Silicon Photonics Transformation from Technology of interest to Products

Bipin D. Dama, Sanjay Sunder, Kal Shastri, Craig Appel, Mark Webster, David Piede, Marco Mazzini, Angelo Miele, Stefan Wiese, Mary Nadeau, John Stayt, Biljana Milivojevic, Han Ta, Peter Metz, Kaushik Patel

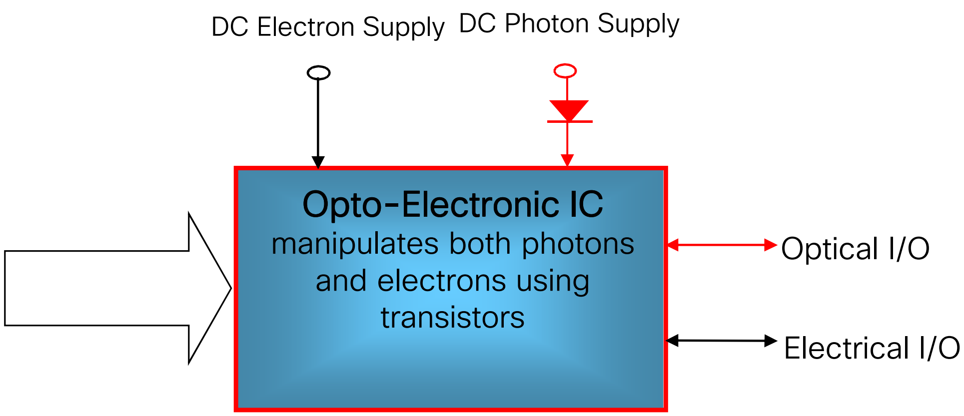
Cisco Systems, Inc.

CICC, Silicon Photonics Forum, San Jose, CA, Sept 28-30, 2015

What is needed for transformation from technology to products

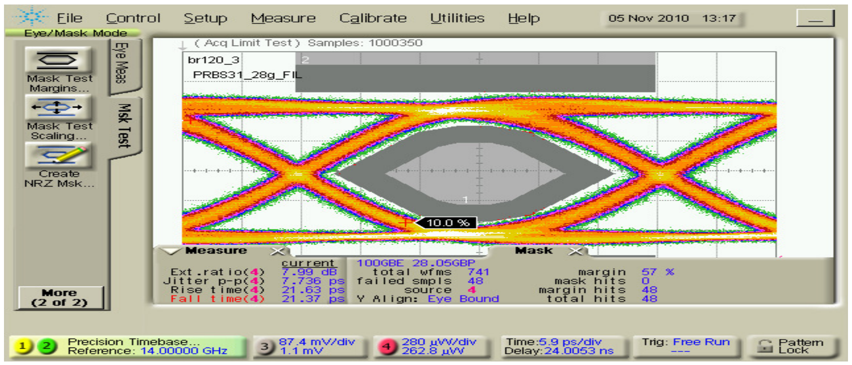
- First thing - Need to have good technology
  - Demonstrated Modulation Formats and Speeds (Performance and Power)
- Design needs to be Scalable
  - Reliability and Quality
  - Repeatability & predictability
- Products need to be cost competitive
  - Yield
  - Assembly/workmanship
  - Component costs
  - Test and tune time <- Focus for this talk

Cisco CMOS Photonics Platform - OASIS

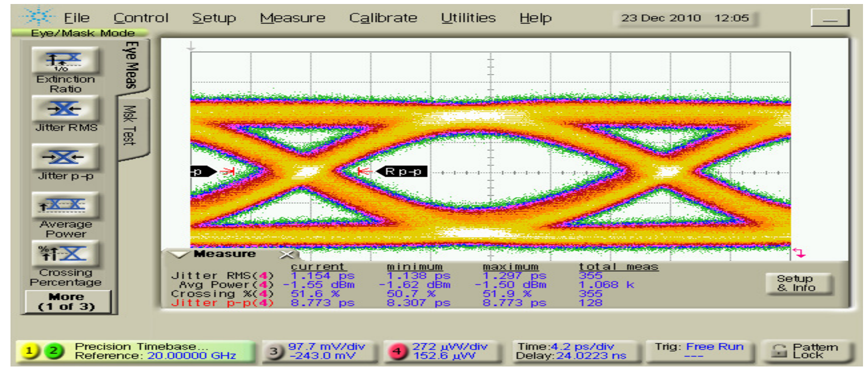


- Integrated Platform, however, not monolithically integrated
- Optical IC in 130nm CMOS SOI. Meets speed and optical loss requirements. Continuous enhancements but no need to change IC node.
- Electrical IC in 65nm->40nm->28nm CMOS depending on speed and electrical power needs.

Cisco CMOS Photonics Modulator Performance



28 Gb/s with Filter ON



40 Gb/s Optical Eye – ER 8dB

Highly Efficient Modulator

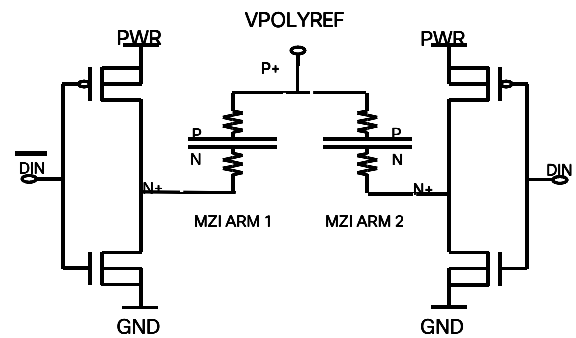
Size < 800 x 15 Micron

V x L < 2 V-mm for Pi phase shift

25X better compared to competition

2 – 5 mW/Gb/s including drivers,

depending upon application



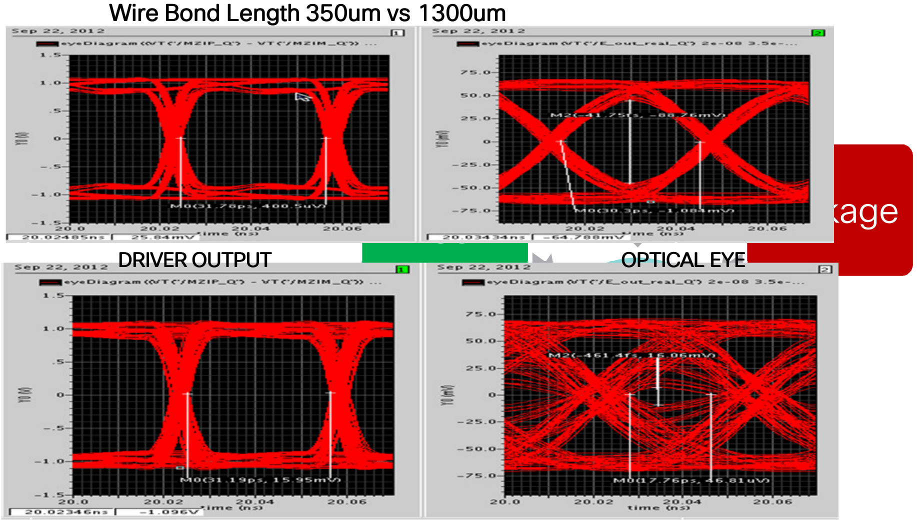
Excellent match between Simulations & Measurements due to well characterized highly accurate Spice Models of Optoelectronic Devices.

Need to simulate design and simulate electrical/optical/packaging interactions reliably

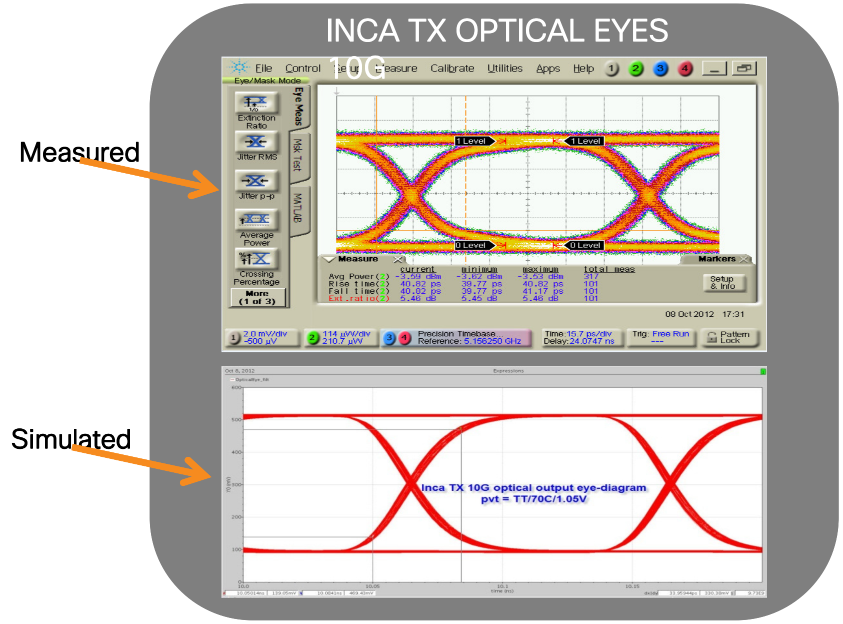
- Electrical, Optical, and Package design must be tightly interwoven

- Good Match with simulation is needed

Wire Bond Length 350um vs 1300um



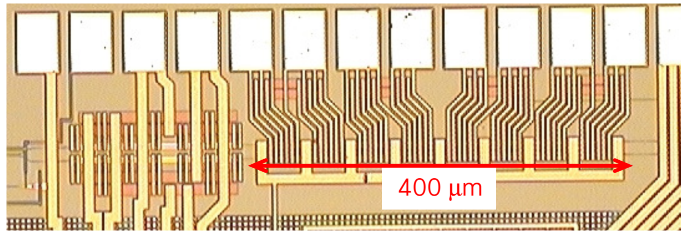
Wire bond length at optical interface is critical



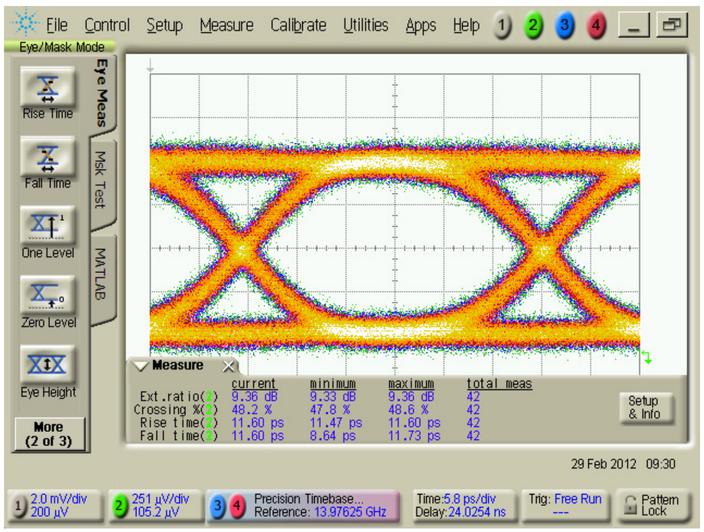
Excellent match between Simulations & Measurements due to well characterized highly accurate Spice Models of Optoelectronic Devices.

