Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: 100 Gbps Optical Wireless Tutorial
Date Submitted: January 2014
Source: Rick Roberts, Juthika Basak [Intel Labs]; Mial Warren [TriLumina]; (USC student name), Professor Alan Willner [University of Southern California]
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Re:

Abstract: This contribution discusses several implementation options to achieve 100 Gbps, switched point-to-point wireless

Purpose: Information Tutorial

Some Thoughts on 100 Gbps Switched Point-to-Point Optical Wireless Communications

OUTLINE

Part 1 - Introduction: 100 Gbps SW pt-pt system topologies
(Rick Roberts – 20 mins)

Part 2 - VCSEL: technology and array processing
(Mial Warren – 20 mins)

Part 3 - Historical: optical modem technology
(Juthika Basak – 20 mins)

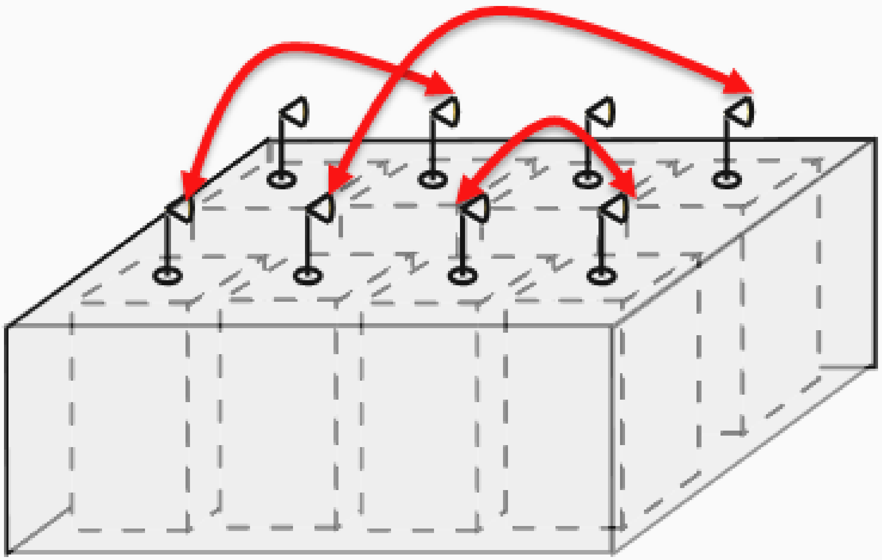
Part 4 - Media Access: 802.15.3 full duplex possibility
(Rick Roberts – 20 mins)

Part 5 - Orbital Angular Momentum Multiplexing
(Alan Willner – 20 mins)

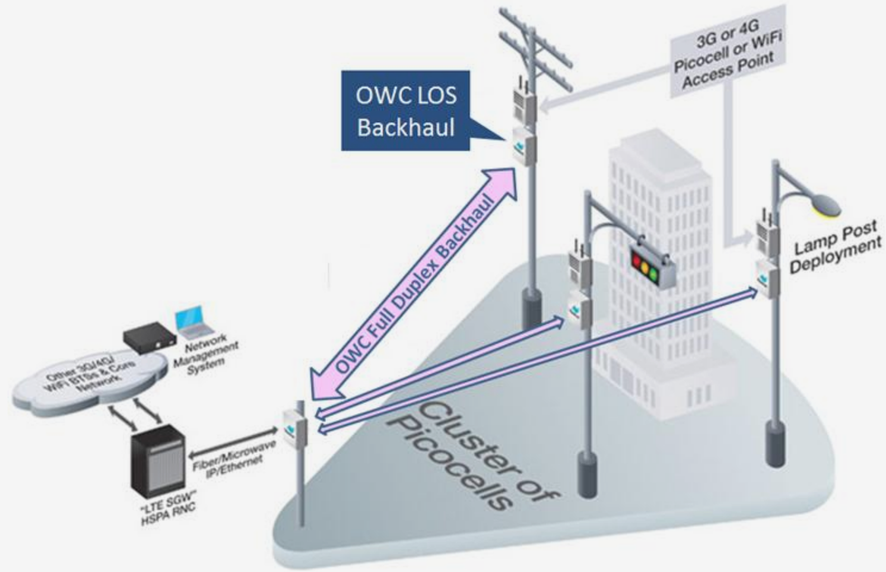
Part 6 - Q&A
(all – 20 mins)

Part 1 – Introduction
100 Gbps SW pt-pt system topologies
(Rick Roberts, Intel Labs)

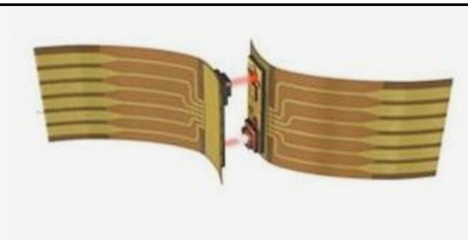
Use Case Refresher



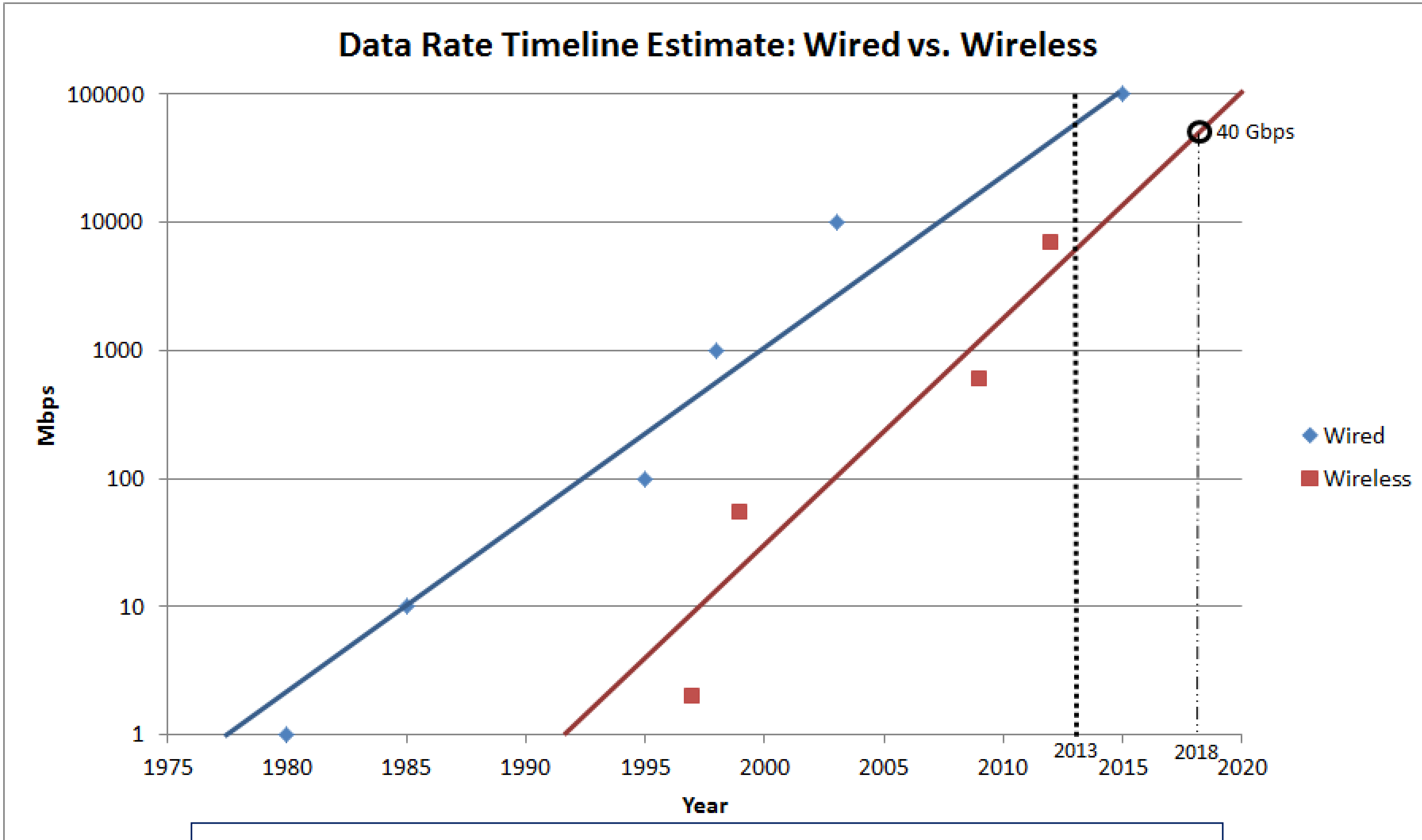
•Data center wireless flyway



Full-duplex small cell backhaul

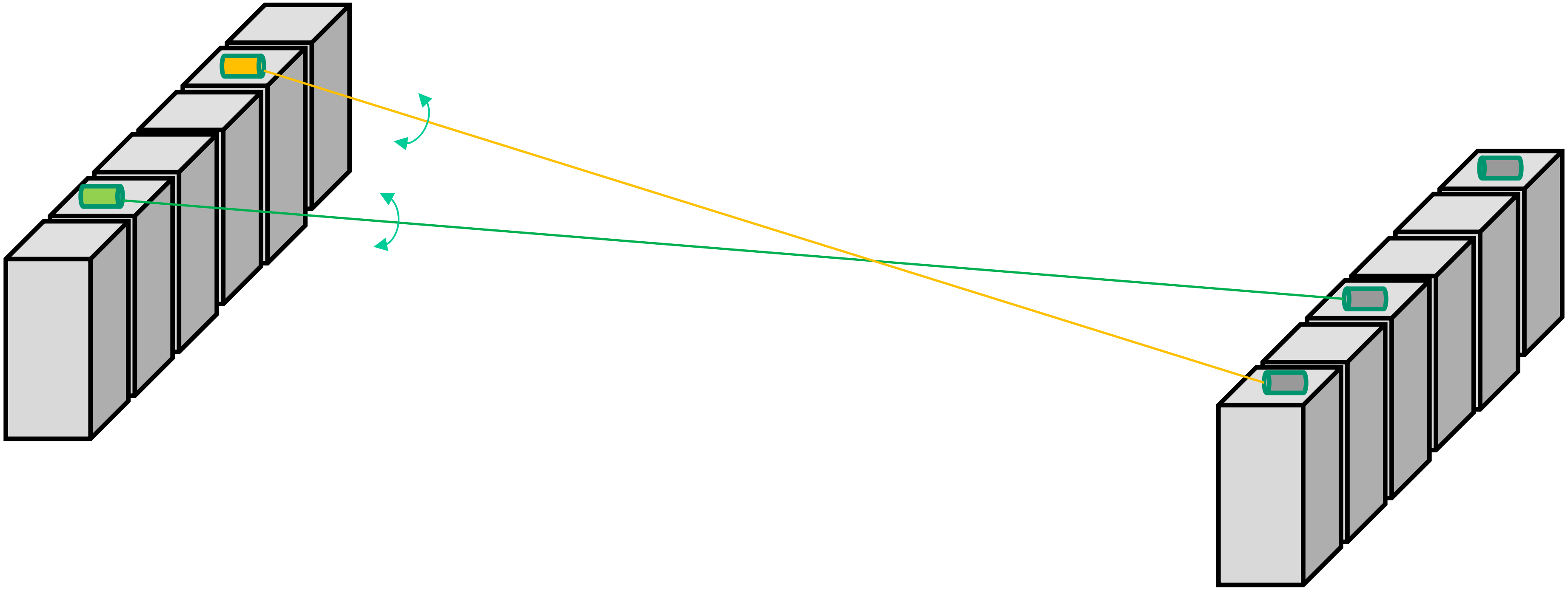


Short distance wireless connectivity



Based on assumptions and suppositions, wireless could be standardizing 40 Gbps solutions in the 2018 time frame.

