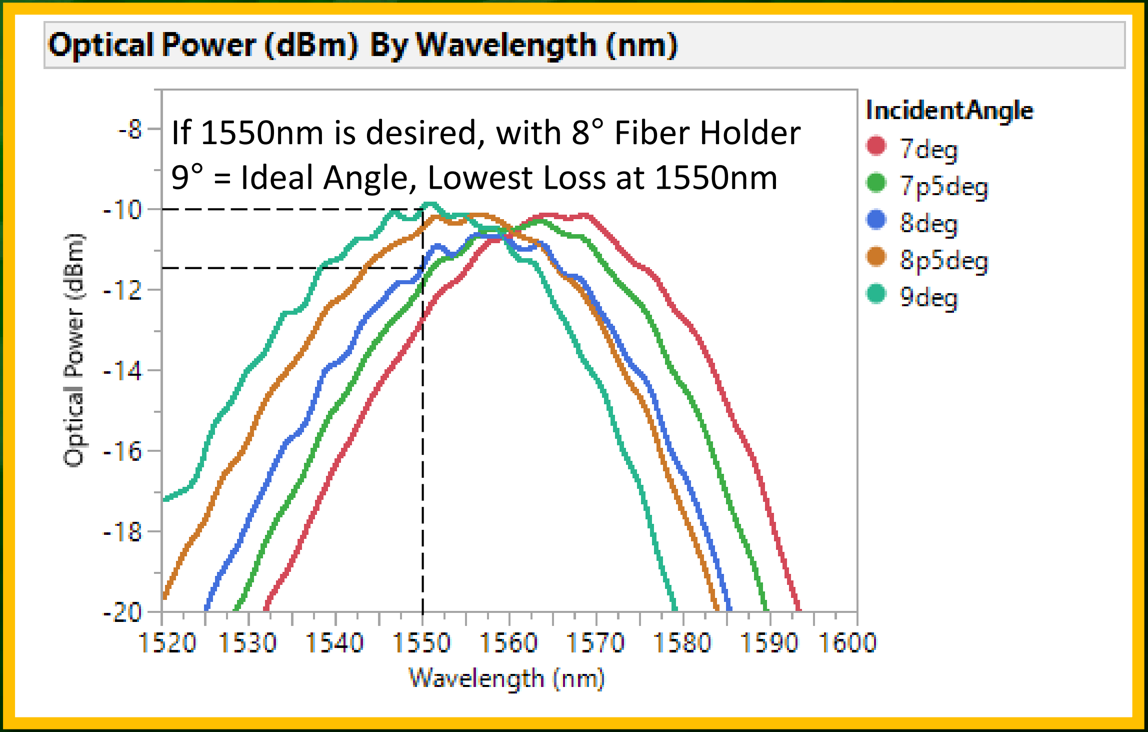


1.2.2. Optimizing Setup – Incident Angle (Wafer-Level)

– 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).

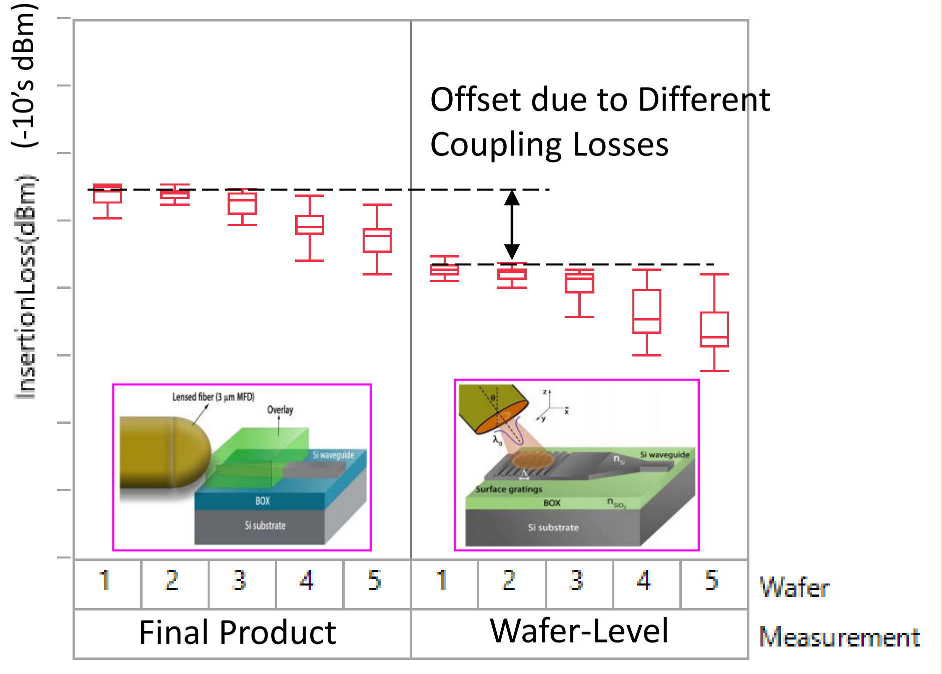
– Critical to determine Optimal Incident Angle before Production Tests (1.5dB improvement).





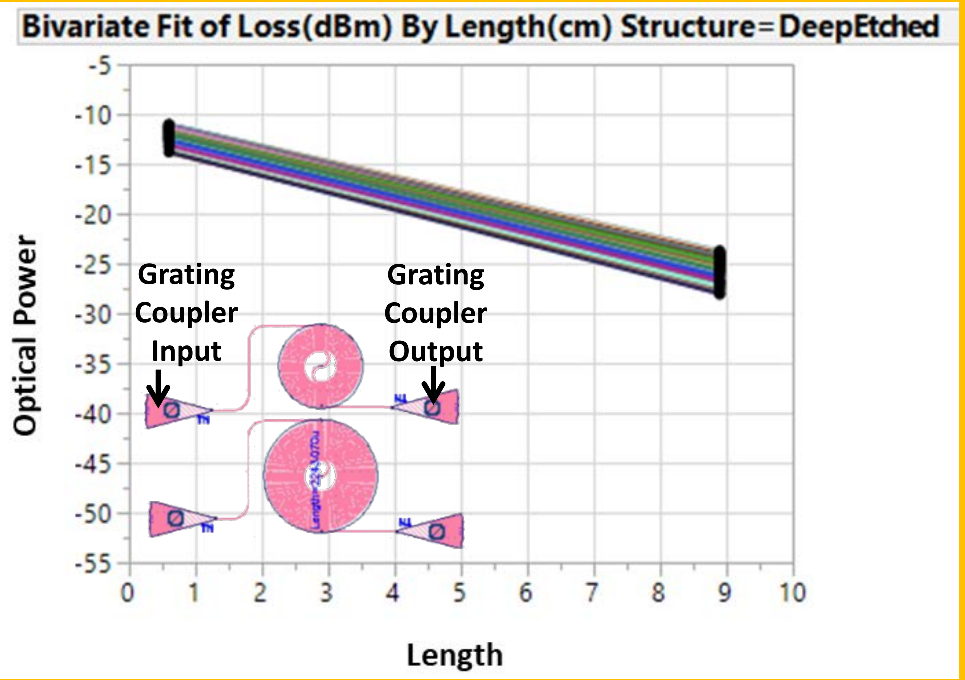
2. Wafer-Level vs Final Product Tests (Passive Device)