Chips@Cisco 2013 Kal Shastri, Bipin Dama, Mark Webster, Mary Nadeau, Craig Appel, Stefan Wiese

Example NRZ Performance

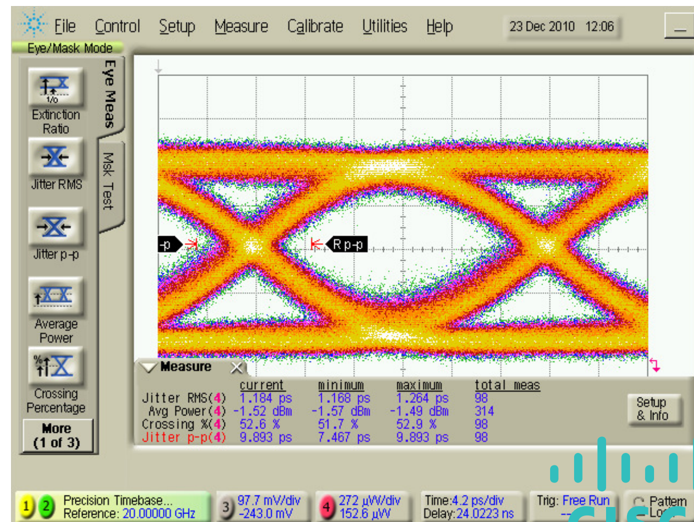


- NRZ Datarate = 28 Gbps
- PRBS-31
- ER > 9dB
- Rise-fall times ~ 17ps (10%-90%)



Wavelength = 1310nm

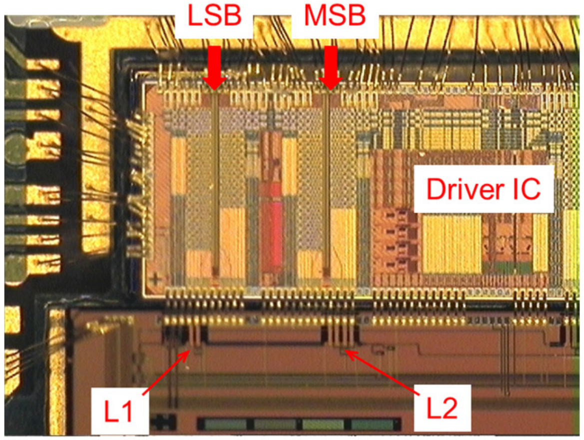
- NRZ Datarate = 40 Gbps
- PRBS-31
- ER > 8dB

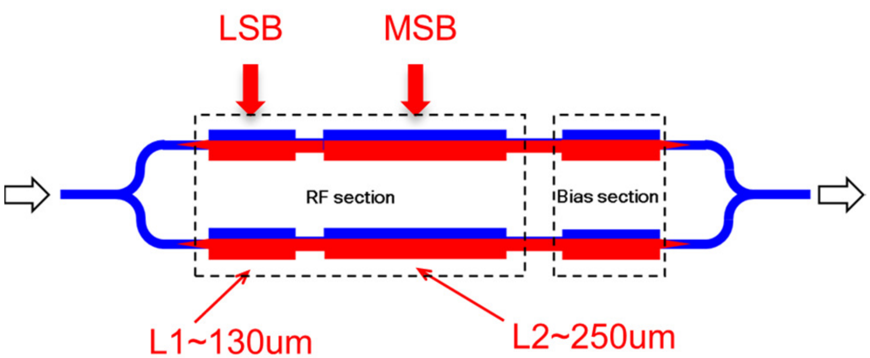


(Increased Vdd >~ 1.2V)

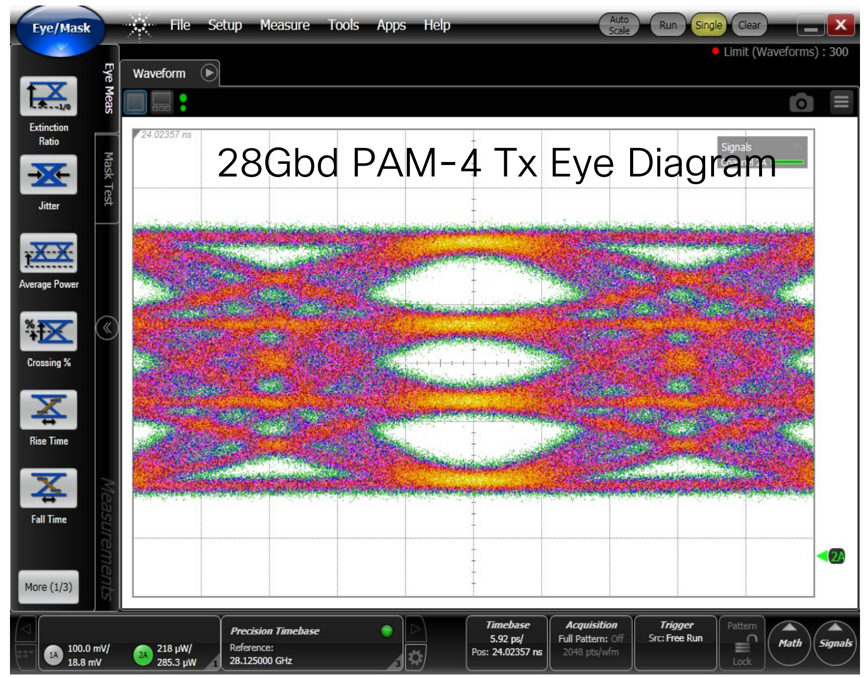
[*] M. Webster et al., “Silicon Photonic Modulator based on a MOS-Capacitor and a CMOS Driver”, CSICC 2014

Demonstration of 28Gbd PAM-4 (56 Gbps)





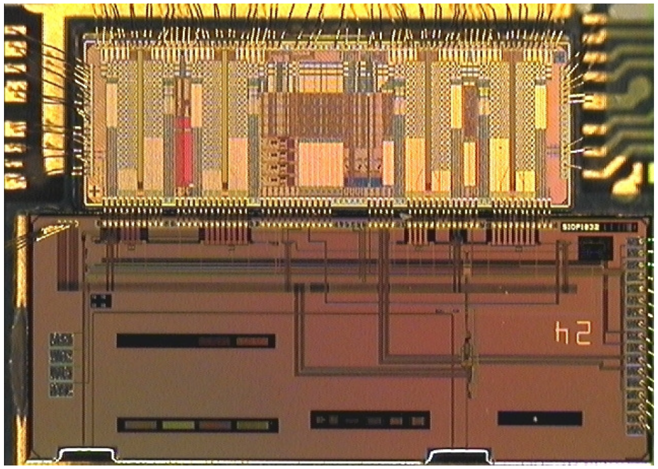
- Driver IC Power ~ 200 mW

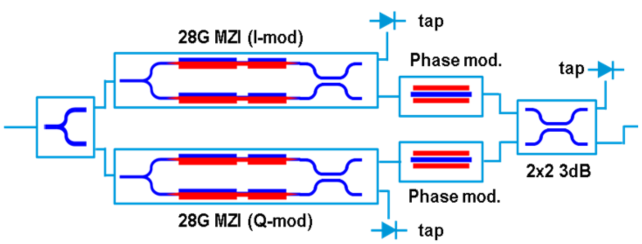


- Experimental 28Gbd PAM-4 Eye
- PRBS-31
- Wavelength = 1310nm.

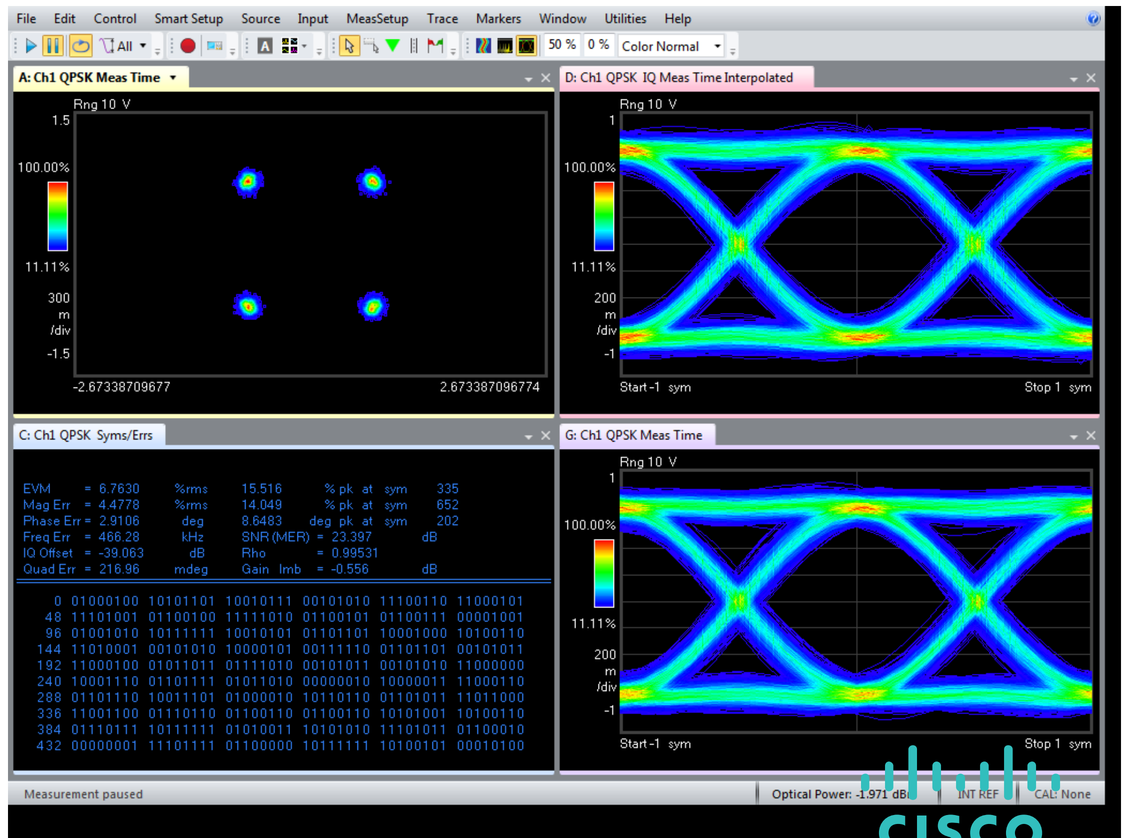
[*] M. Mazzini et al., “25GBaud PAM-4 Error Free Transmission over both Single Mode Fiber and Multimode Fiber in a QSFP form factor based on Silicon Photonics”, OFC 2015