IEEE802.15.SG 100G is only considering switched beam applications … the manner of how the beams are switched is postulated to be out-of-scope of the standard.

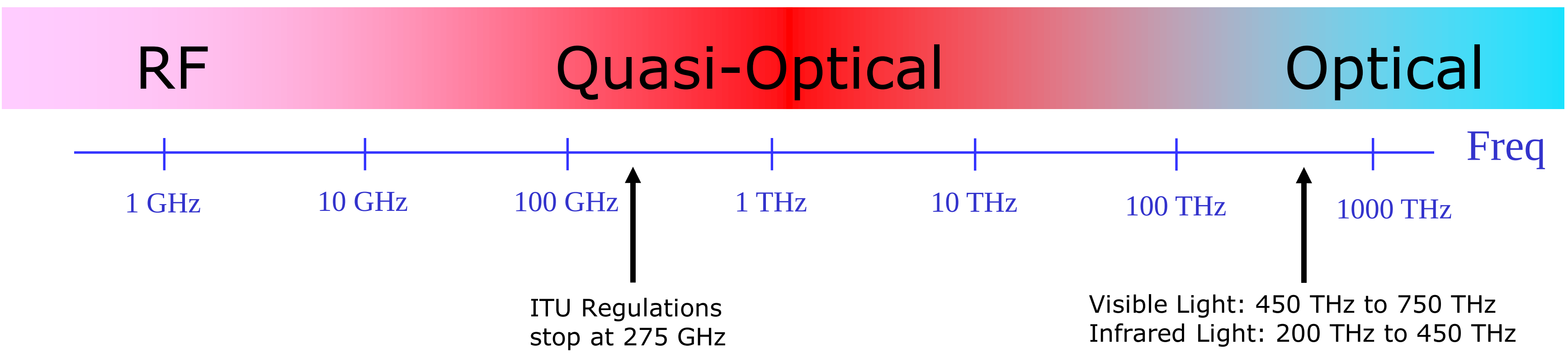


For example, the data center use case may not require arbitrary connectivity between any given racks; rather, connectivity is confined to those racks that serve as wireless access points.

Candidate solutions are:

- 60 GHz
- TeraHertz
- Optical Wireless

Tutorial Subject

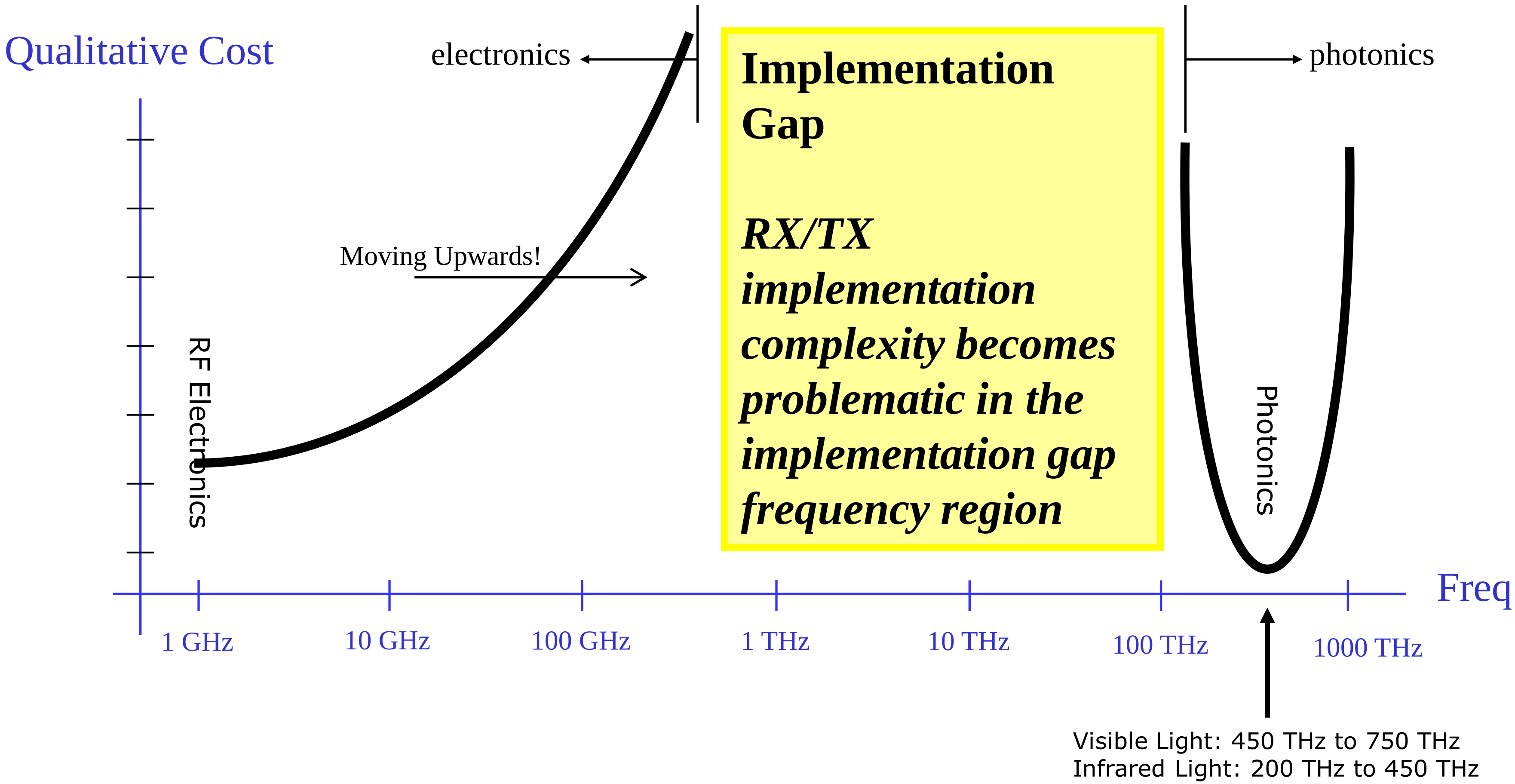


Influencing factors

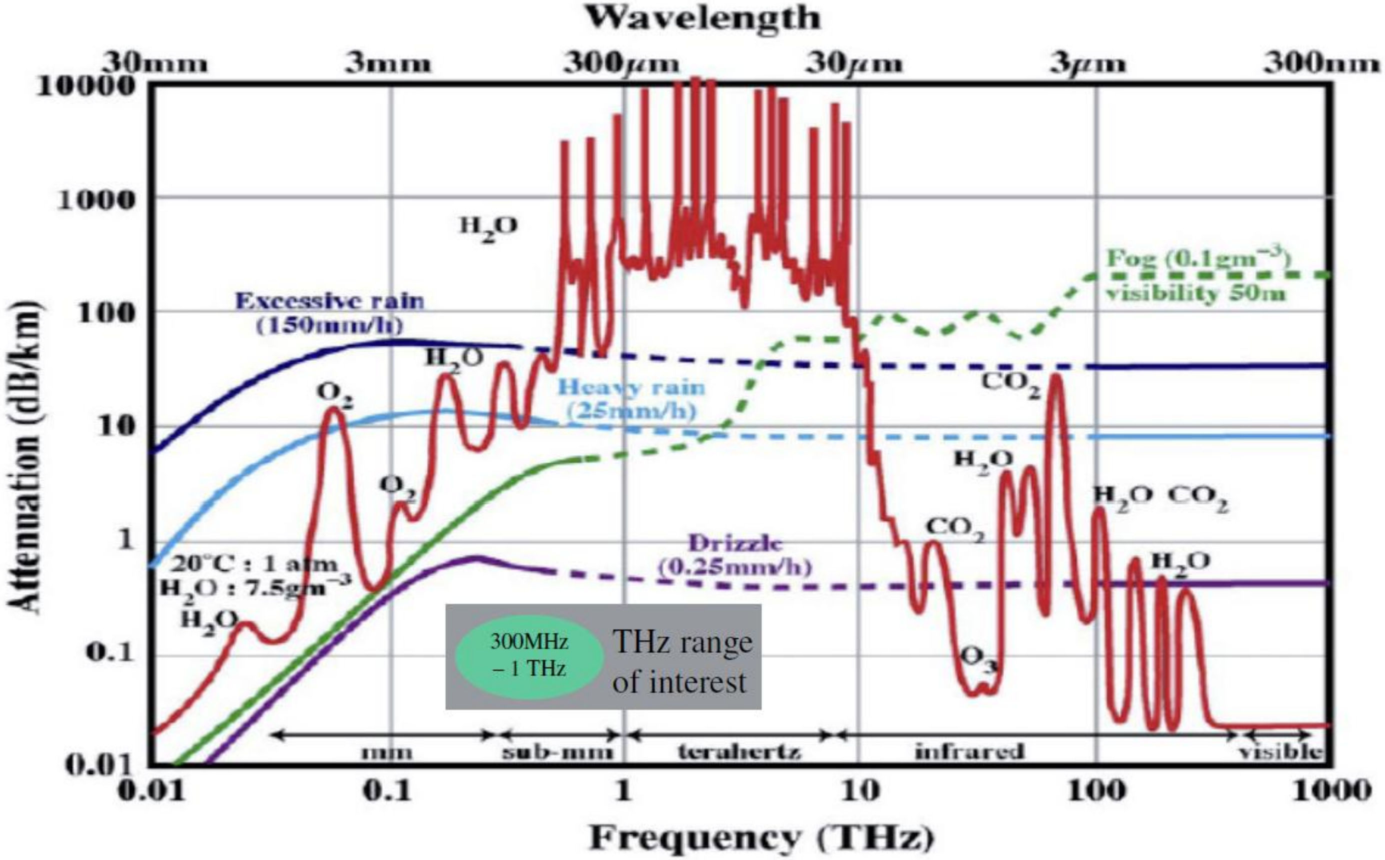
- regulations
- cost/performance tradeoff
- implementation complexity
- time to market

The implementation gap …

- the cost black hole
- the closer you get, the higher the cost!