Offset bet wfr-level & final product



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

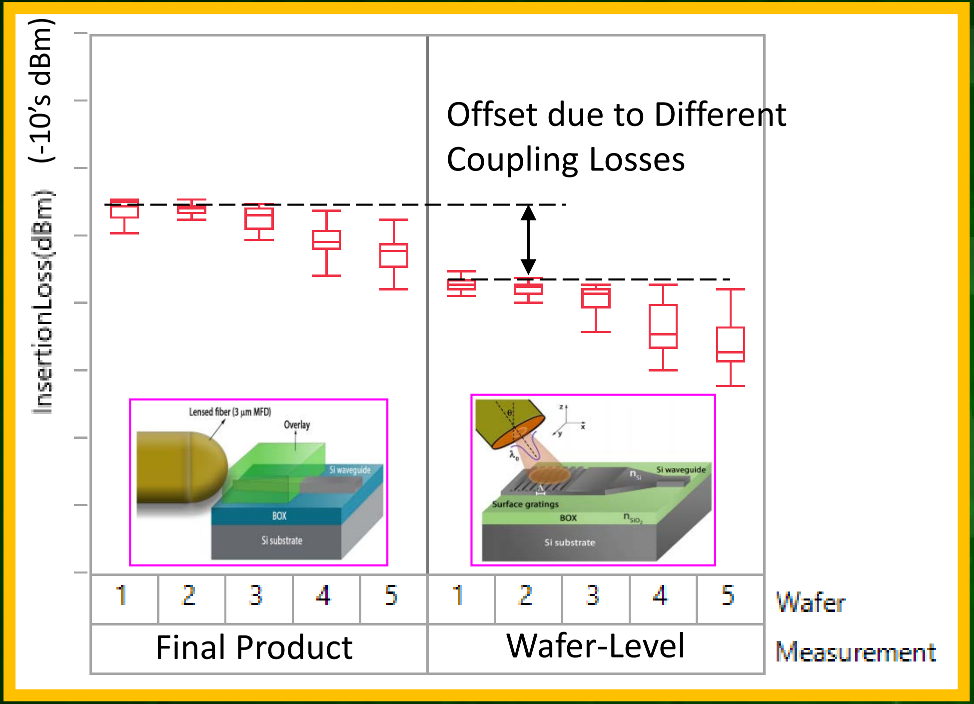
Obtaining Coupling Losses



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

2. Wafer-Level vs Final Product Tests (Passive Device)

Offset bet wfr-level & final product



- Critical to correlate Wafer-Level & Final product Tests
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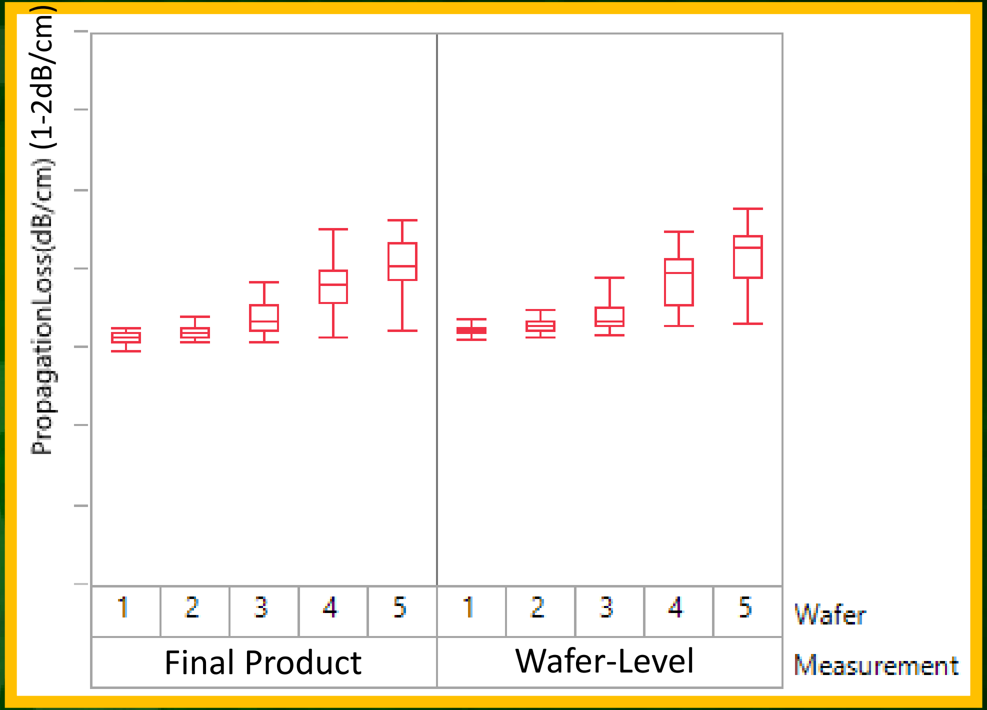
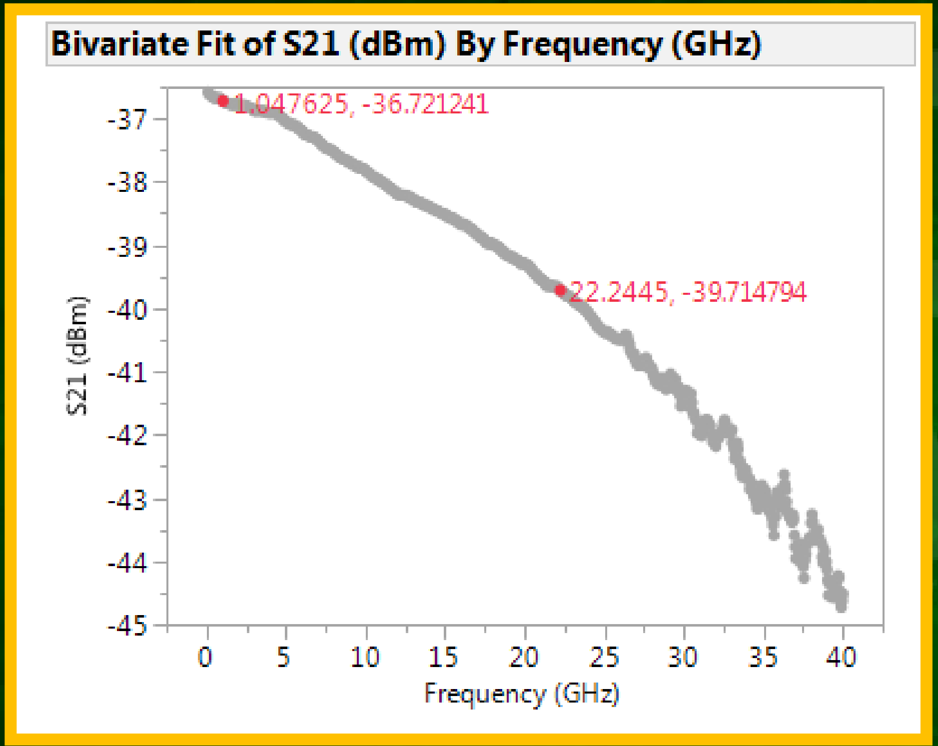
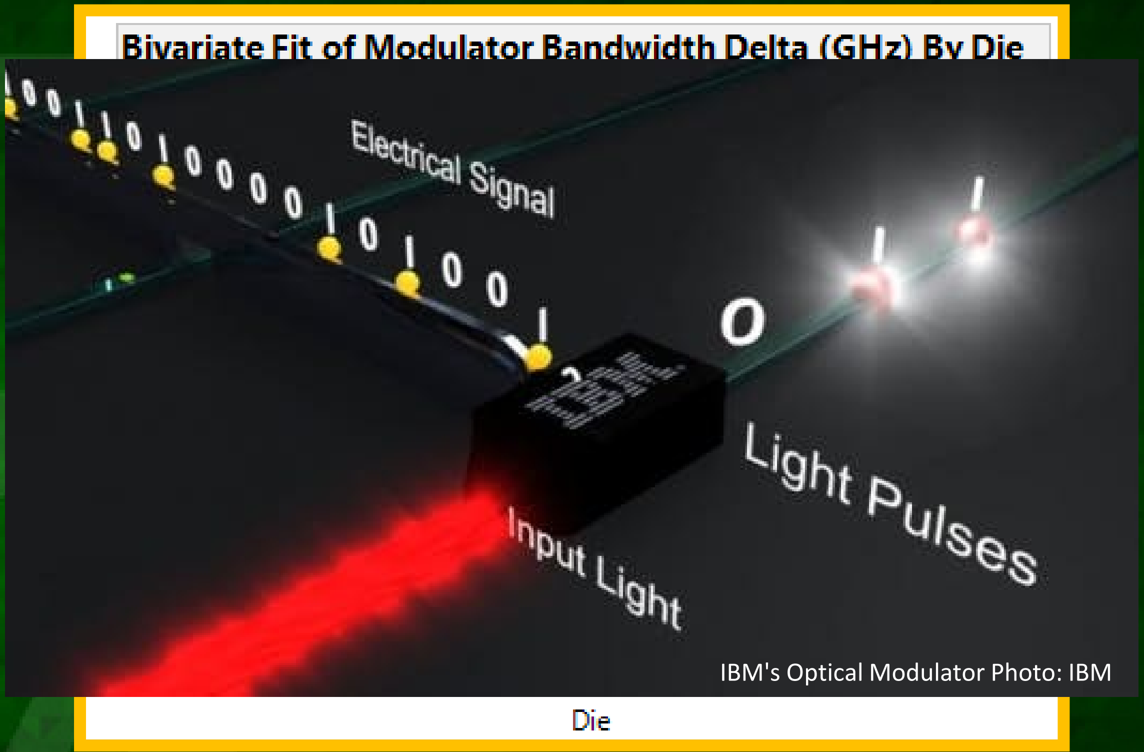
After Coupling Losses Correction