Demonstration of 28Gbd QPSK (56 Gbps)





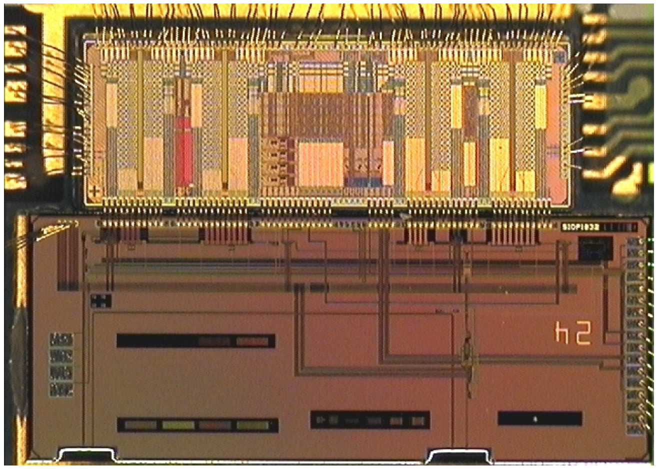
Data: I0 = I1 = PRBS31 and Data Q0 = Q1 = PRBS31



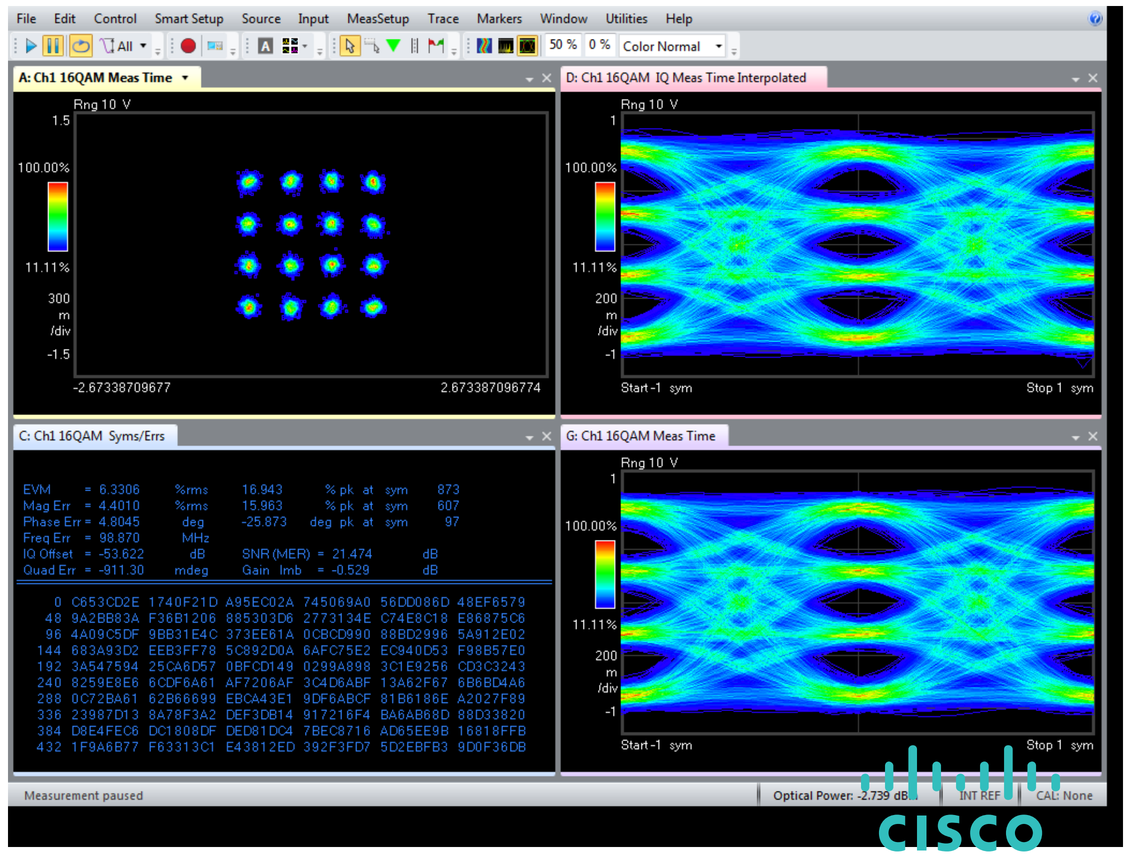
- Uses 1V CMOS Driver IC (40nm node)
- Wavelength = 1547.72nm
- 2 Segments of L1~250um, L2~500um
- Total IC Power = 430 mW all lanes on (QAM-16)

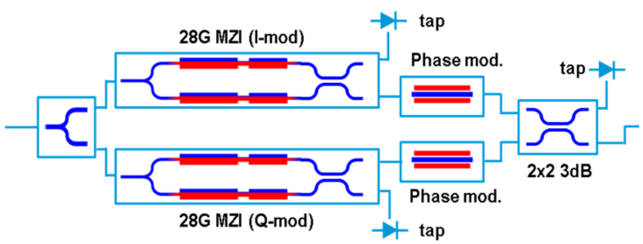
[*] A. Shastri et al., “Ultra-Low-Power Single-Polarization QAM-16 Generation without DAC using a CMOS Photonics based Segmented Modulator”, JLT Mar-2015

Demonstration of 28Gbd QAM-16 (112 Gbps)



Data: I0, I1, Q0, Q1 independent PRBS31



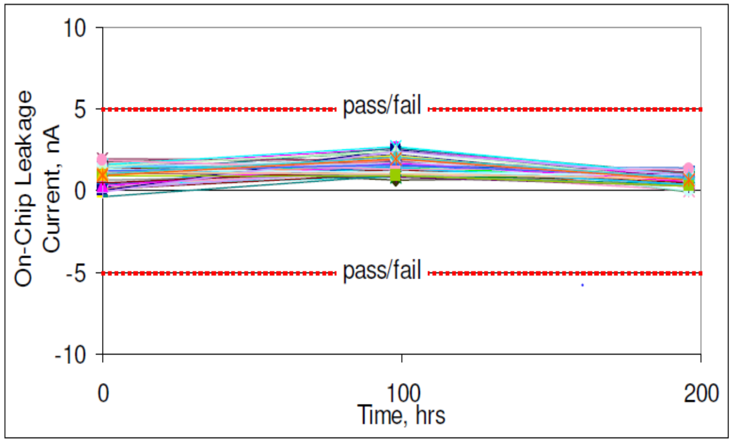


- Uses 1V CMOS Driver IC (40nm node)
- Wavelength = 1547.72nm
- 2 Segments of L1~250um, L2~500um
- Total IC Power = 430 mW all lanes on (QAM-16)

[*] A. Shastri et al., “Ultra-Low-Power Single-Polarization QAM-16 Generation without DAC using a CMOS Photonics based Segmented Modulator”, JLT Mar-2015

Meeting Carrier Class Performance and Reliability Requirements

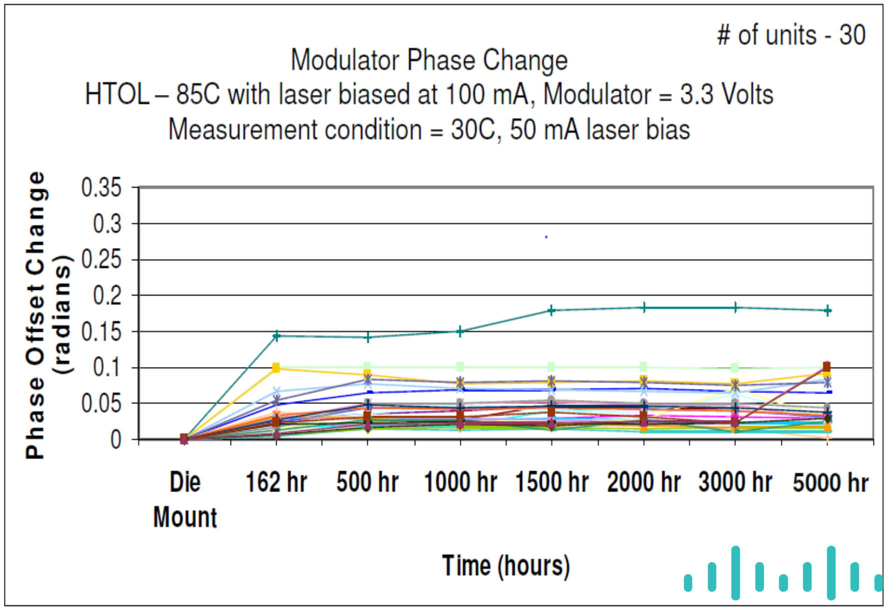
HAST - Modulator



Stress Conditions: Temp = 130 ºC, Humidity = 85% RH
Measurement Conditions: Room Temp, Modulator Bias = 1.4 V

Successfully passed 192 hours of HAST
which far exceeds requirement of 96 hours

HTOL – MZI Phase Offset Change



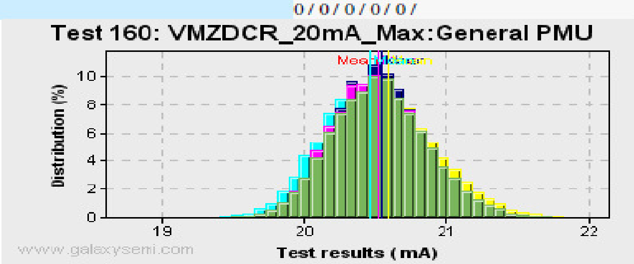
[*] A. Miele & D. Piede, Packaging and Reliability of CMOS Photonics, OFC 2014

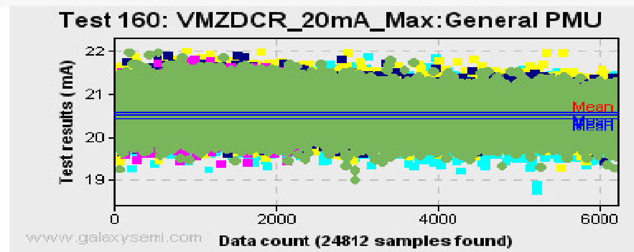
Wafer level test or Die level test?