Atmospheric Attenuation



Interestingly enough, atmospheric attenuation is a minor concern below ~300 GHz and above ~10 THz. Given fog loss, IR seems no worse than THz atmospheric loss.

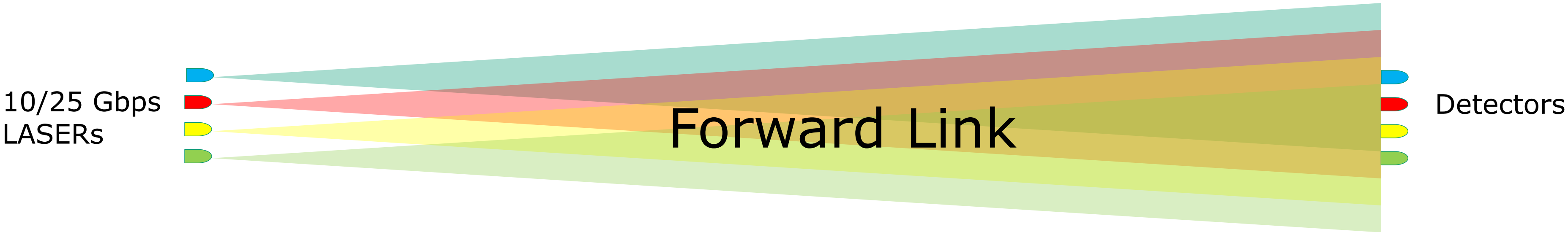
Consider two OWC transmission methods …

1. Space Division Multiplexing

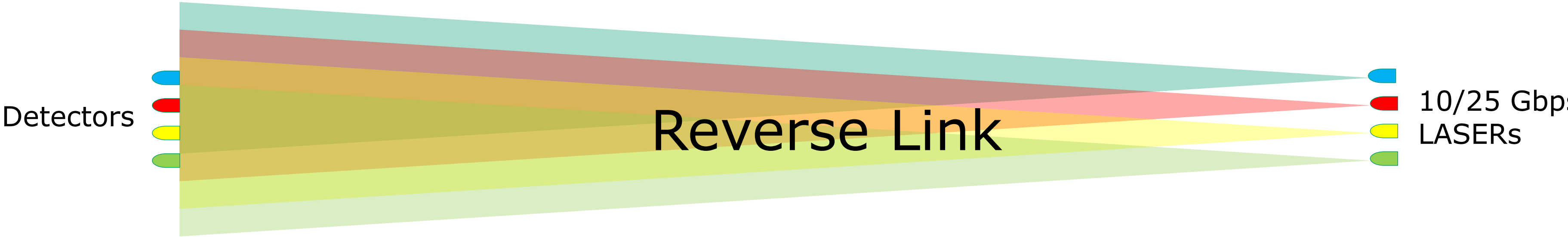
2. Wavelength Division Multiplexing

Not clear at this time which approach to use.

Full-Duplex Space Division Multiplexing

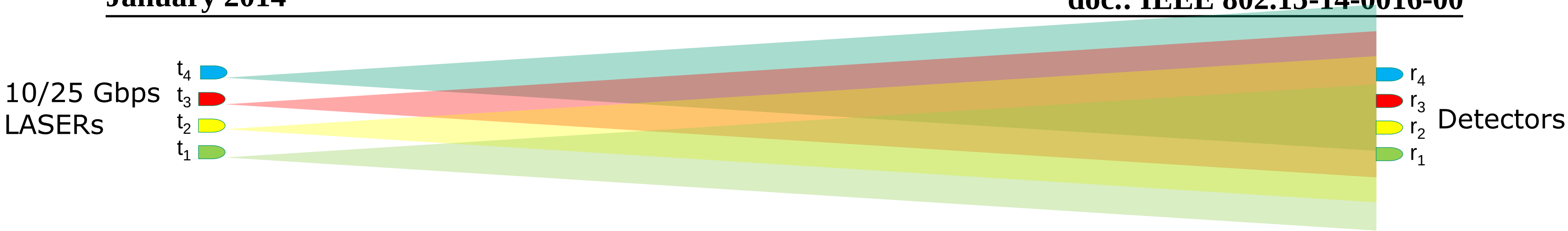


- Space Division Multiplexing (*SDM and not WDM*)
- 4 lanes @ 10/25 Gbps per lane
- LASER beams may be oversized to mitigate alignment jitter



Problem: we get severe cross talk between lanes which results in non-identity H matrix.

Solution: spatially separate the sources and sinks based upon a beam pattern minimum separation criteria determined by the beam pattern.



The H matrix describes how the signals interfere with each other.

$$R = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \cdot \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \end{bmatrix} = H \cdot T$$

Matrix entry h_{ij} means interference in the j^{th} receiver from the i^{th} transmitter.

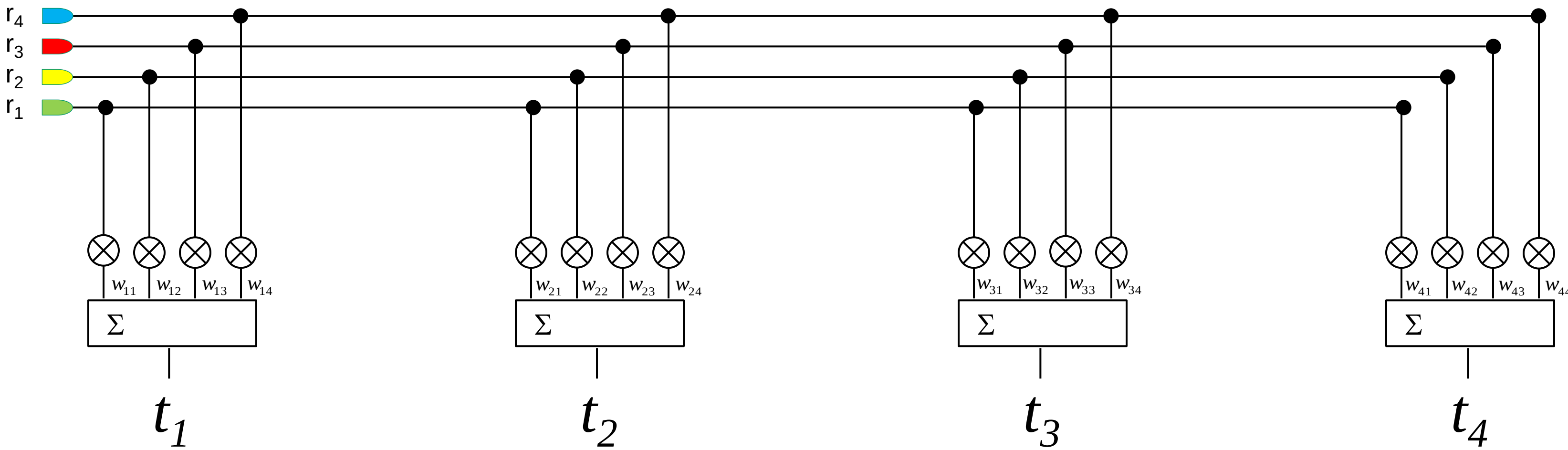
Here the interference is not multipath generated; but rather, is due to the beam spreading of the transmitted signals. The values of the H matrix are determined by the transmitter beam pattern and the receiver field-of-view.

We recover the original transmission at the receiver using the inverse H matrix to determine the decoupling network coefficient "weight" values.

$$S = H^{-1} \cdot R = W \cdot R = \begin{bmatrix} w_{11} & w_{12} & w_{13} & w_{14} \\ w_{21} & w_{22} & w_{23} & w_{24} \\ w_{31} & w_{32} & w_{33} & w_{34} \\ w_{41} & w_{42} & w_{43} & w_{44} \end{bmatrix} \cdot \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix}$$

Theoretically the weights are calculated and applied as shown below.

$$R = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \cdot \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \end{bmatrix} = H \cdot T \qquad S = H^{-1} \cdot R = W \cdot R = \begin{bmatrix} w_{11} & w_{12} & w_{13} & w_{14} \\ w_{21} & w_{22} & w_{23} & w_{24} \\ w_{31} & w_{32} & w_{33} & w_{34} \\ w_{41} & w_{42} & w_{43} & w_{44} \end{bmatrix} \cdot \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix}$$



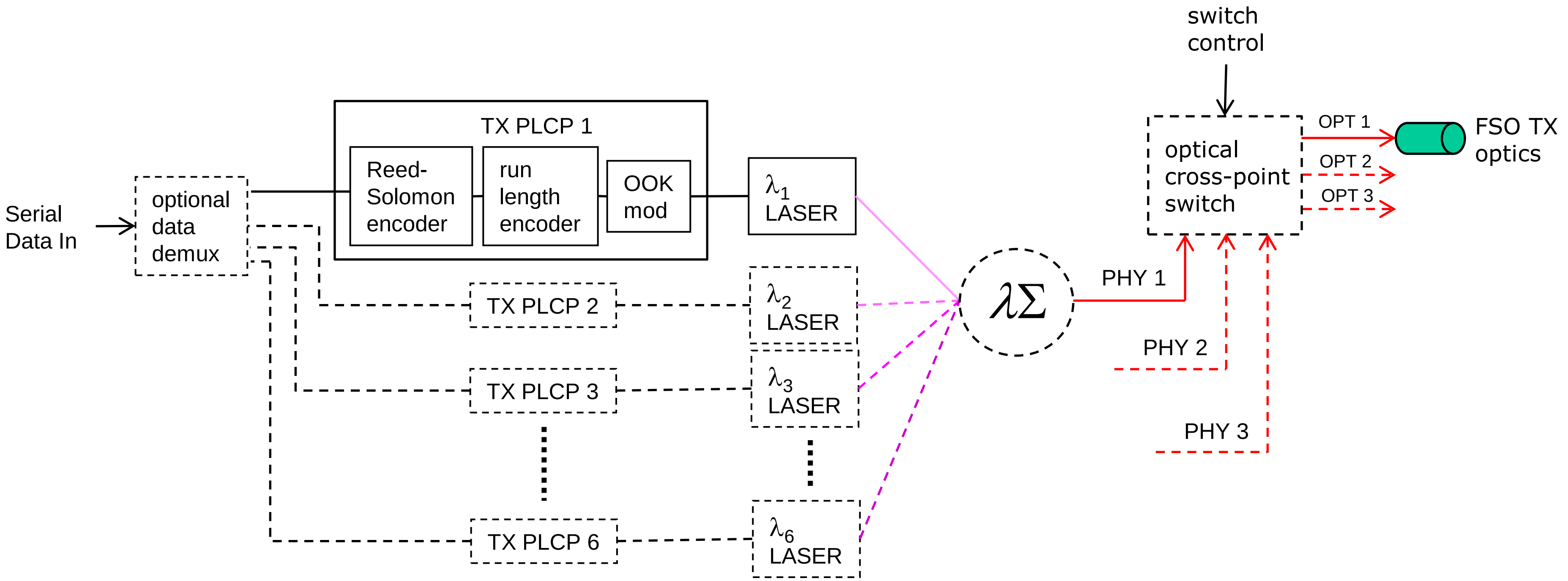
It is believed the training should be time sequential … turn on each transmit source and fill in the *H* matrix row by row. The *H* matrix is then inverted and the weights values extracted.