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

2. Wafer-Level vs Final Product Tests (Active Device)





IBM's Optical Modulator Photo: IBM

- Testing Optical Modulator (E-O)
- Measure 3 dB Bandwidth for all Dies through Grating Couplers.
- Small Difference in BW for Same Die
- Good Correlations between Wfr-level & Final Product Tests.

3. 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	

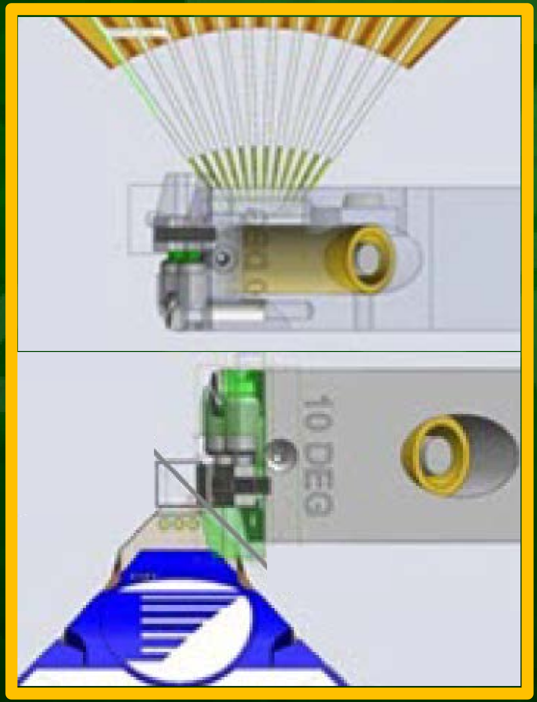
Photonics Device Tests

Photonics IC Tests

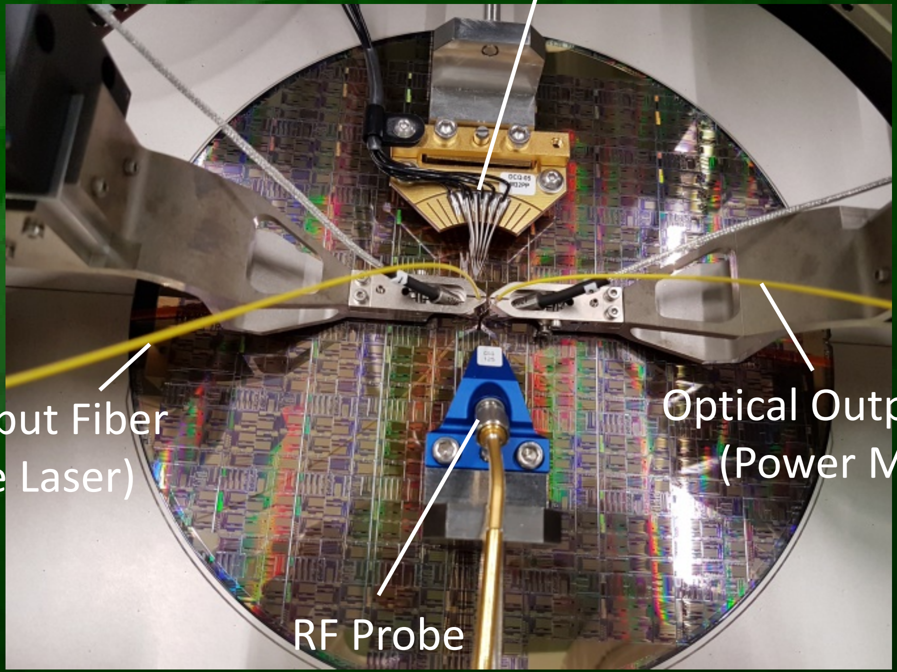
3. Achieving Automatic Production Photonics Tests