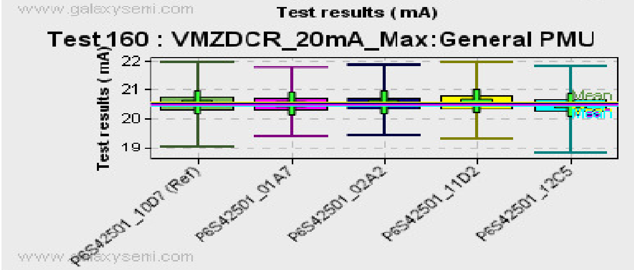
- Wafer level IC tests are a must for Known Good Dies in production, however, most of the time the initial designs are done using Multi-Project-Wafer shuttles. The foundry provides only diced ICs
- Typically the shuttle based diced Ics are used to build optical modules in initial phase until complete testing and validation of the modules is completed
- Die level IC tester are very useful for getting Known Good Dies even in this phase

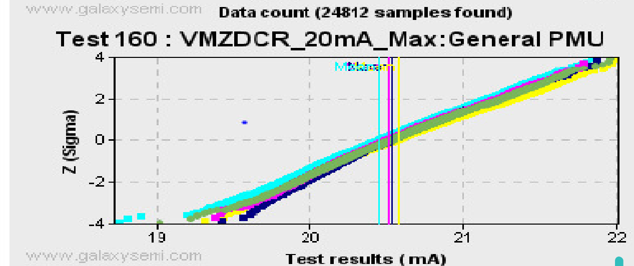
High Yield Known Good Die Based Design – Example MZIDC Tune Current Wafer Level Test Results

Test	160
Groups colors	P6S42501_10D7 (Ref) P6S42501_01A7 P6S42501_02A2 P6S42501_11D2 P6S42501_12C5
Name	VMZDCR_20mA_Max:General PMU
Test type	(Parametric, Multiple results
Low L.	18.06 mA
High L.	28.218 mA
Samples	24528 / 9680 / 21235 / 20016 / 24812 /
Mean / Max.shift	20.533 mA / 20.5163 mA / 20.537 mA / 20.5763 mA / 20.4537 mA / (−0.39%)
Sigma / Max.shift	332.521 uA / 324.992 uA / 311.181 uA / 350.255 uA / 336.013 uA / (−6.42%)
Cp	5.09 / 5.21 / 5.44 / 4.83 / 5.04 /
Cpk / Max.shift	2.48 / 2.52 / 2.65 / 2.39 / 2.37 / (7.03%)
Failures	0 / 0 / 0 / 0 / 0 /