Implementation issue: realization of the multi-tap transversal filter with bi-phase linear weights

Eric Torkildson, Upamanyu Madhow, Mark Rodwell, *Indoor Millimeter Wave MIMO: Feasibility and Performance*, IEEE TRANS ON WIRELESS COMMUNICATIONS, VOL. 10, NO. 12, DEC 2011

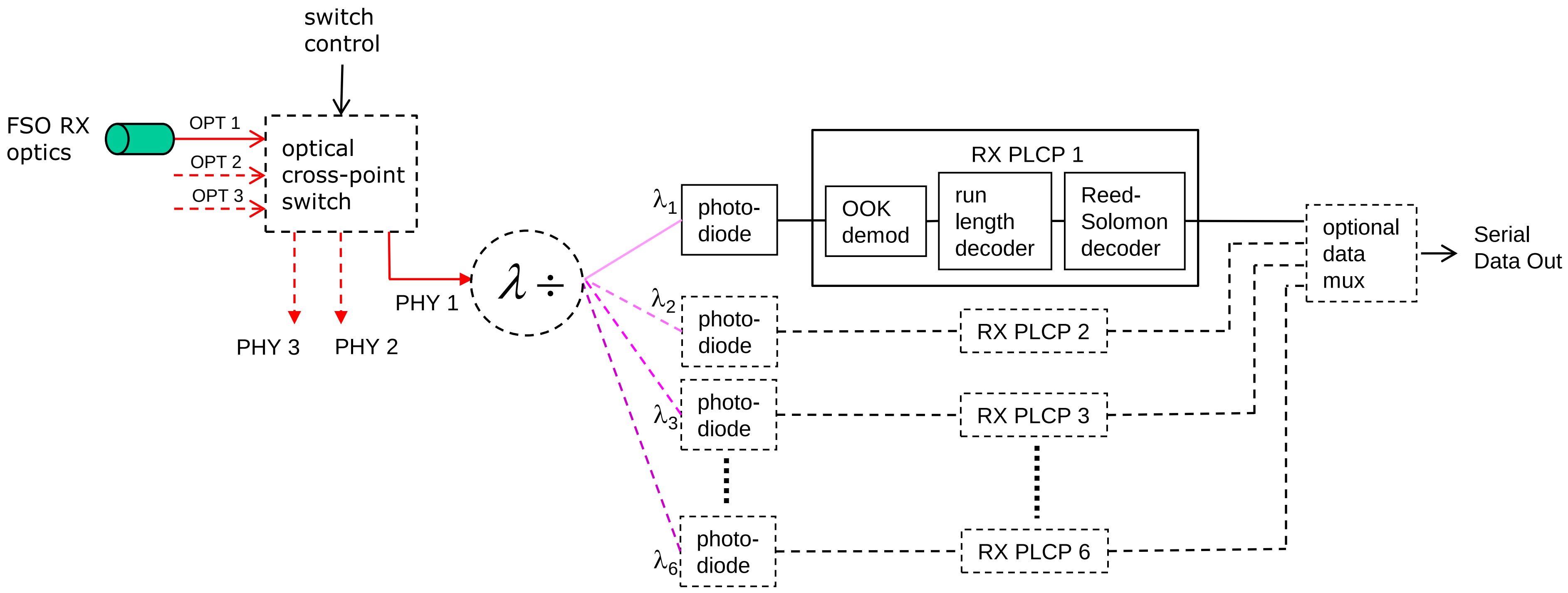
Wavelength Division Multiplexing

WDM PHY TX Block Diagram

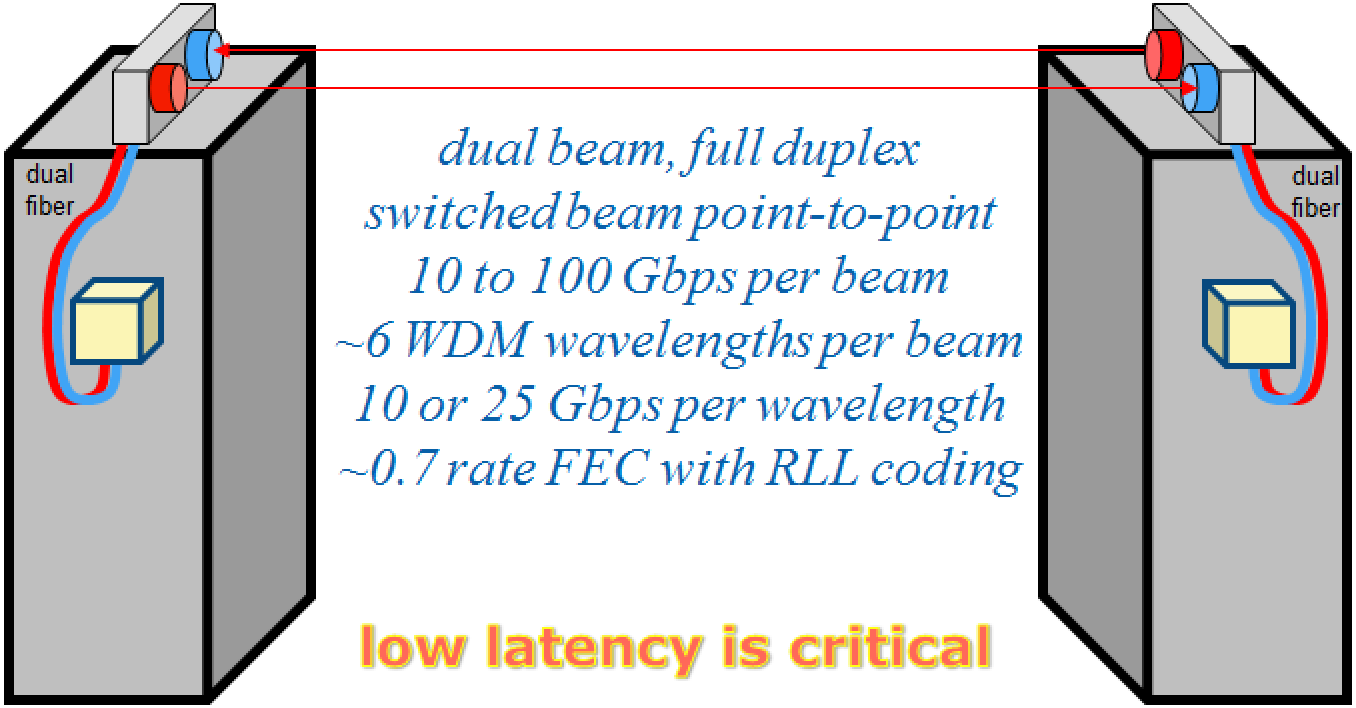


Wavelength Division Multiplexing

WDM PHY RX Block Diagram



WDM OWC Conceptual Deployment



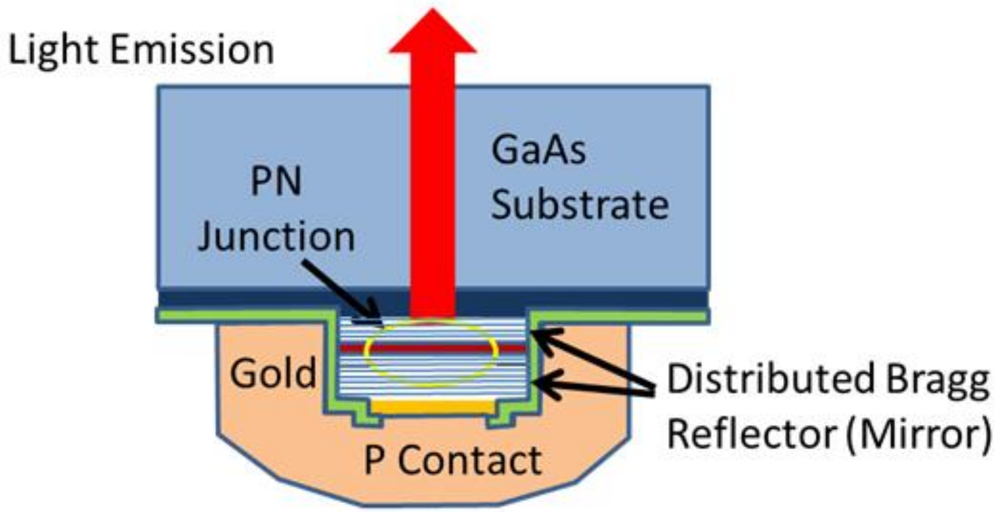
Operation is beam switched, fixed point-to-point (no beam training), with a fiber optic tether between the free space optics and the optical processor.

Part 2 – VCSEL
Technology and array processing
(Mial Warren, TriLumina Corp.)

TRILUMINA

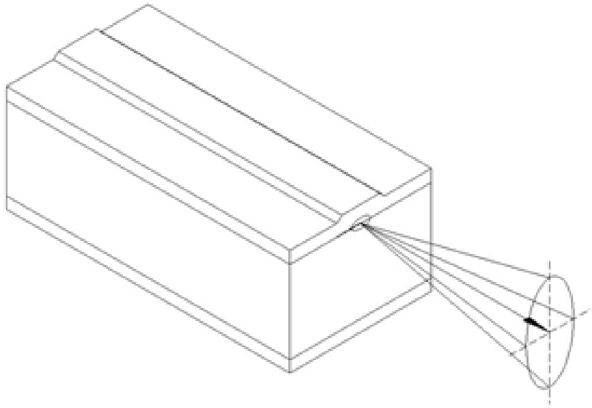
Introduction to Light Engine®
VCSEL Array Technology

The Bottom-Emitting Vertical Cavity Surface-Emitting Laser (VCSEL)



Recent Review: "Advances in VCSELs for Communication and Sensing," Larsson, IEEE J. Selected Topics Quantum Electronics, 17, 2011, pp 1552-1567.