- **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

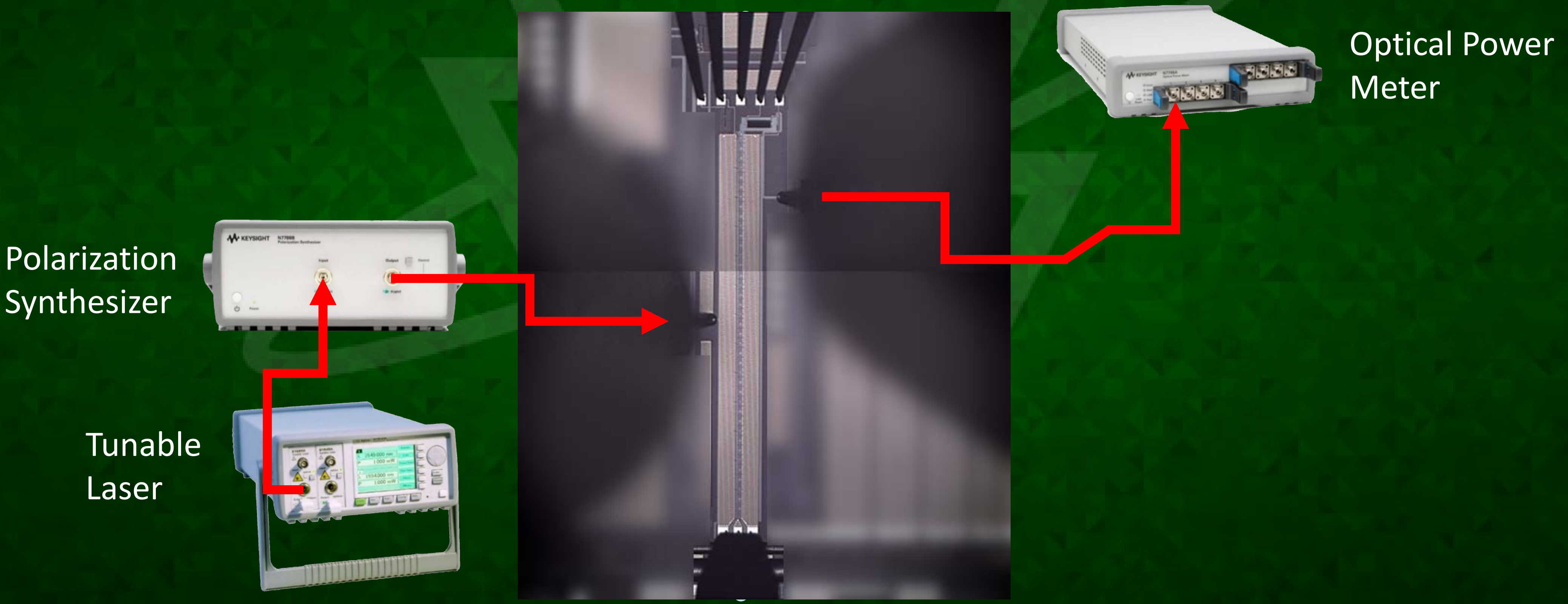


Design Rules for Fiber Array



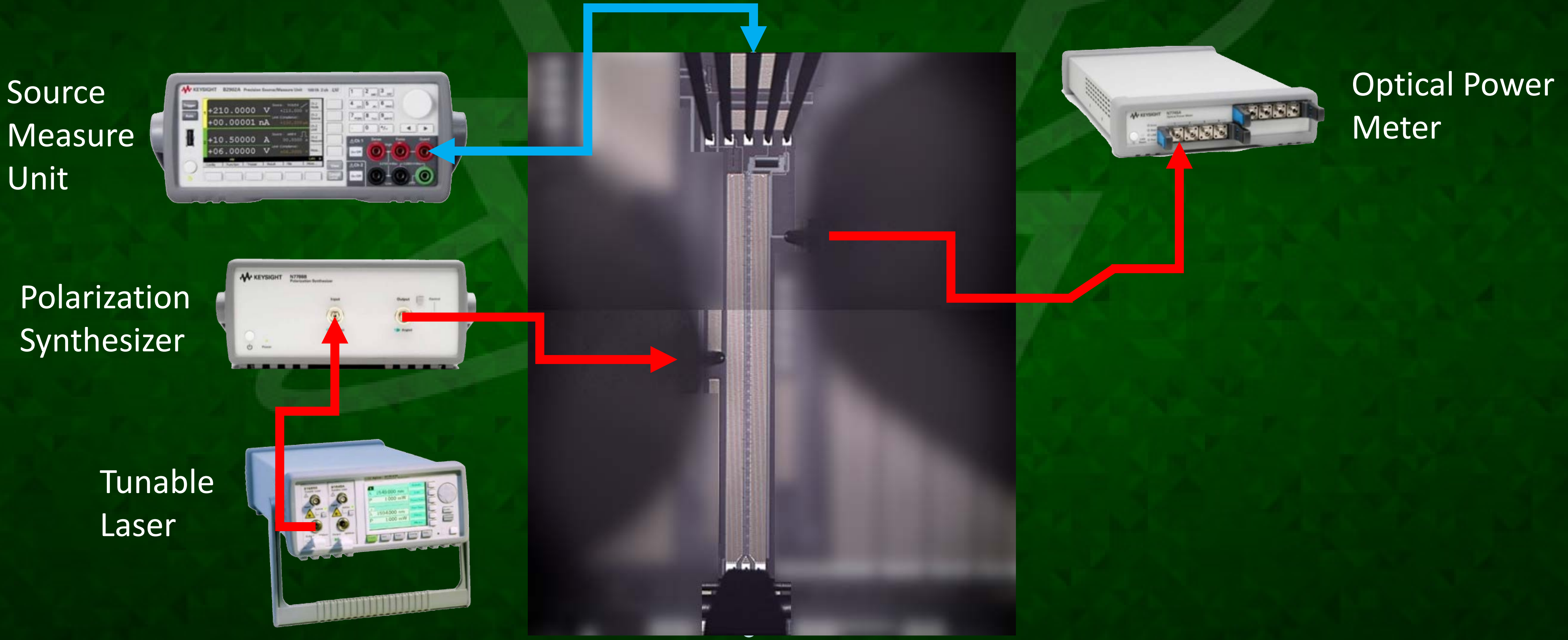
3. Achieving Automatic Production Photonics Tests

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



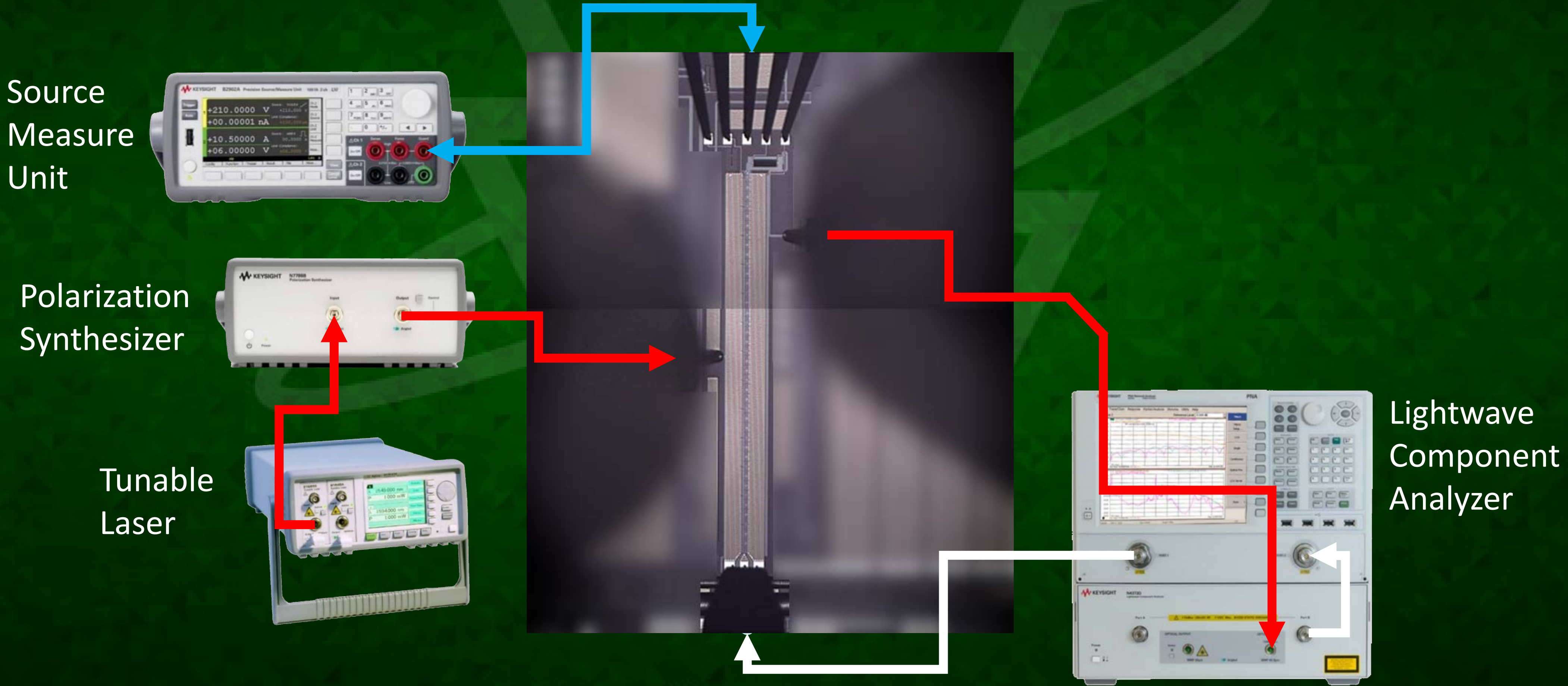
3. Achieving Automatic Production Photonics Tests