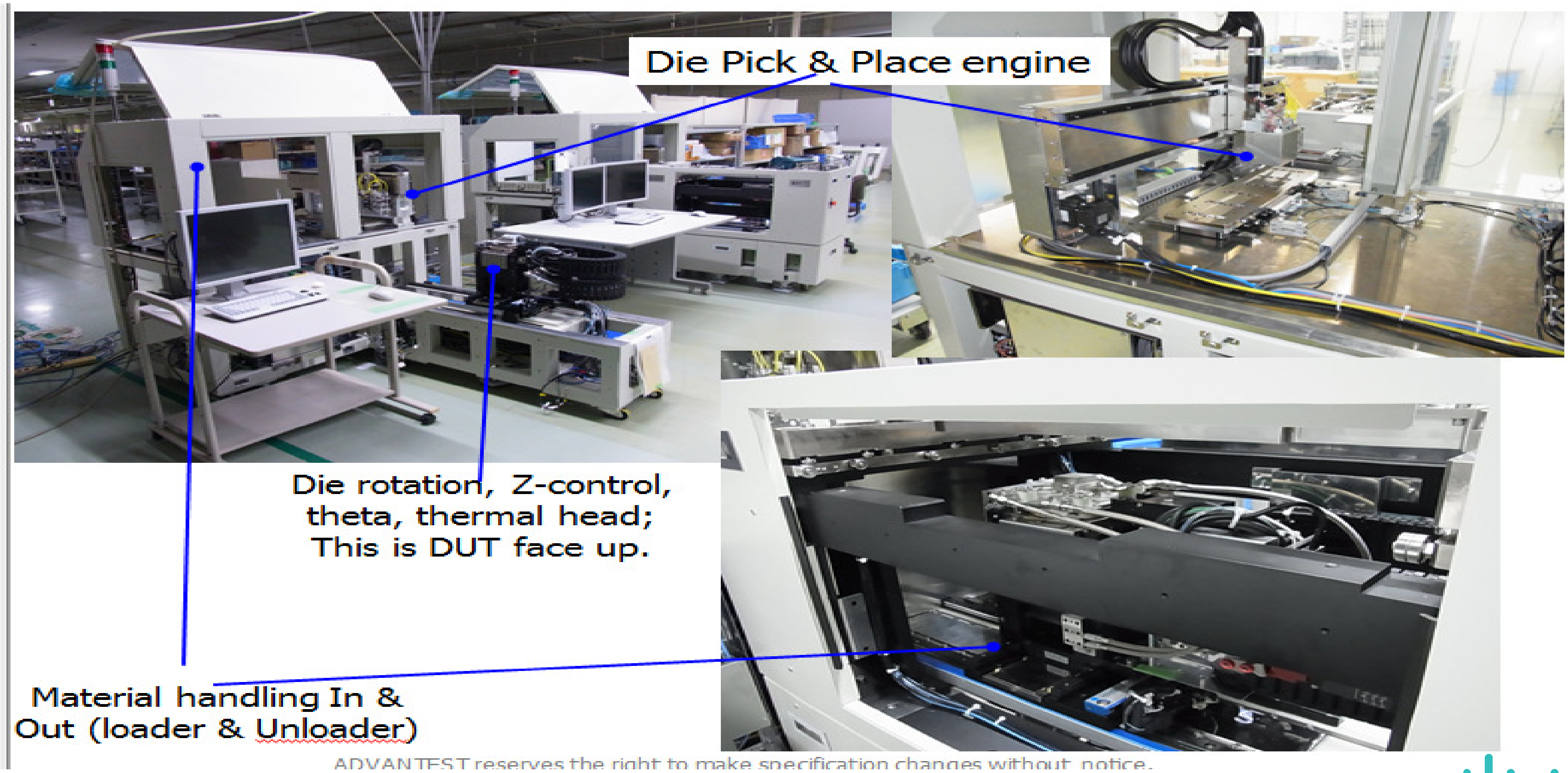




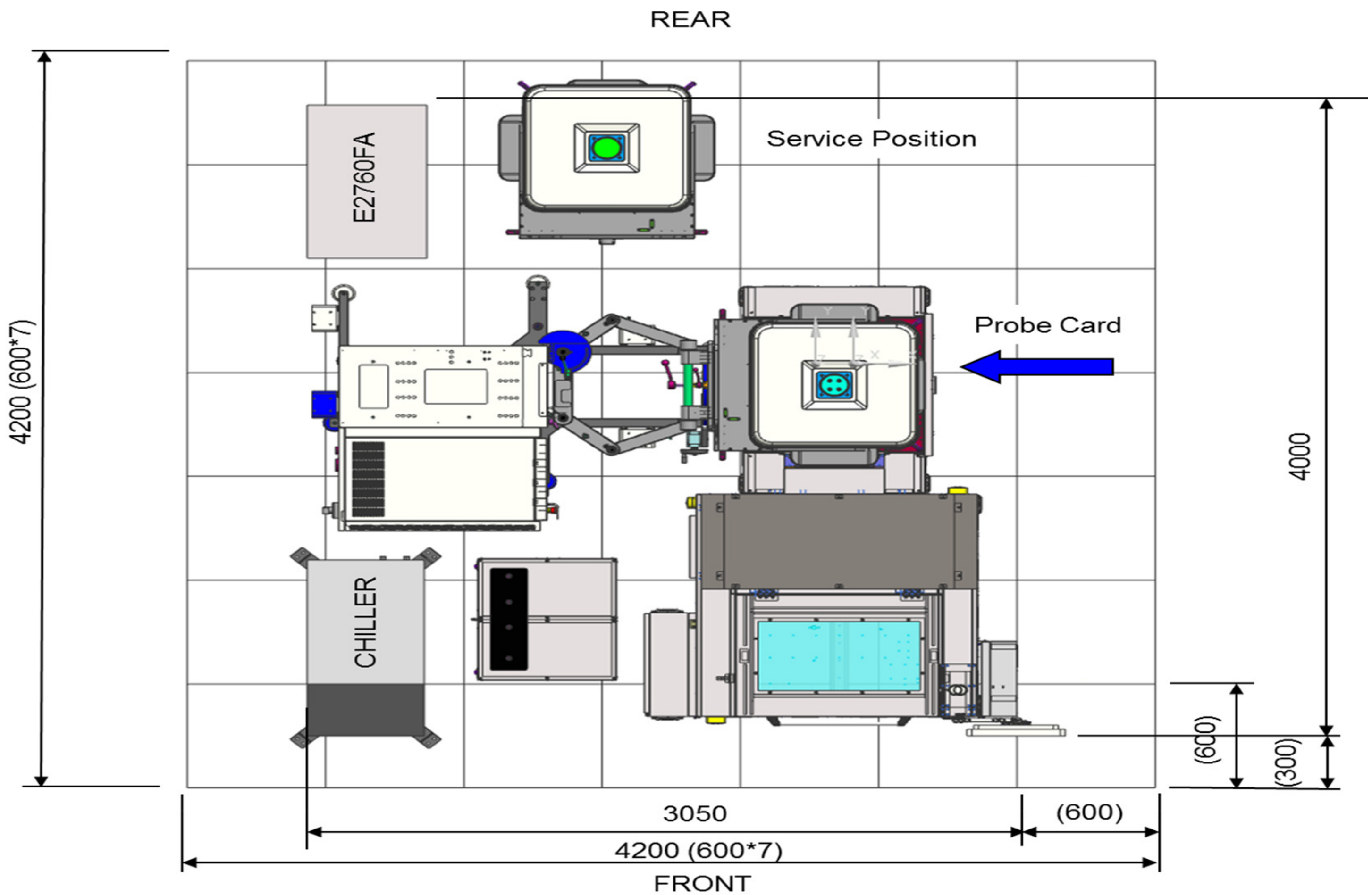




High precision bare die handler

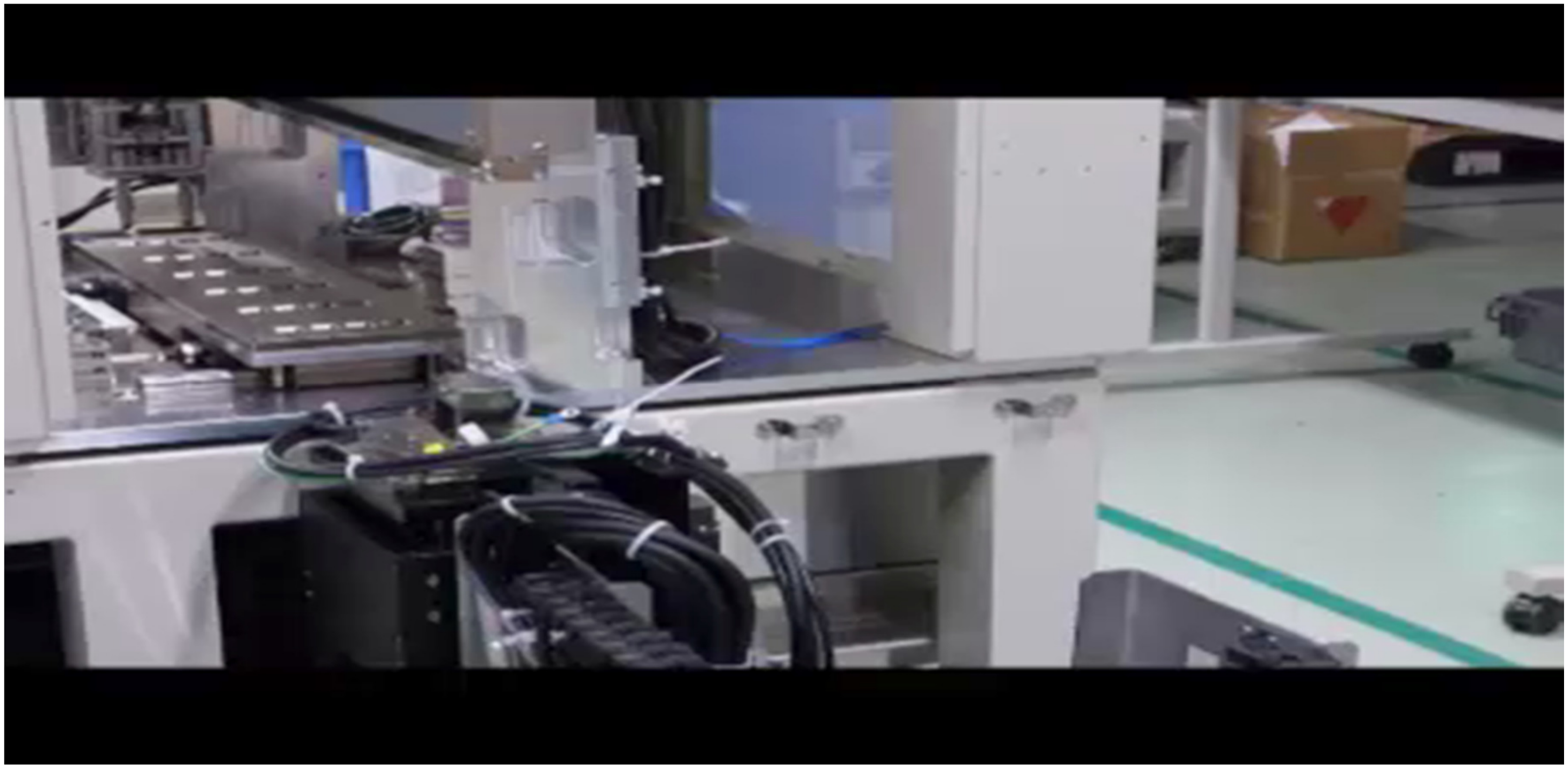


High precision bare die handler



Bipin D. Dama – Cisco Systems, Inc – CICC 2015

High precision bare die handler



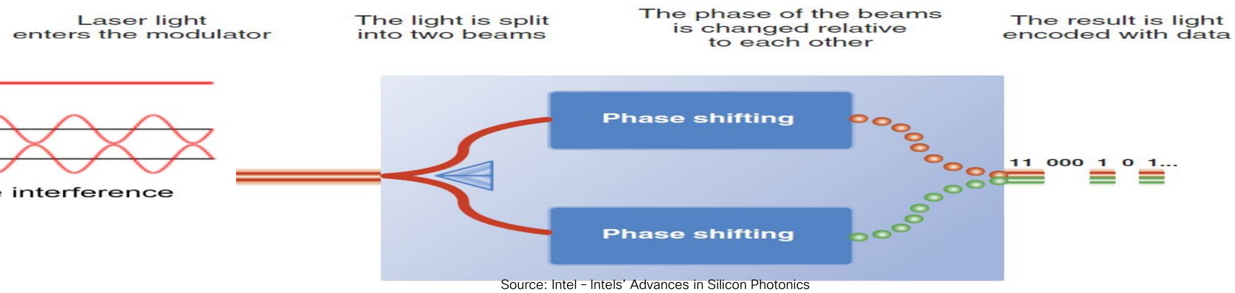
Why do we need to tune each MZI modulator

- Why is tuning needed from part to part?
- Although the silicon based MZI are smaller in size, they still are of the order of 100’s of um
- The split arms cover multiple 100’s wavelength distances. The two arms of MZI are optically not identical due to slightest imperfections resulting in partial wavelength mismatches
- MZI requires matching at a single wavelength level – this can only be achieved by individually tuning each MZI

Optical Modulation

- Light wave can "add" or "subtract" based on the phase

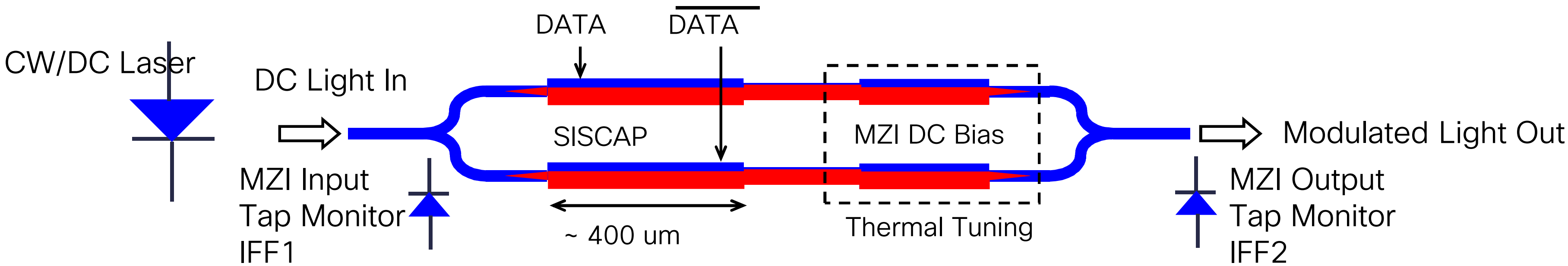
Source: http://en.wikipedia.org/wiki/Constructive_interference



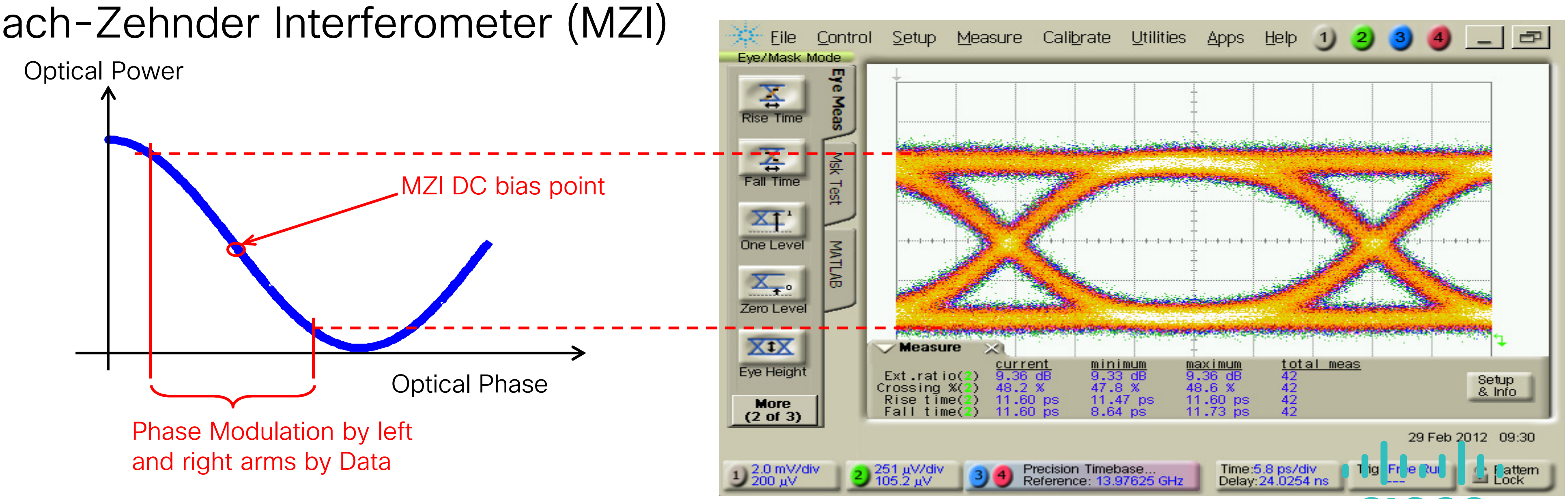
Source: Intel – Intels' Advances in Silicon Photonics

- Change in refractive index -> phase shifting -> modulation
- Change in silicon refractive index by introducing charge in the path of the light (RF data) or heating one arm with respect to the other (Thermal MZIDC Bias tuning)
- Charge based phase change is fast (ps)
- Thermal phase change is slow (us)