Comparing VCSELs and Edge-Emitting Diode Lasers

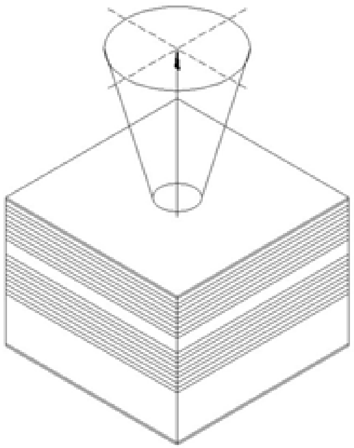


Pro

- High modulation bandwidth
- Long production history + High Volumes
- High brightness
- Narrow linewidth (DFB lasers)
- Moderately high power (~100 mW)

Con

- Die level testing only
- Hermetic packaging required (catastrophic optical damage)
- Asymmetric beam



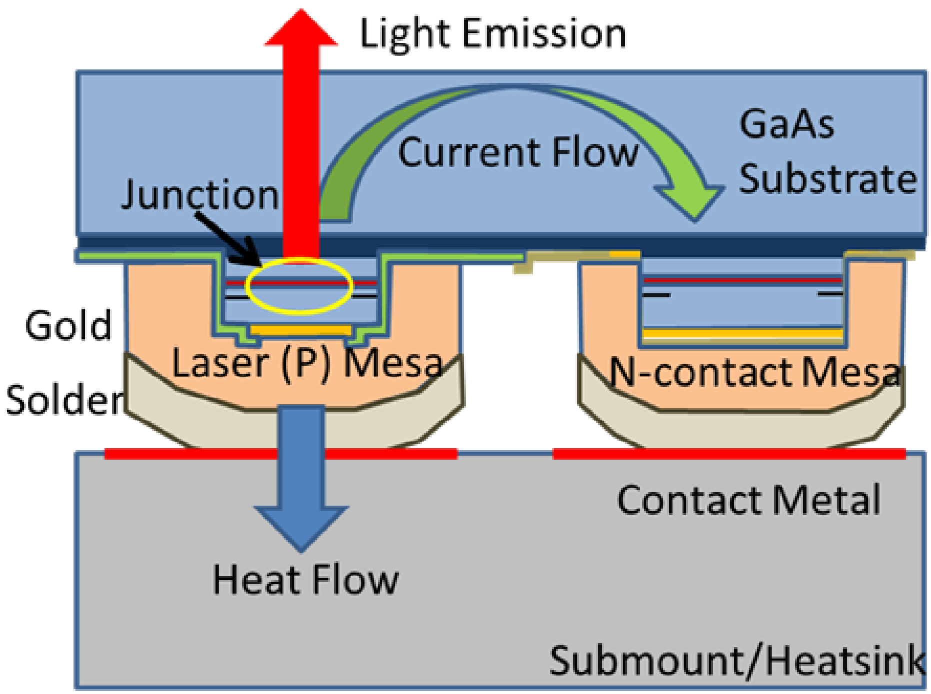
Pro

- High modulation bandwidth
- Symmetric, moderate divergence beam
- Wafer scale testing
- Proven high volume manufacturing and reliability (~100M/yr)
- Two-dimensional arrays
- Low packaging cost and complexity

Con

- Low Power

Scaling to Two Dimensional Arrays



2D arrays of VCSELs

Multiple P and N mesas contact to submount in parallel

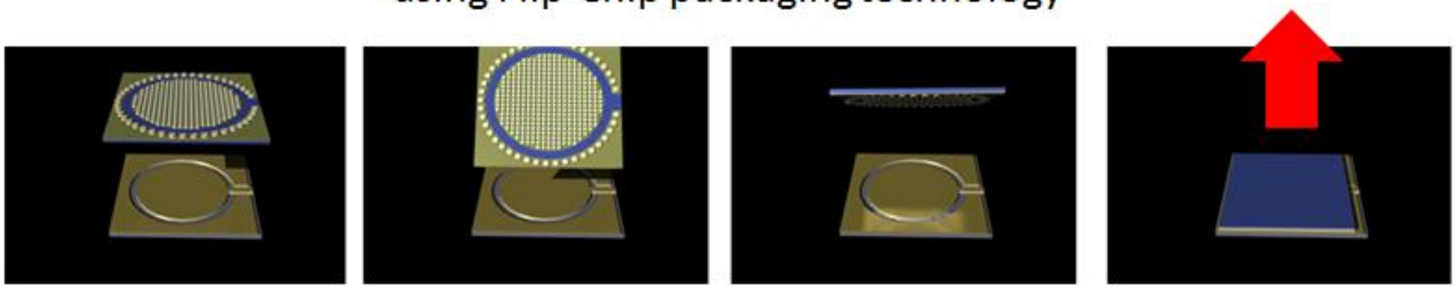
Low parasitic capacitance

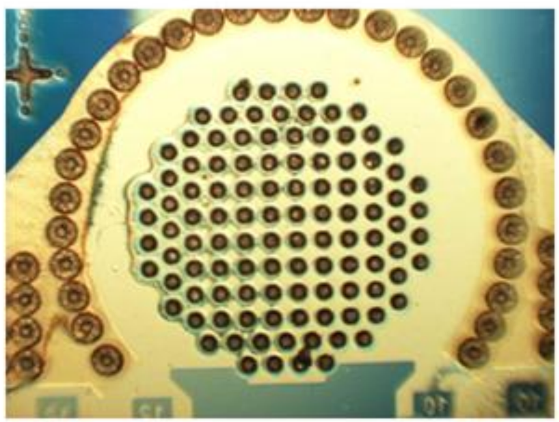
Integral heat sinking

Patent Reference: Joseph, J. US Patent 7,949,024, 2011

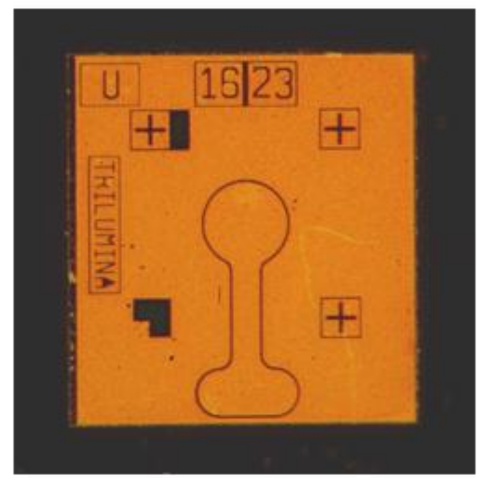
Flip-Chip Assembly on RF Waveguide

High Power Laser Array Integrated with High Speed Electrical Waveguide using Flip-Chip packaging technology

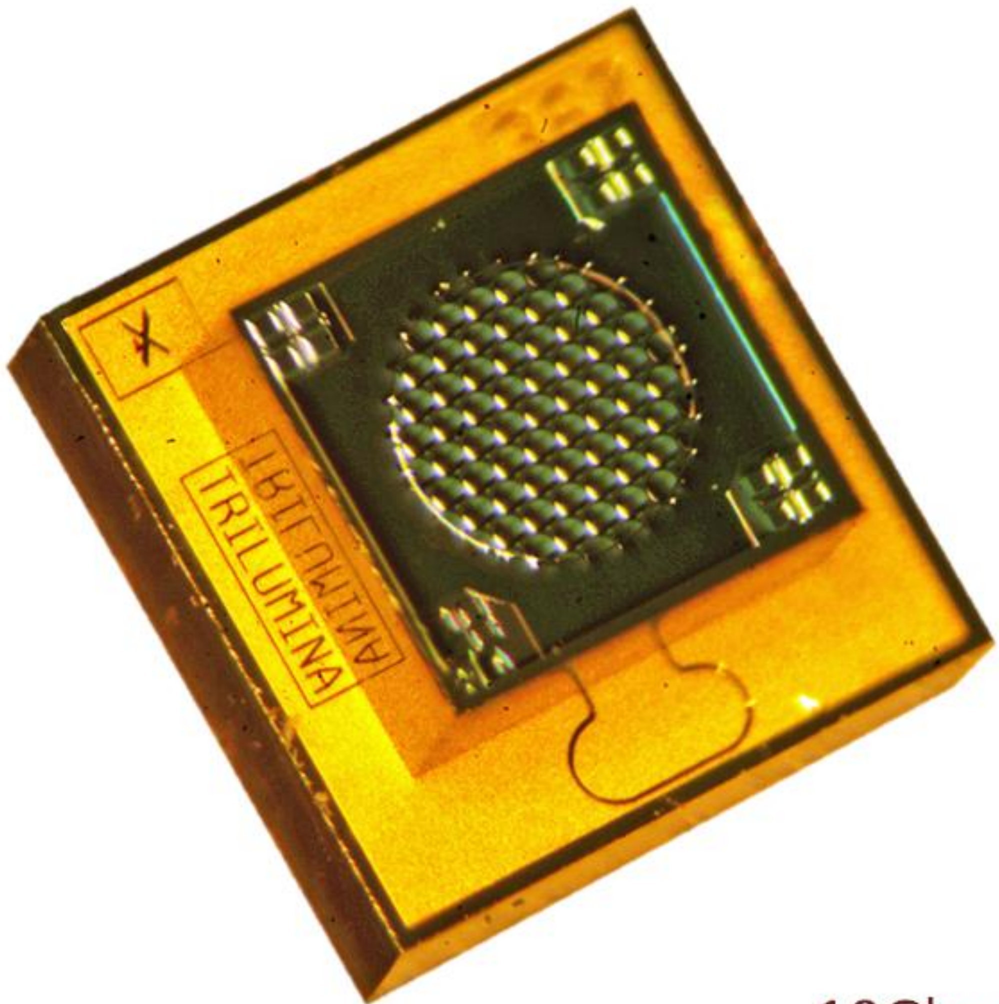




Individual VCSEL mesas with solder bumps – outer mesas are n-contact structures



Gold-plated submount coplanar waveguide with GSG contact

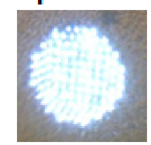


10Gbps Light Engine®
1mm² Si Submount

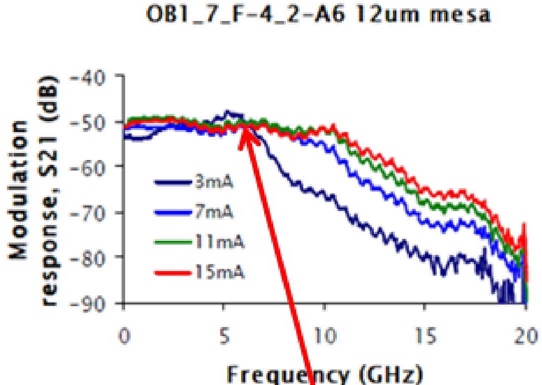
Scaling Power with Speed

Low capacitance design allows us to produce devices with high power and high bandwidths with very small form factors