- **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”)



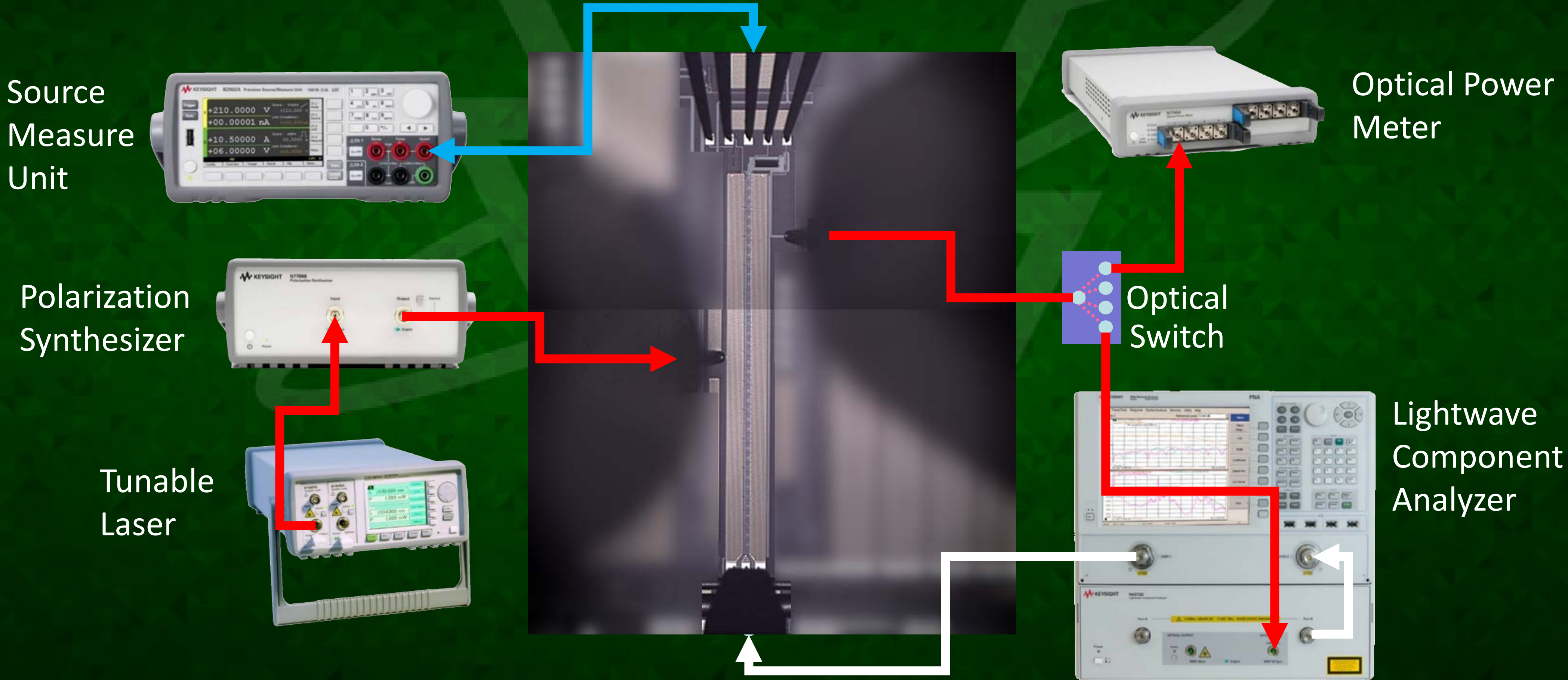
3. Achieving Automatic Production Photonics Tests