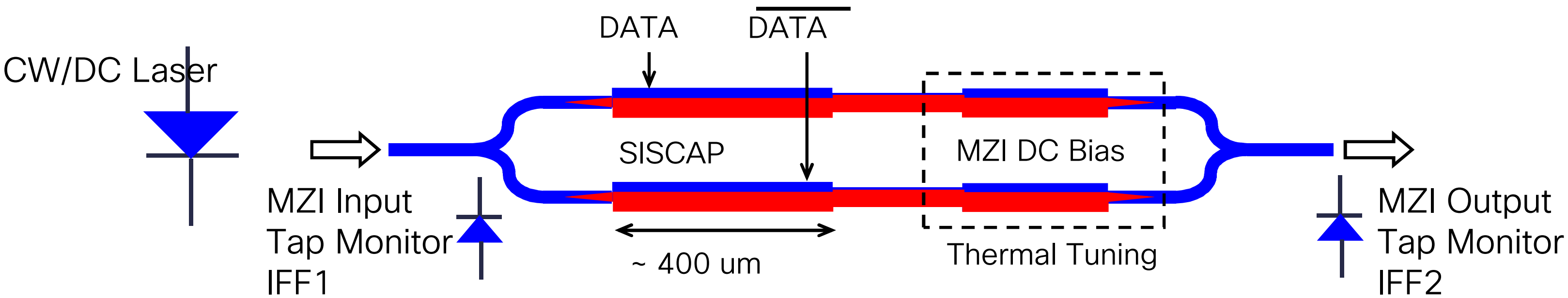
The MZI – Optical Behavior



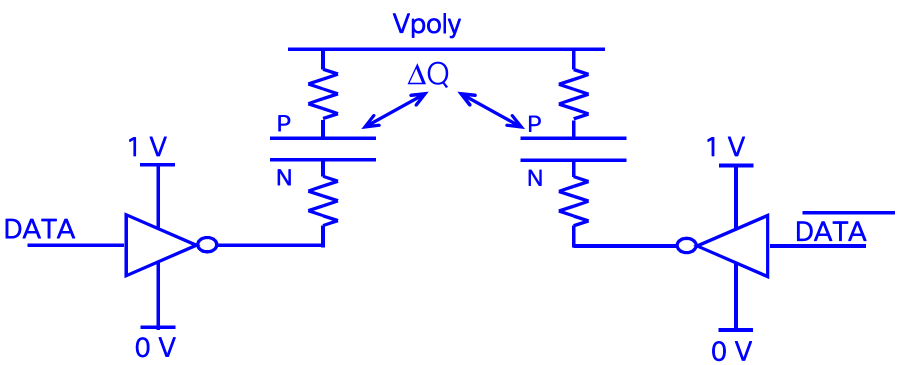
Mach-Zehnder Interferometer (MZI)



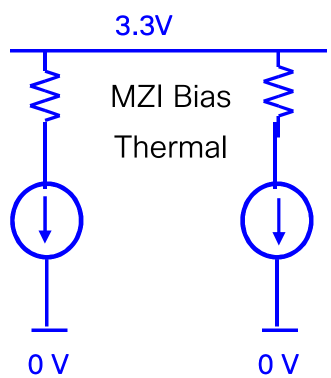
The MZI – Electrical Model

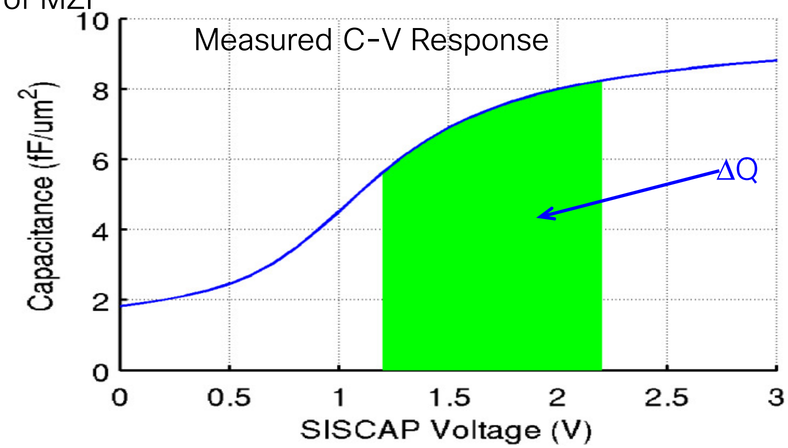


Electrical Equivalent Representation of MZI
Treated as a Lumped Element Model



Electrical Equivalent Representation of MZI
Thermal Tuning Circuit





Testing and Tuning Time and Cost for Silicon Photonics Modules

- Each MZI needs to be tuned – effectively requiring each part to be individually tuned and tested
- Traditional control schemes of using dither tone in LiNob require larger photo-detector currents, our photo-detectors produce nA of currents and dither tone method is not usable
- Some applications may require over temperature tuning and testing
- Testing and tuning time can be a significant cost adder
- Have to do add as much built-in-self-test as possible
- Needs auto tune, tune once and remember forever – alternatively tune at power-up keeping in mind power on time constraints

Example Test and tune for Active Optical Cable

Voltage Sense Calibration	MZI DC Quadrature Bias Tuning	Temperature Tuning	Laser Constant Power Tuning	CPU Assembles all tuning and configuration settings and programs into flash

Voltage Calibration

Set supply voltage to 3.3V	Read Voltage Reading	Calculate Offset and program into offset registers	Apply same offset to all VMZI DC Bias voltage registers

- Non-calibration accuracy has been about 100mv-300mv in 3.3V scale
- Total time = 1.25ms

Temperature Calibration

Assume room temp

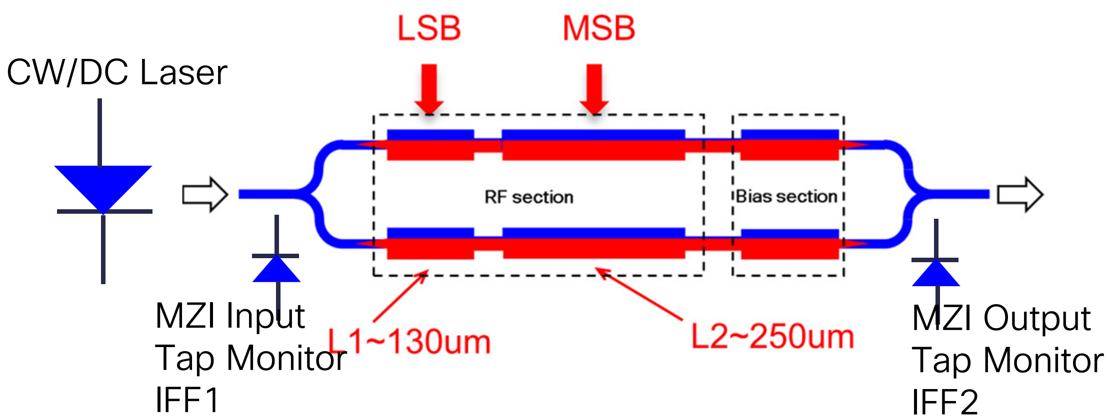
Read Temp Reading

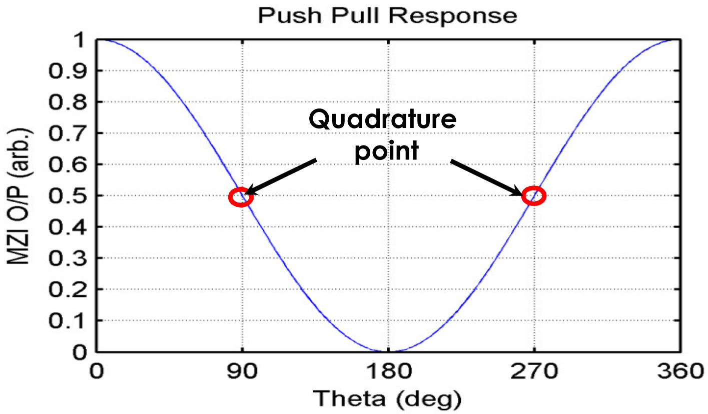
Calculate Offset and program into offset registers

- Non-calibration accuracy has been +/- 5 degrees
- Total time = 0.475ms

MZIDC Quadrature Bias Tuning – AOC

- Most important and most time consuming
- Blind algorithm is to sweep over MZDC settings, note IFF2 current. Find Max and Min and then find Mid point of MZDC thermal power as quadrature point (for NRZ or PAM modulation)

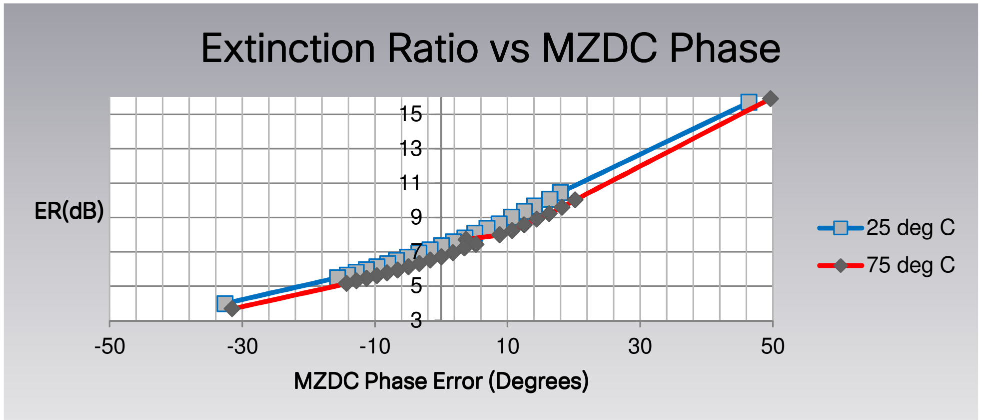


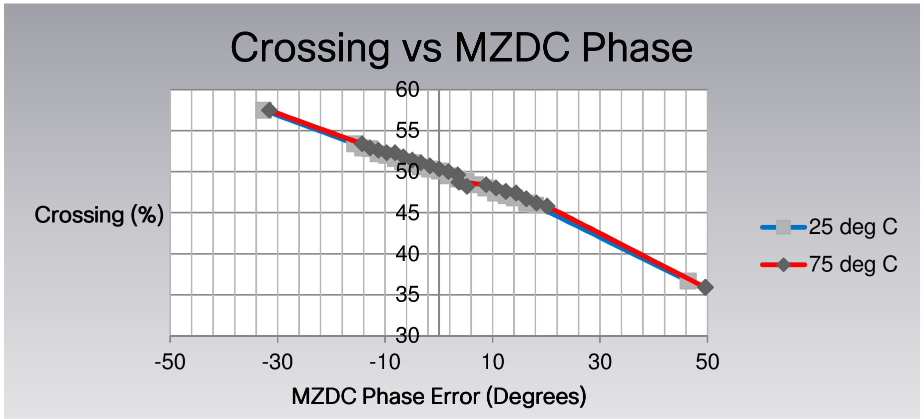


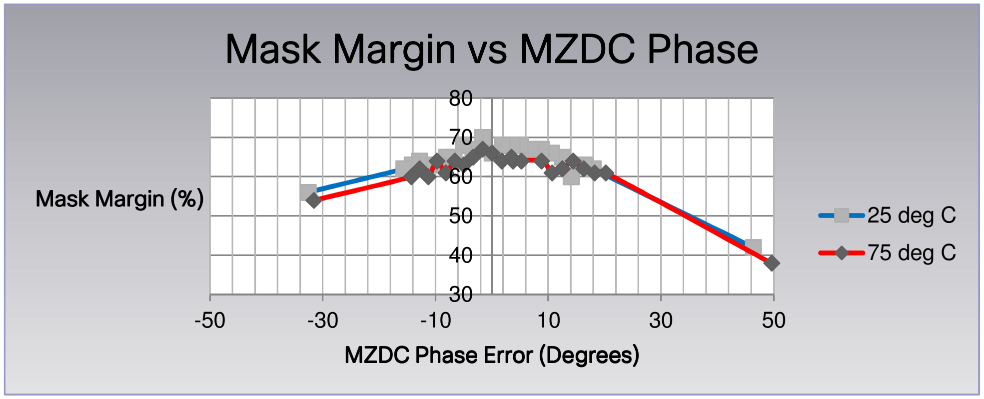
$$Ideal \quad MZI \quad output = \frac{1 + \cos(\theta)}{2}$$