105 element device below was **2mm x 2mm ~ 250 mW**

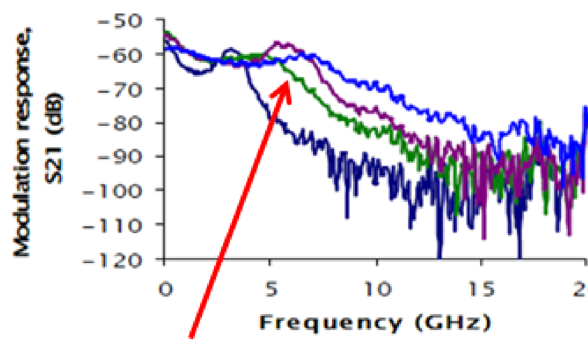


Single 12um VCSEL
(same fabricated wafer and near location as array)



3mA bias on individual VCSEL ~ 7GHz at -3dB

105 element Array of 12um aperture VCSELs
(same fabricated wafer and near location as array)

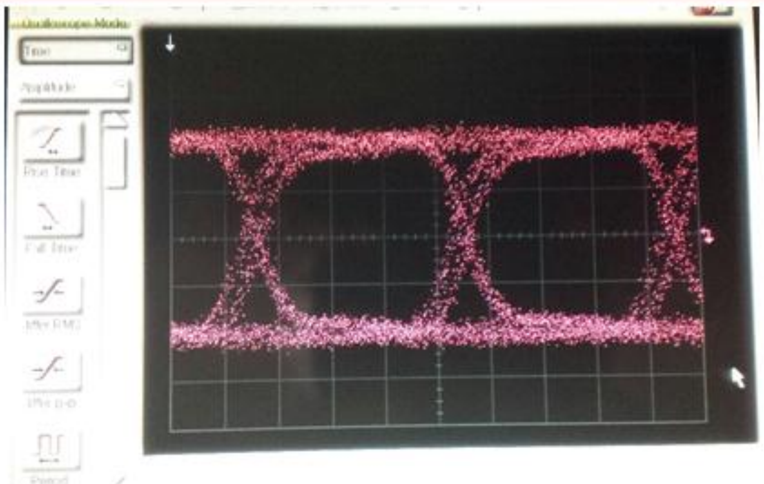


3mA bias per element in 105 VCSEL array ~ 7GHz at -3dB

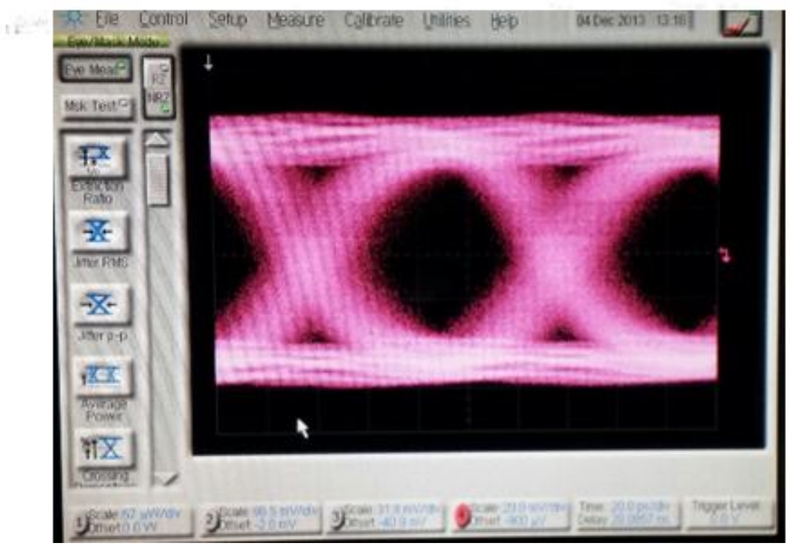
Note: The frequency Response indicates there is little to no penalty for frequency compared to the 3mA single device frequency response

Safaisini, R., Joseph, J. and Lear, K. "Scalable, High-CW-Power High-Speed 980-nm VCSEL Arrays," IEEE J. Quantum Electron. vol. 46, no. 11, pp. 1590-1596, Nov. 2010.

Example Eye Patterns

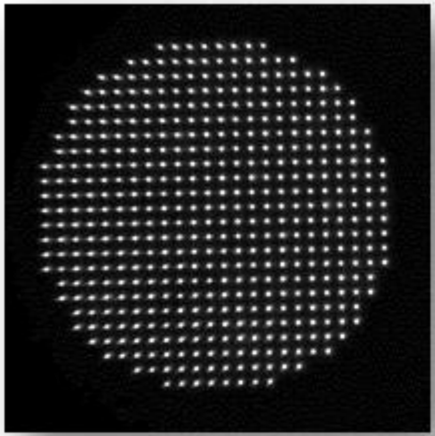


5 Gbps 37 element array
25mW



10 Gbps 37 element array
25mW

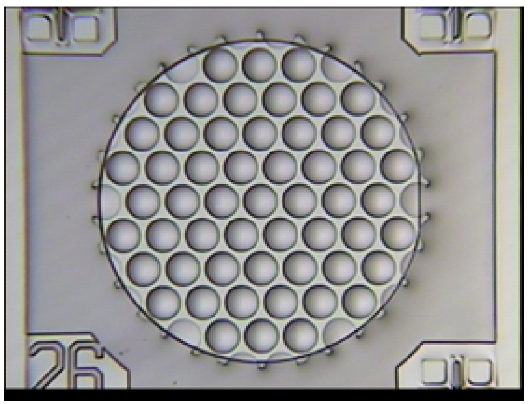
How Far Can We Scale?

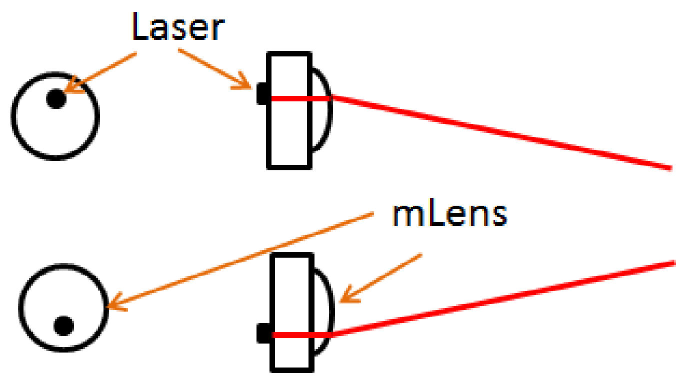


468 Element Array for High Power

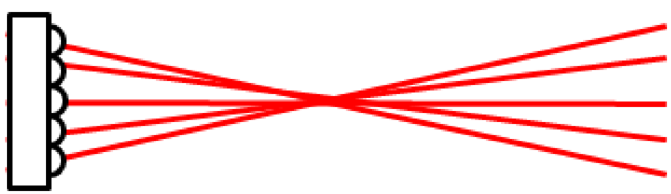
Monolithic Integrated Microlenses

Allow Beam Combination, Shaping and Direction

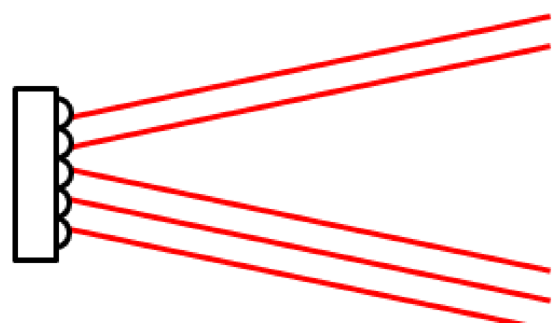




Lens can control divergence of individual lasers.
Offsetting lens can control direction of beam.