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

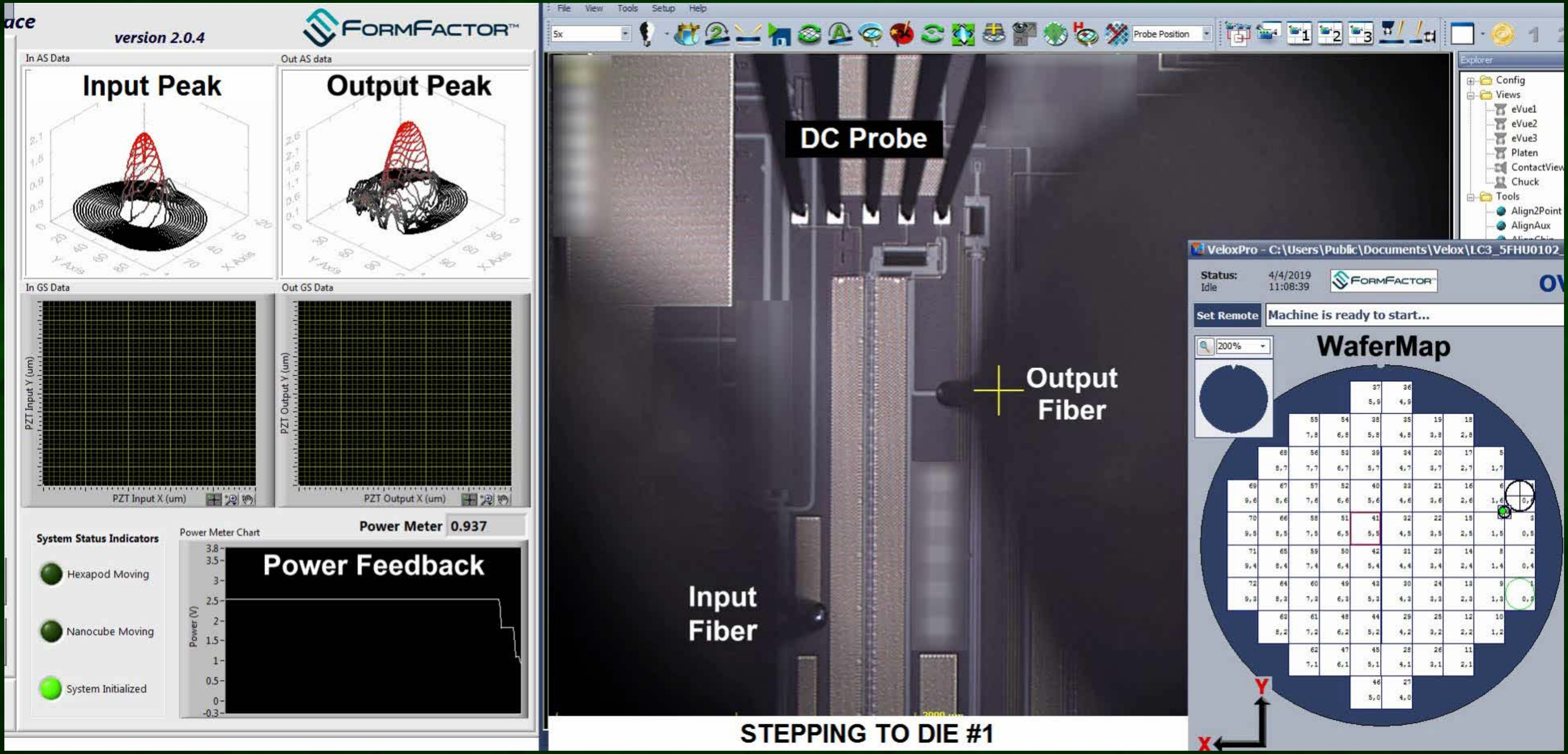


3. Achieving Automatic Production Photonics Tests

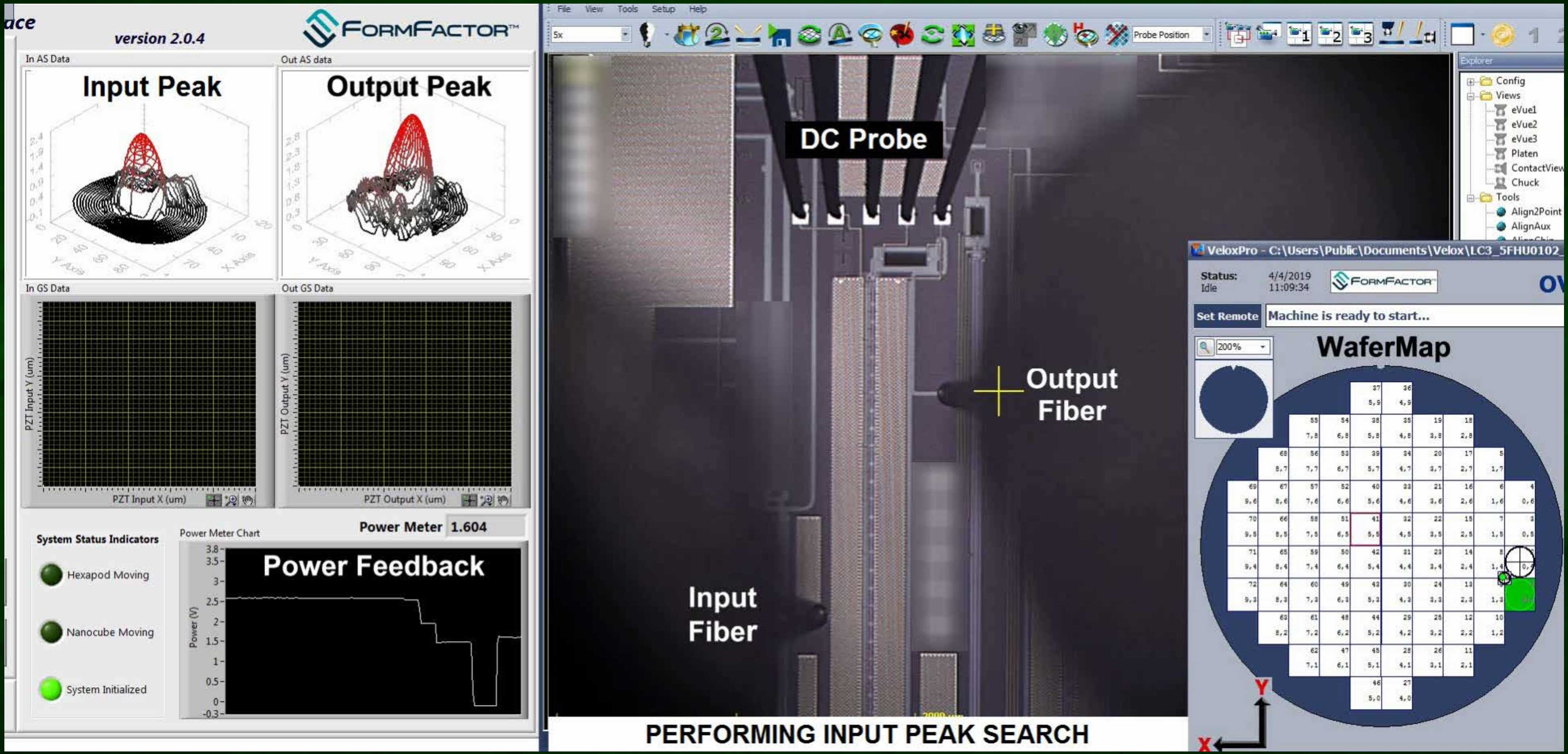
- **Implement Automatic Testing Architecture - Modulator as Example**
  - Instrument Automation implemented with an Optical Switch. (automation vs power budget)



3. Achieving Automatic Production Photonics Tests



3. Achieving Automatic Production Photonics Tests



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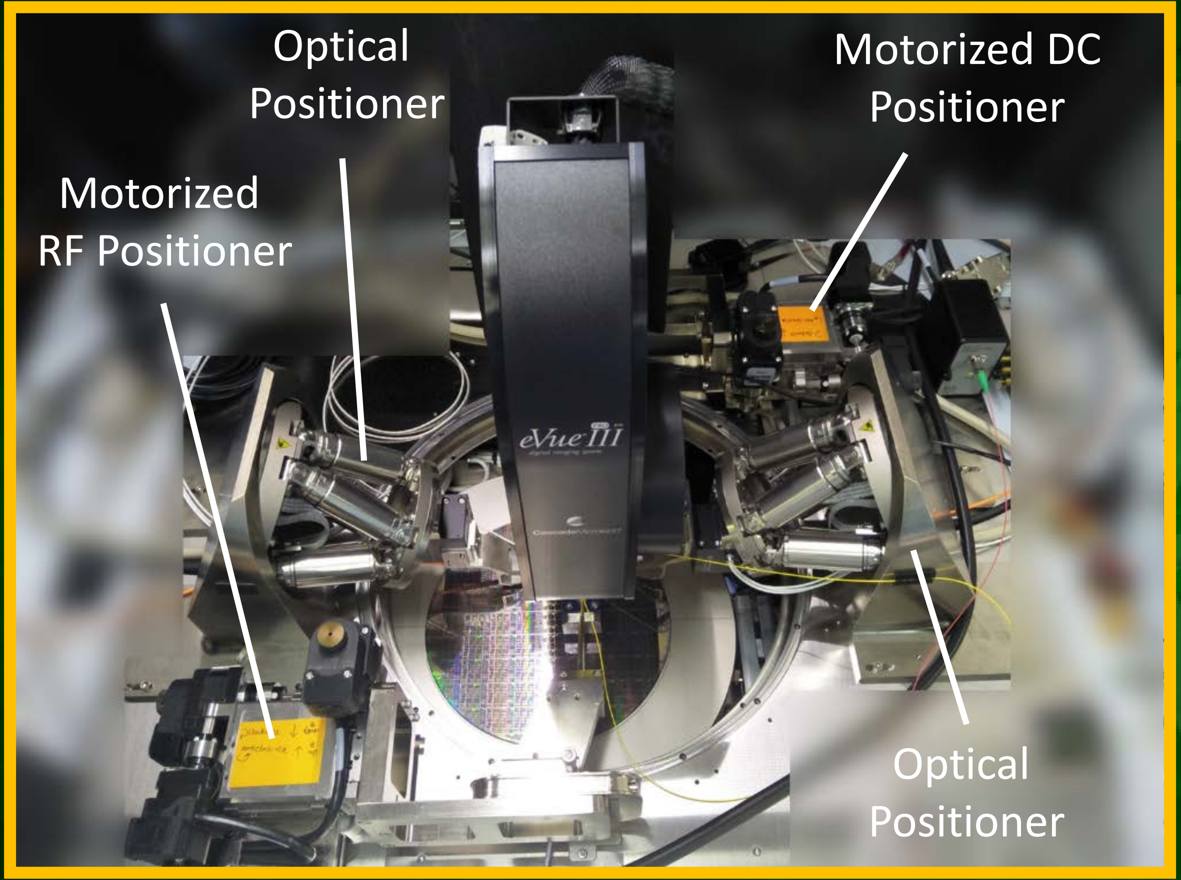

- 2 Optical & 2 Motorized DC/RF positioners
- Handle diff. layout with remote commands
- Fully Automatic 300mm Probe System
- Automatic Wafer Loading/Unloading

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?**
  - 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.

Acknowledgement

- **GLOBALFOUNDRIES Singapore**
  - Jun Hao Tan
  - Szu Huat Goh
  - Jacobus LEO

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Thank You! Questions?