Variation in Extinction Ratio, Crossing, Mask Margin

- Measured @ 25 deg C & 75deg C







Observations

- Optical parameters are fairly insensitive to quadrature point error except extinction ratio
  - ER ~5dB variation over +15 to -15 degrees error in MZDC setting from Q-point
  - Crossing ~7% variation over +15 to -15 degrees error in MZDC setting from Q-point
  - Mask Margin ~10% variation over +15 to -15 degrees error in MZDC setting from Q-point
- Optical parameters are fairly insensitive to temperature
  - ER <1dB variation over 50 deg C
  - Crossing ~1% variation over 50 deg C
  - Mask Margin <5% variation over 50 deg C
- Optical parameters are also insensitive to wavelength except IFF1 which is very sensitive to wavelength
  - IFF1~1dB variation over +30nm to -30nm wavelength change
  - Crossing ~1% variation over +30nm to -30nm wavelength change
  - Mask Margin ~9% variation over +30nm to -30nm wavelength change

- Expected life time drift and PVT variations are negligible so only need to tune at production and not in operation – no dynamic tuning

MZDC Quadrature Bias Calibration

Set Laser in Constant Current – target mA	Set IFF1 and IFF2 ranges	Coarse Sweep to find max/min MZDC values. Repeat 10 times and find the average value	Setup for Fine Maxima and Fine Minima. Read 20 times and find average for min and max	Find quadrature point as middle of Maxima and Minima MZI DC Bias setting

- Total time: 154.655ms

Constant Laser Bias Current Tuning

Set laser bias to target in mA	Read IFF1	Set target as read IFF1 value and interpolate in look-up table based on pre-char data

Total time = 2.3ms

- IFF1 has large variation over +30nm to -30nm wave length change, however does not change much with aging
- Assumes characterized tap coupler strength change with respect to temperature to fill up look up table

Configuration Registers

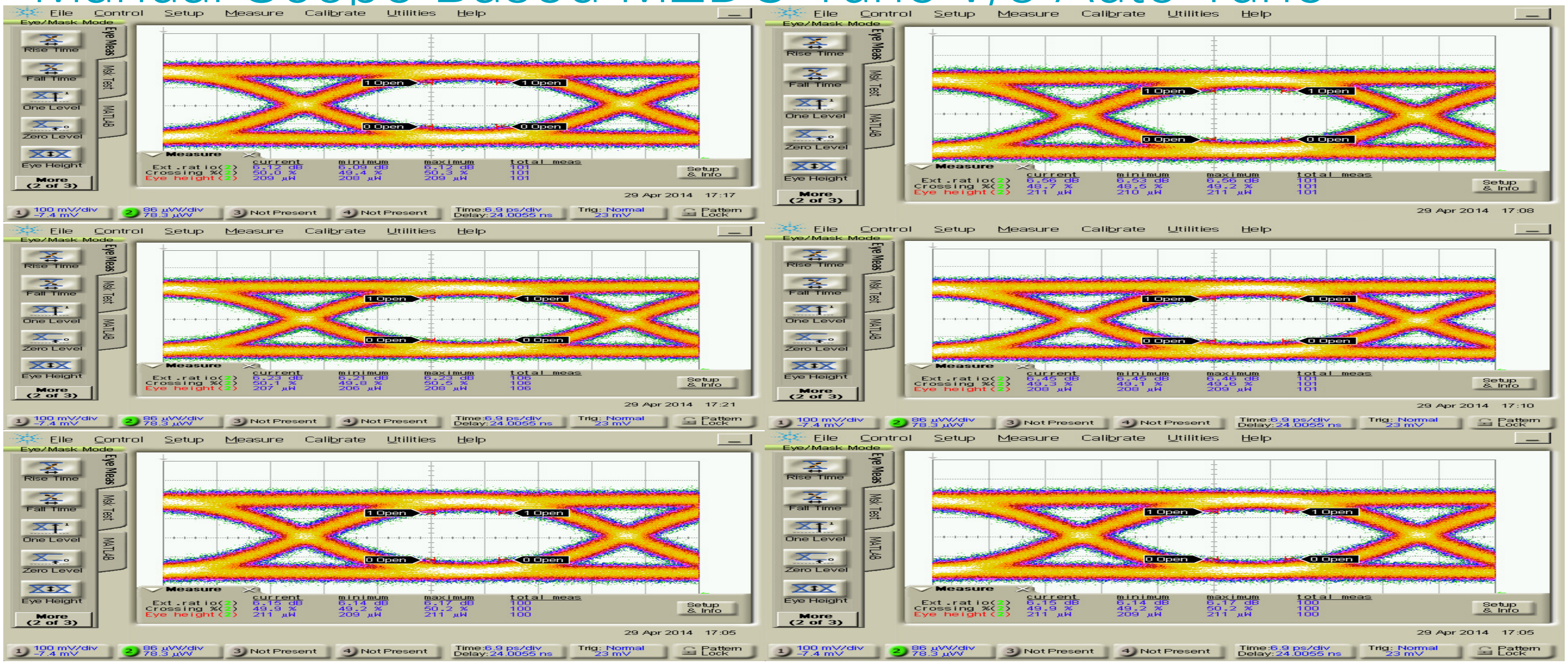
- Default values of registers are good except for the “tuned” values after configuration
- Micro will need to save these registers in memory and reload them each time after power up.
- Total time = 20ms

Total Tune Time

Tuning Step	Tuning Time
Voltage Tune	1.25ms
MZDC Tune	154.66ms
Temperature Tune	0.48ms
Constant Laser Power Tune	2.3ms
Config Registers	20ms
Total Time	178.69ms = ~200ms <<< 2seconds

- Tune time of 0.2seconds << target of 2 seconds << typical tune time
- Typical tune time 30 minutes to 1 hour

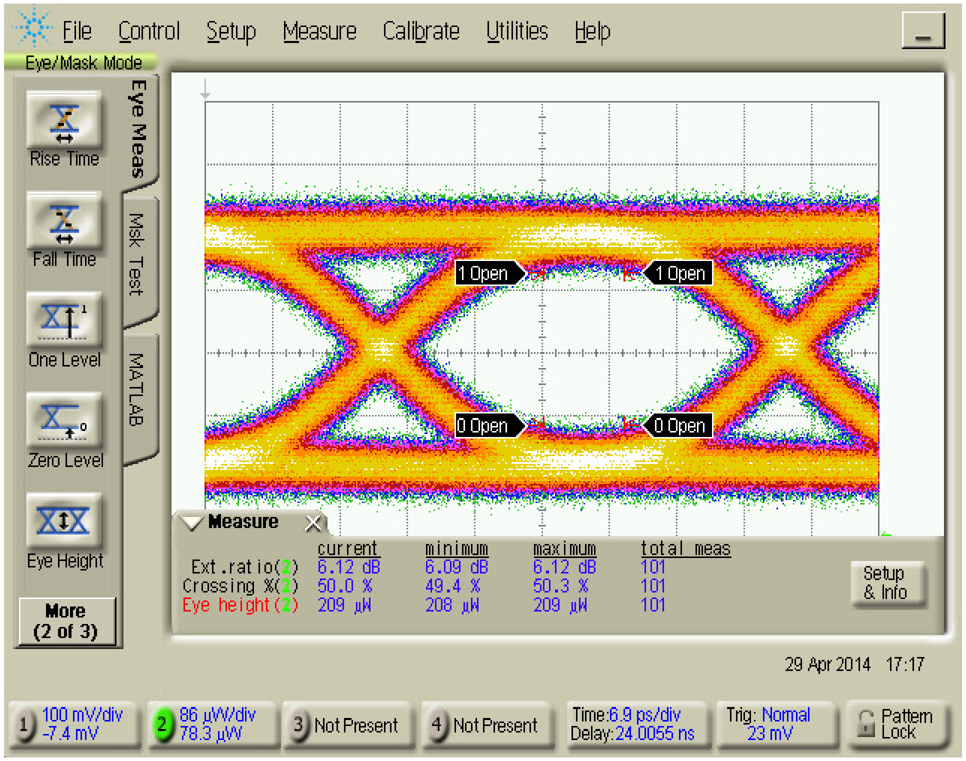
Manual Scope Based MZDC Tune v/s Auto Tune