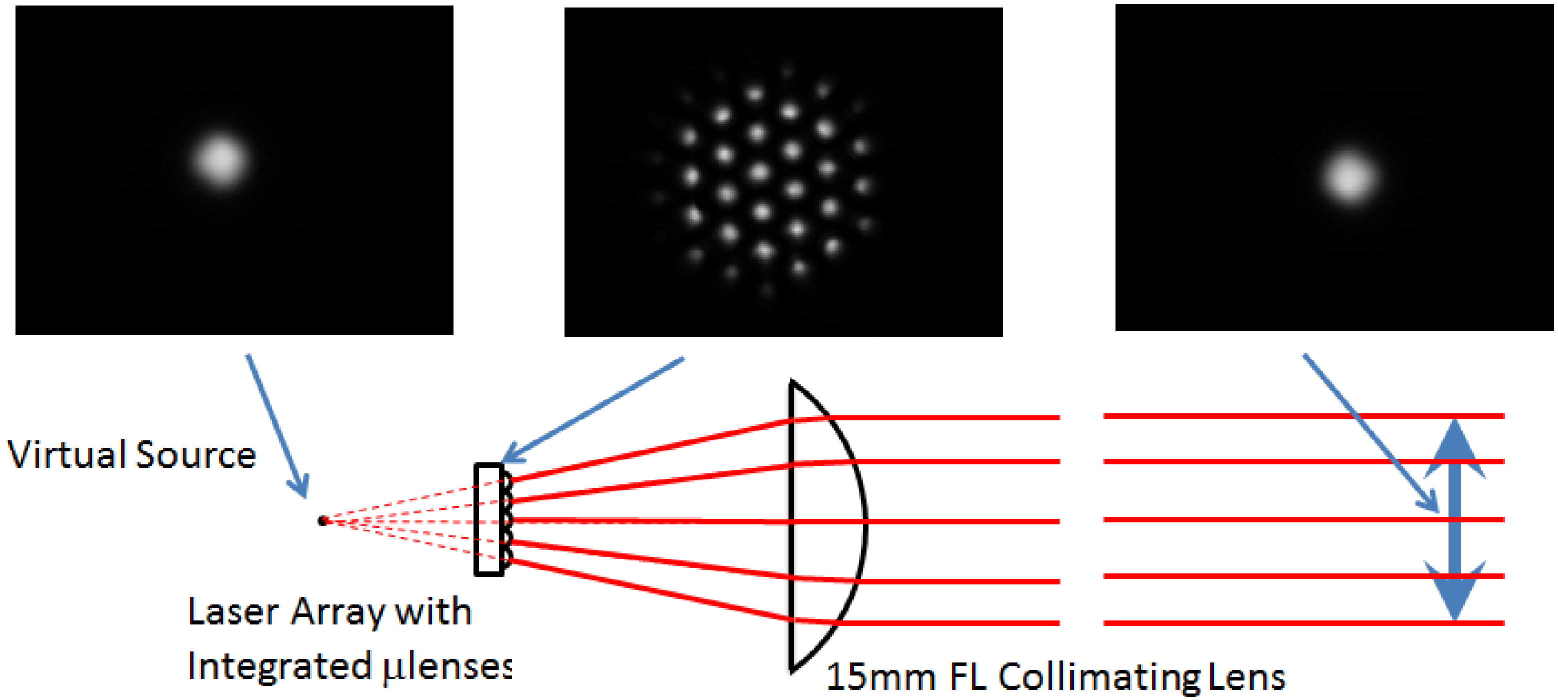
Converging/Diverging



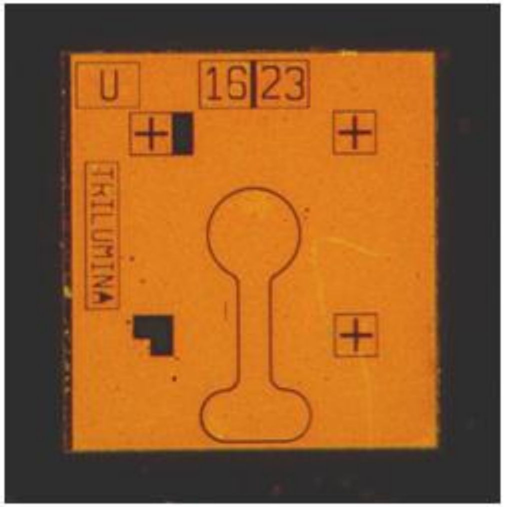
Splitting/Direction

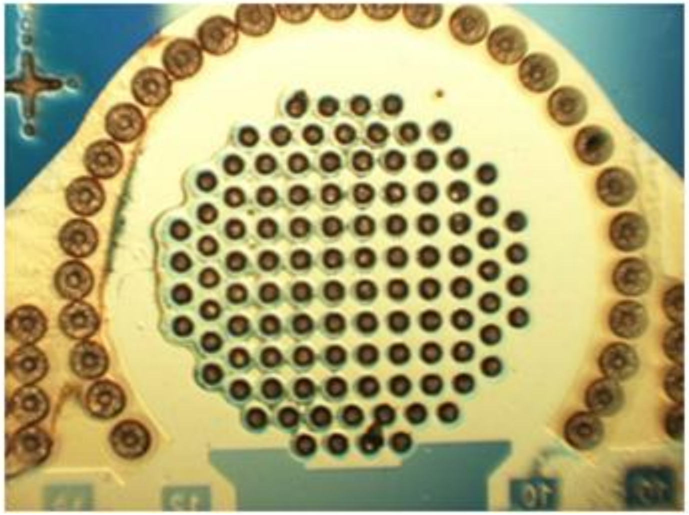
Incoherent Beam Combining

Offset micro-lenses allow creation of a real or virtual single optical source from the laser array for higher brightness and improved collimation. Allows for Z-height compression – small form factor.

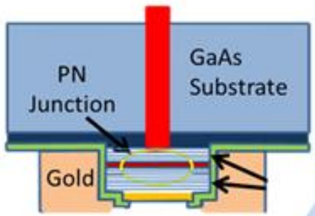


- Multiple lasers in one device
- Self compensating design allows power redistribution to all active elements
- “Graceful degradation” individual elements fail but the array survives

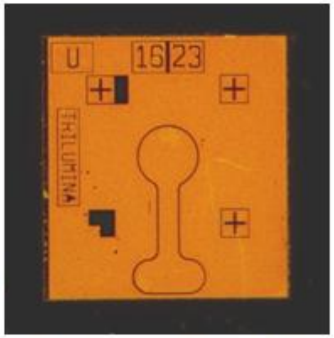




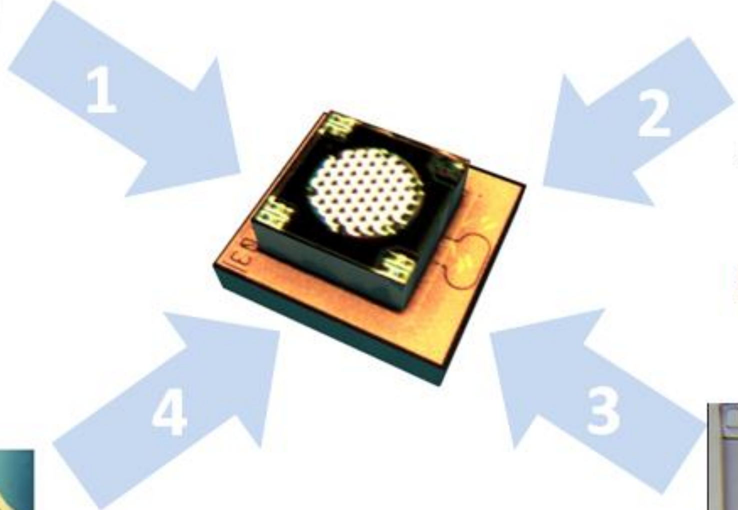
TriLumina Technology

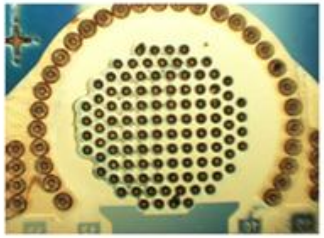


Fast VCSELS
(Low Power)

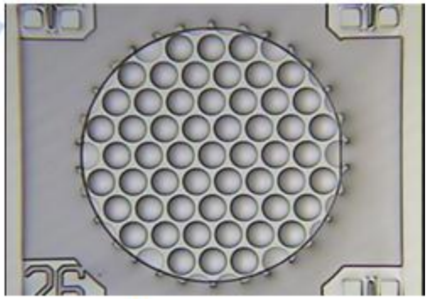


2D Array of VCSELs
Contacted to Single
Electrical Waveguide
(Power)

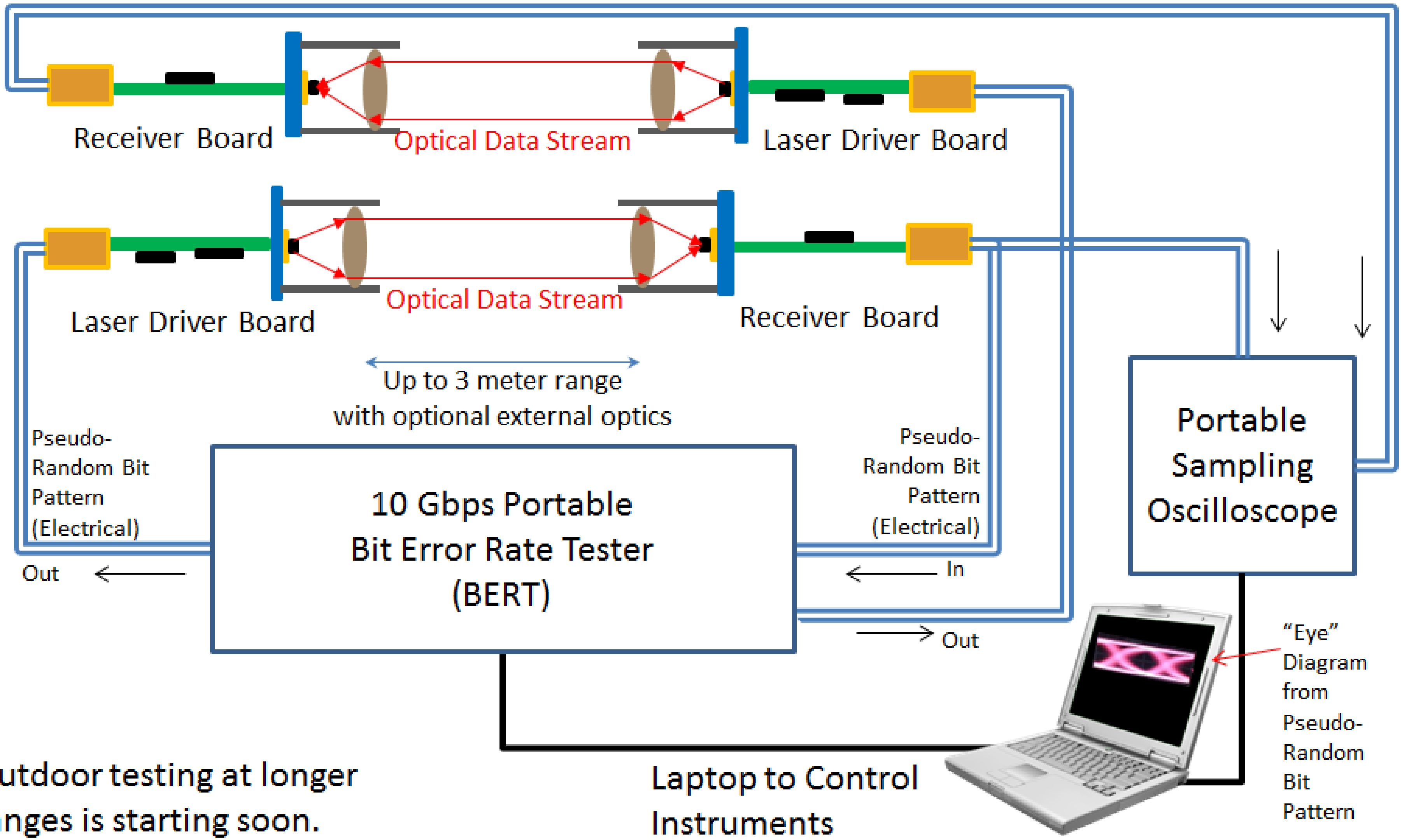




Reliability and Robust Processing
(Leverage existing
Manufacturing Techniques)