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Backup Slides

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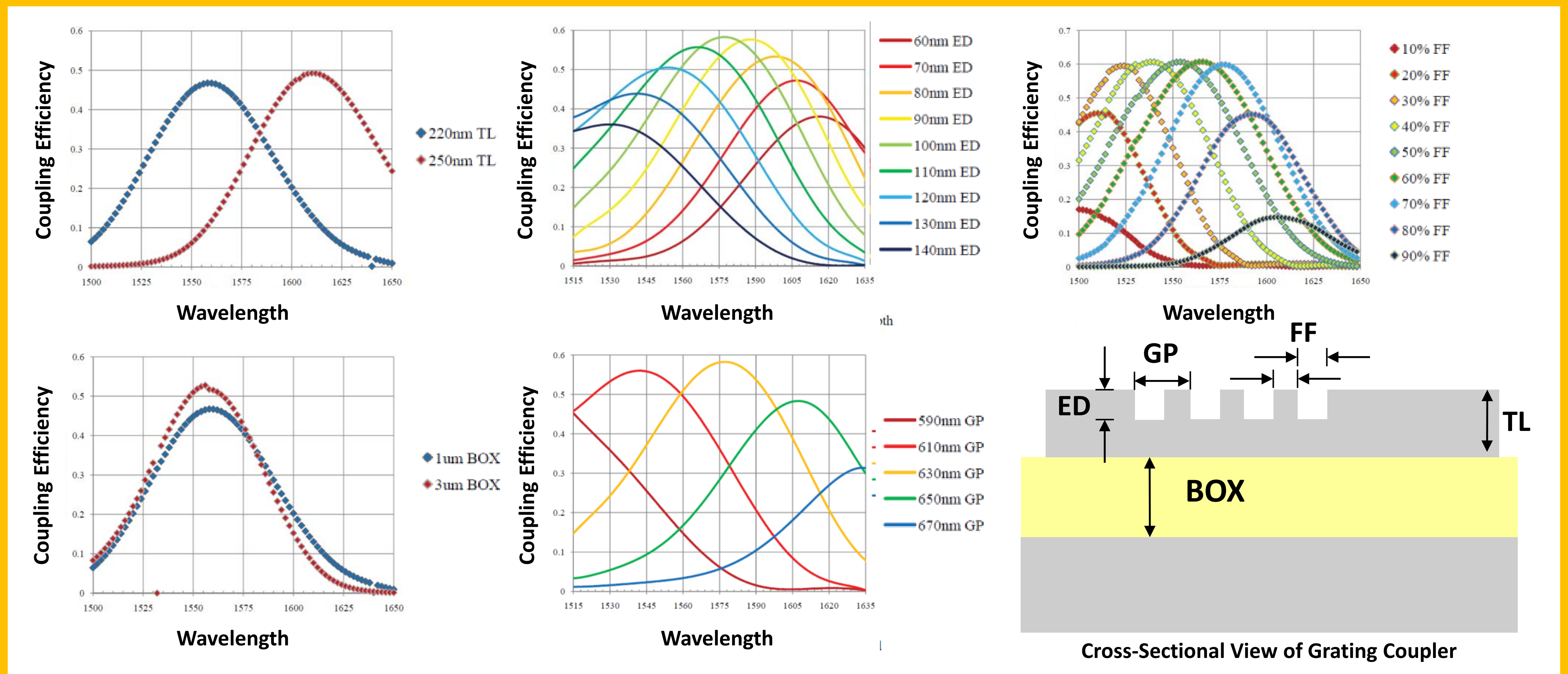
June 2-5,2019

Factors affecting Performance of Grating Coupler

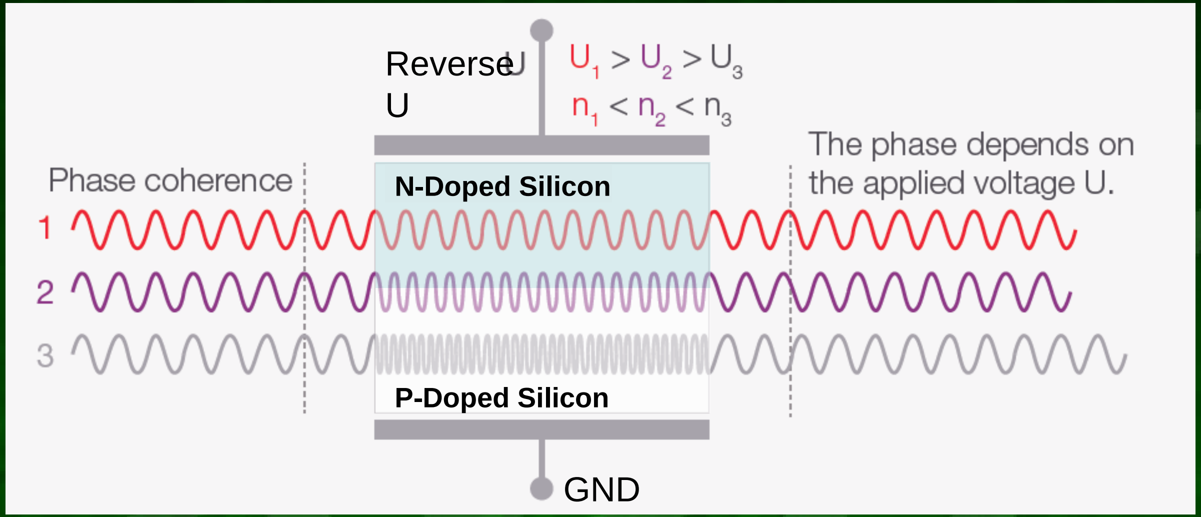
- Top Silicon Thickness (TL), BOX thickness, Etch Depth (ED), Grating Period (GP) and Fill Factor (FF) are known to have impacts on the Coupling Efficiency, Peak Wavelength and Bandwidth.

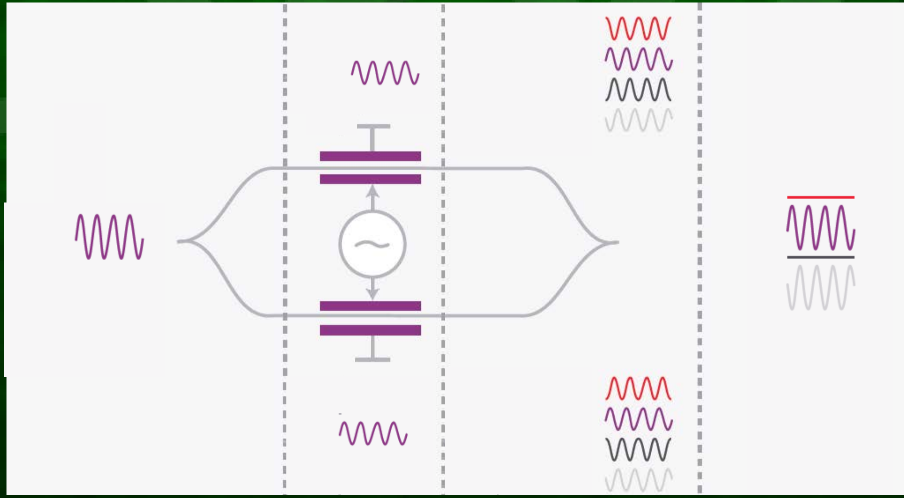


Cross-Sectional View of Grating Coupler

Wirth, Silicon Grating Couplers for Low Loss Coupling between Optical Fiber and Silicon Nanowires, Dec 2011