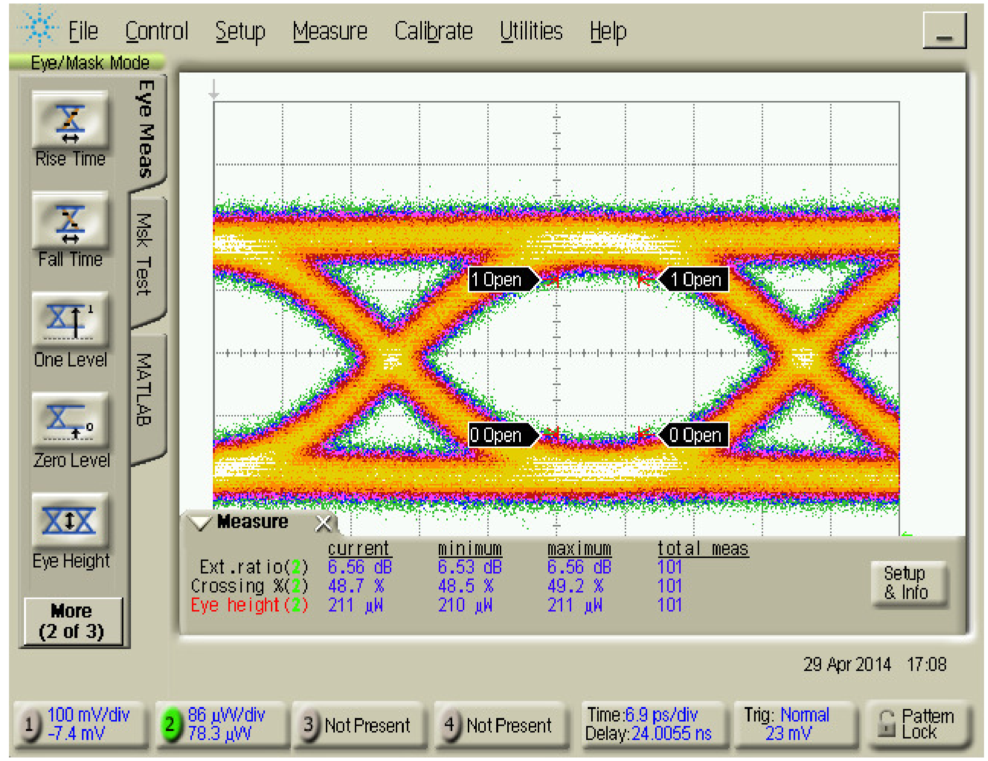
Manual Tune

Auto Tune

Manual Scope Based MZDC Tune v/s Auto Tune

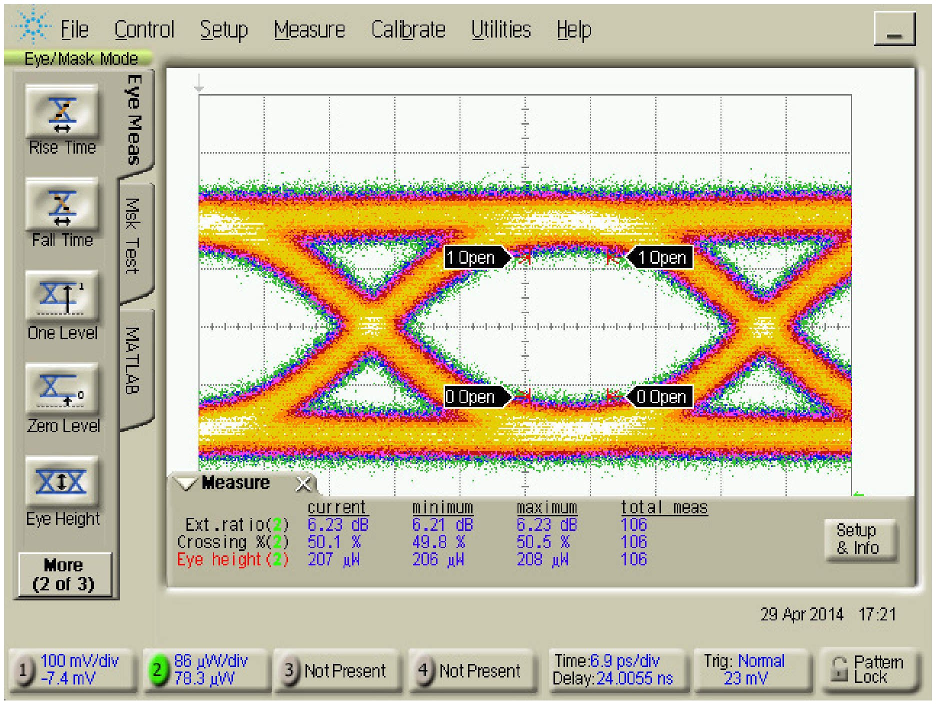


Manual Tune

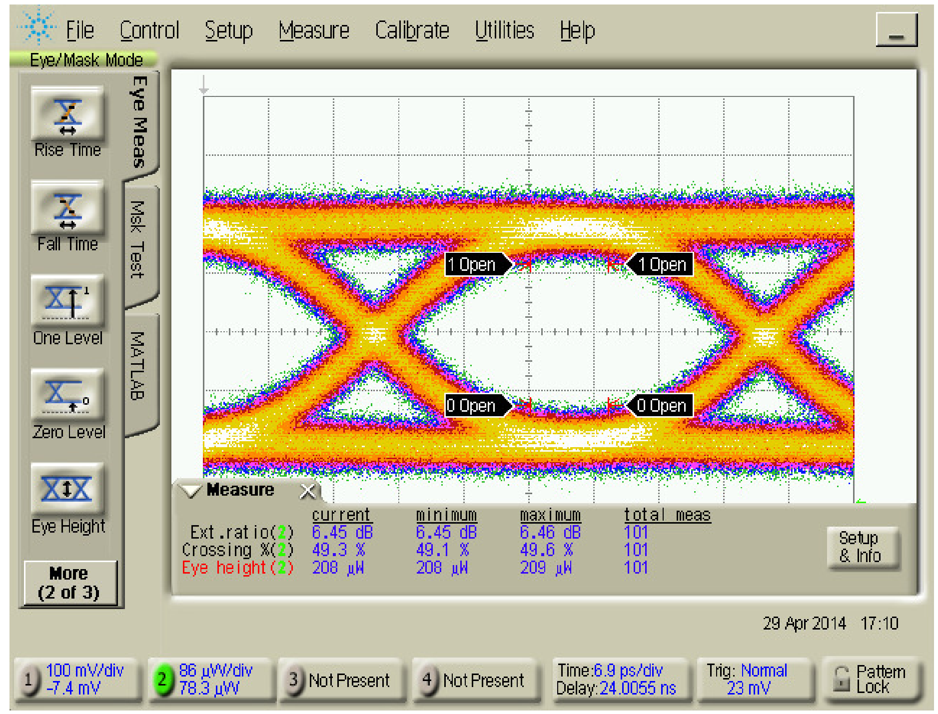


Auto Tune

Manual Scope Based MZDC Tune v/s Auto Tune

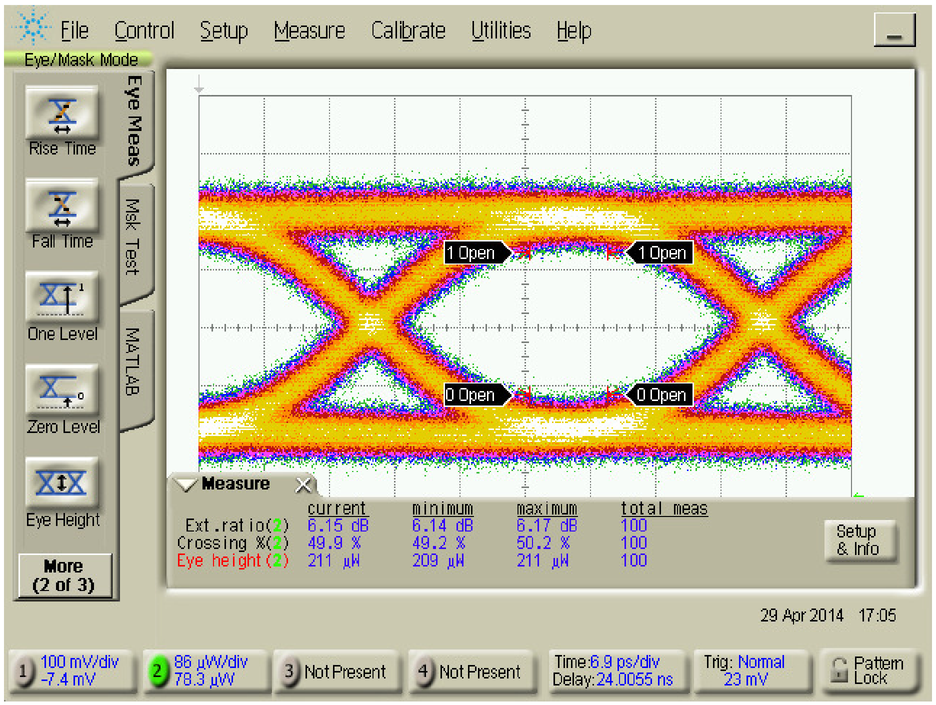


Manual Tune

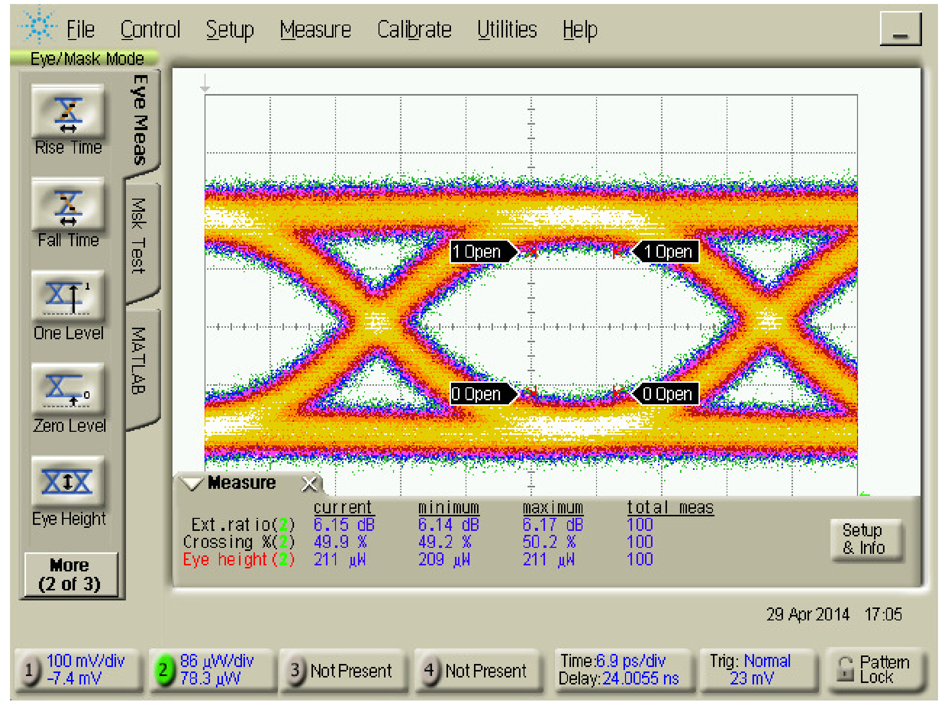


Auto Tune

Manual Scope Based MZDC Tune v/s Auto Tune



Manual Tune



Auto Tune

Thank you.