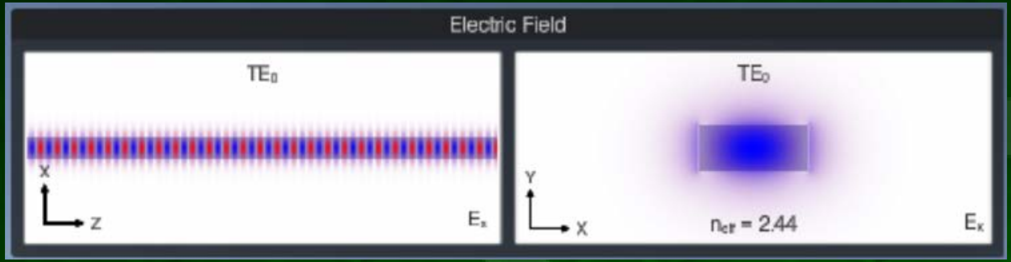
Mach-Zehnder Modulator

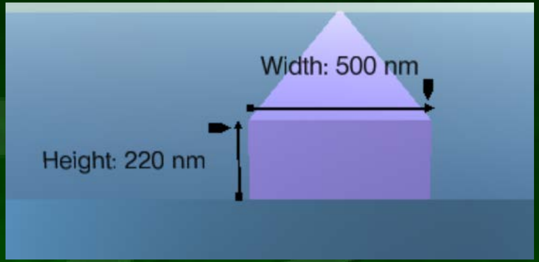


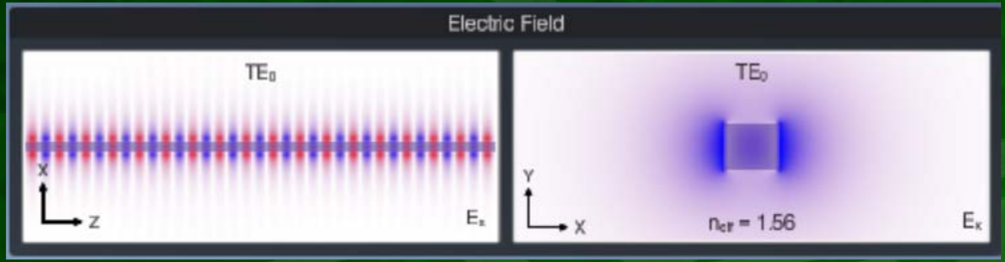


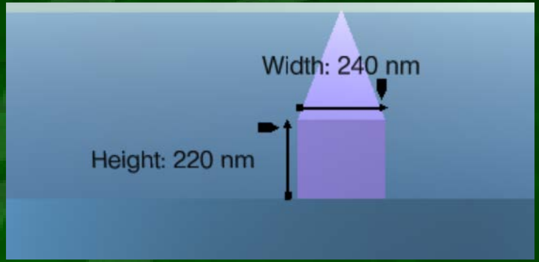
[1] Modified from KeySight Whitepaper, *Everything You Need to Know about Complex Optical Modulation*, Sep 2018, 5992-2888EN

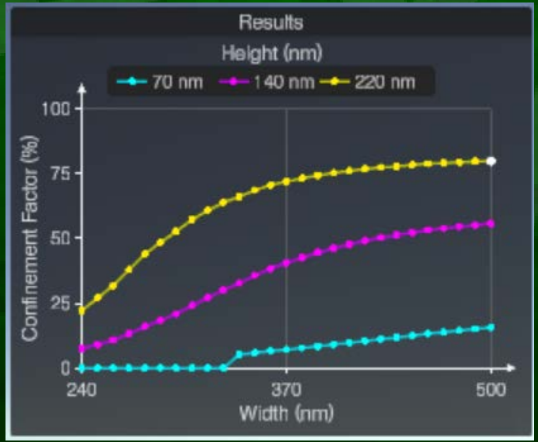
Inverse Taper Edge Coupler





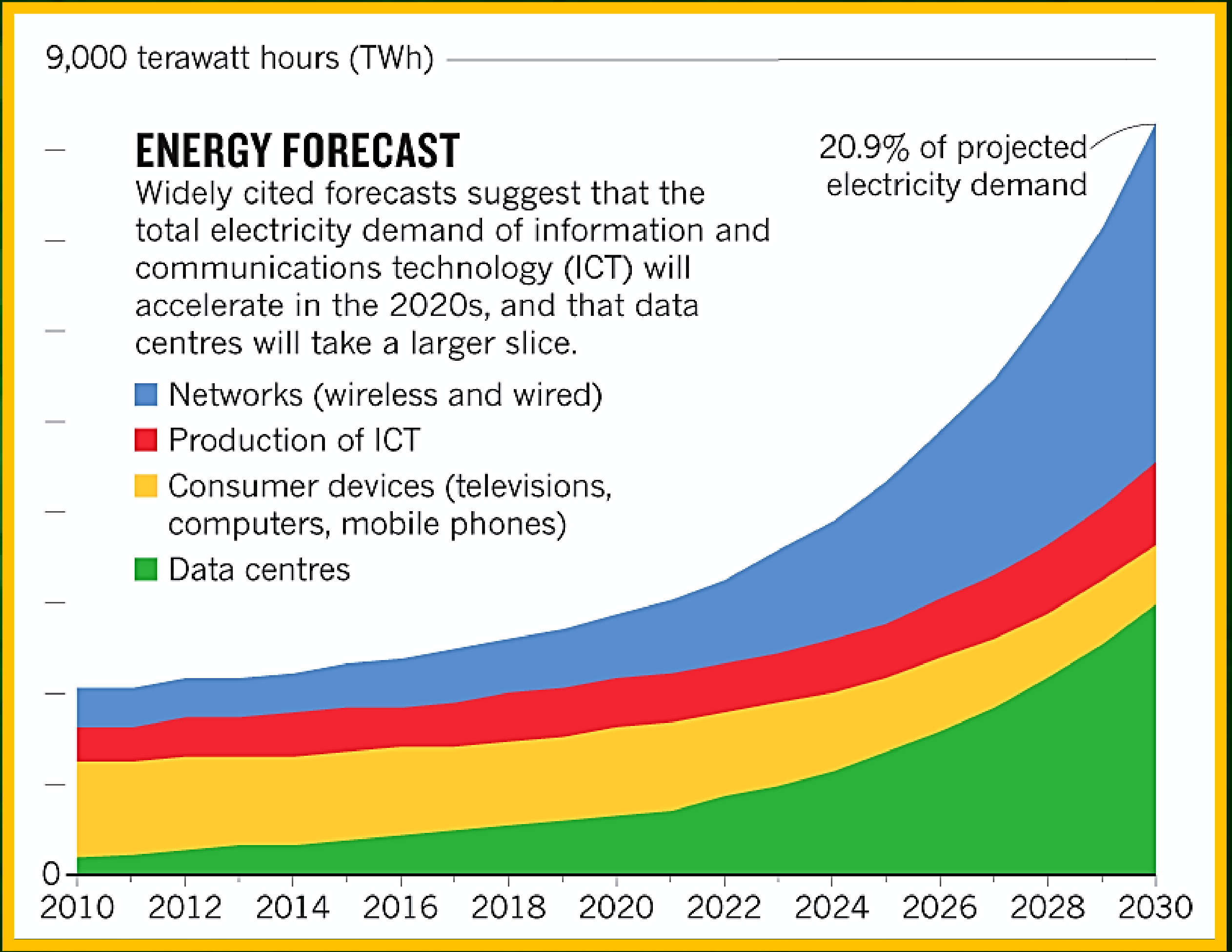






Requirements for Data Center – Energy Efficiency

- ***Information Technology to consume 21% of Earth's power by 2030.**
  - Data Centers and Wired Access are largest consumers.
- **†3% Total Electricity (in 2016), will double every 4 years.**
  - 24% consumption by 2028?
- **#Governments are now Regulating Data Centers!**



* https://www.nature.com/articles/d41586-018-06610-y Andrae, A. (2015). † Why Energy Is A Big And Rapidly Growing Problem For Data Centers - Radoslav Danilak # White House gets tougher on data centers in new policy - Billy Mitchel