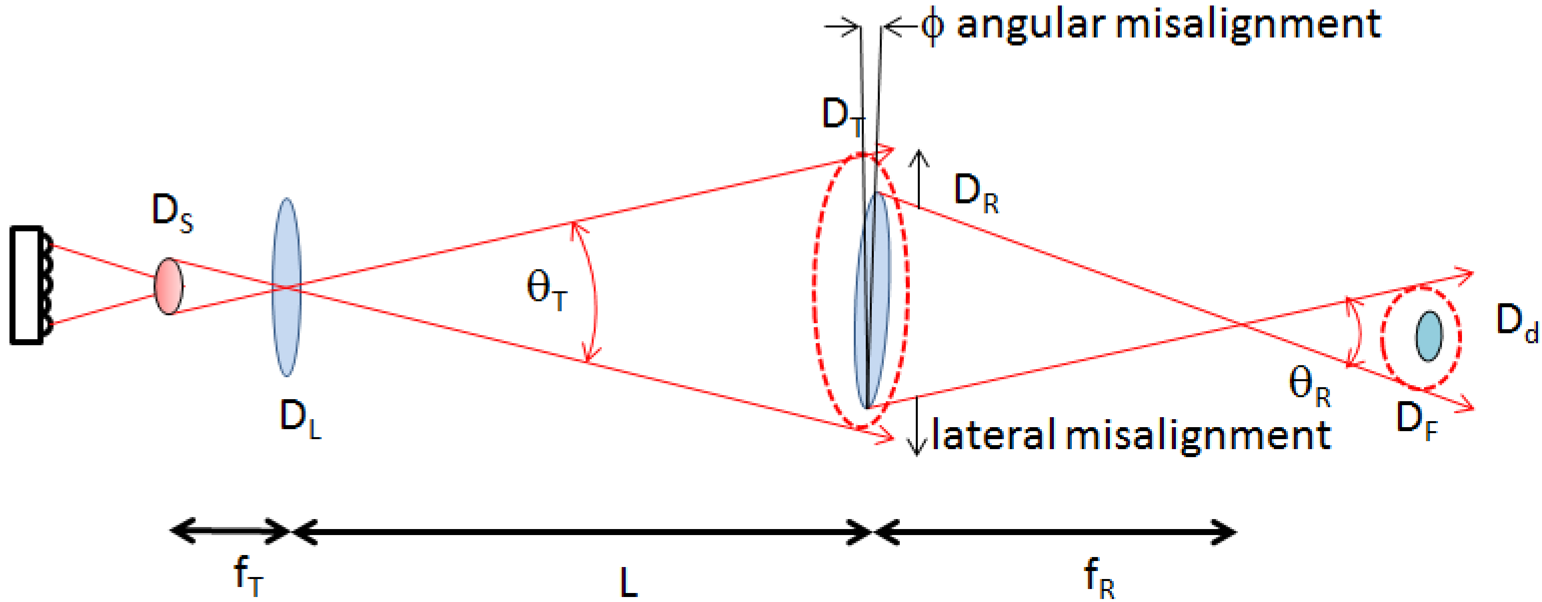
Microlenses
(Optical Properties)



Outdoor testing at longer ranges is starting soon.

Short Range Links without External Optics

- Low Cost, Size, Weight, and Power (CSWaP)
- High Bandwidth, High Efficiency
- Low Joule/Bit
- High Reliability, High Resiliency
- Flexible and Scalable Array Architecture
- No cabling or penetrating connectors



Source size determines Tx divergence: $\tan \theta_T = D_S/2f_T$

Diameter of Tx beam: $D_T = \theta_T/2 \cdot L + D_L$ Diameter of receiving optic: D_R

Diameter of detector: D_d Diameter of Rx focal spot: D_F

Optical coupling efficiency:

η = Area Tx beam/Area Rx optic · Area detector/Area focus spot = $(D_R/D_T)^2 \cdot (D_d/D_F)^2$

Alignment tolerance for angular misalignment of Rx and lateral misalignment of Rx to the Tx beam ~ D_F/D_d - overfill of detector

Modulation

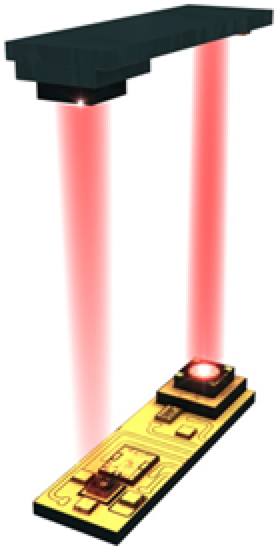
- Optical receivers use photodiode “square law” detectors
- VCSELs are a coherent laser source
- The lasers in the arrays are mutually incoherent
  - We are using incoherent beam combining
  - TriLumina VCSEL arrays are not phase locked arrays
- ∴Cannot use coherent detection schemes (QAM, etc.)
- Limited to amplitude modulation
- How do we extend the bandwidth of optical links using VCSEL arrays?

RF comparison: “Short-Range Wireless Infrared Transmission: The Link Budget Compared to RF,” Wolf and Kreß, IEEE Wireless Comm April 2003, pp 8-14.

Bandwidth Advancement

- Baseband Data Rate
  - Single VCSEL bandwidth is continuing to improve – approaching 50 GHz
- Spatial Multiplexing
  - Multiple channels in parallel separated by short distance
- Coarse Wavelength Division Multiplexing
  - Aggregate data rate of a multiple VCSEL arrays where each array sub-group is assigned a specific wavelength within the band of the technology
- PAM – Pulse Amplitude Modulation
  - OOK with multiple amplitude levels and linear detection levels
  - Need ample link margins to maintain S/N ratio

Spatial Multiplexing

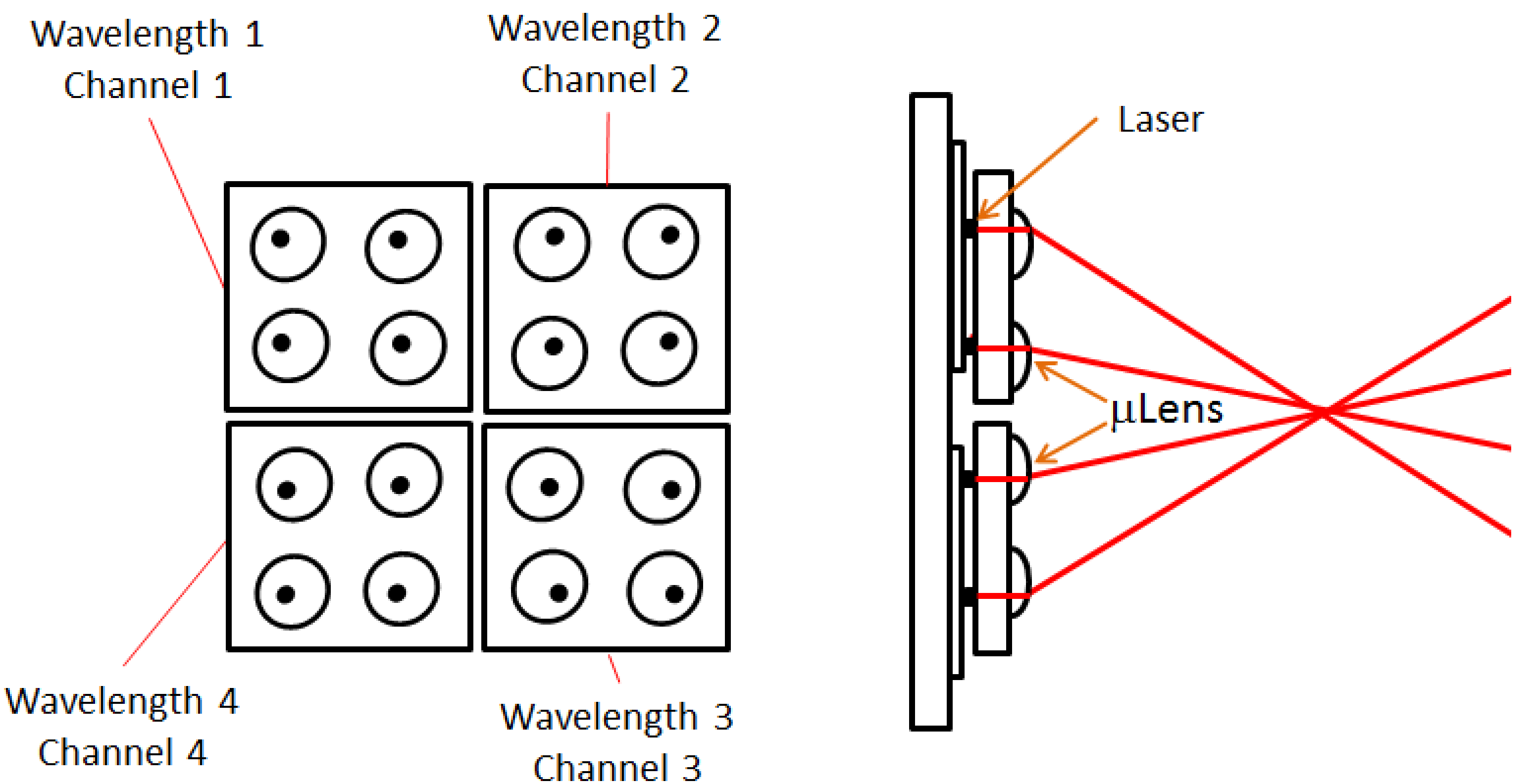


Single Channel
Bidirectional Link

Four Channels

4 Wavelength (Coarse) CWDM – Single Focal Point

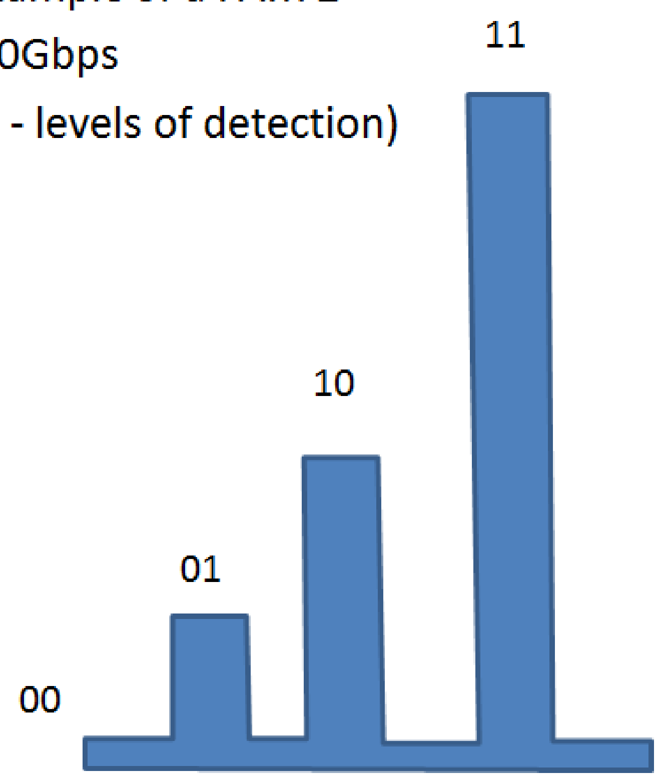
Manufacturing tolerances limit channel wavelength spacing to several nanometers (> 1THz)



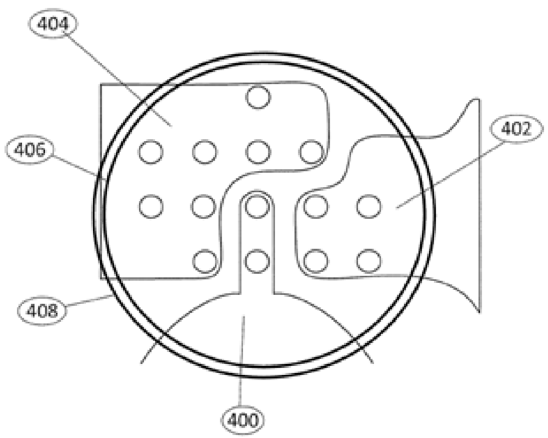
Pulse Amplitude Modulation (PAM)

PAM Requires High Link Margins and Linear Detection

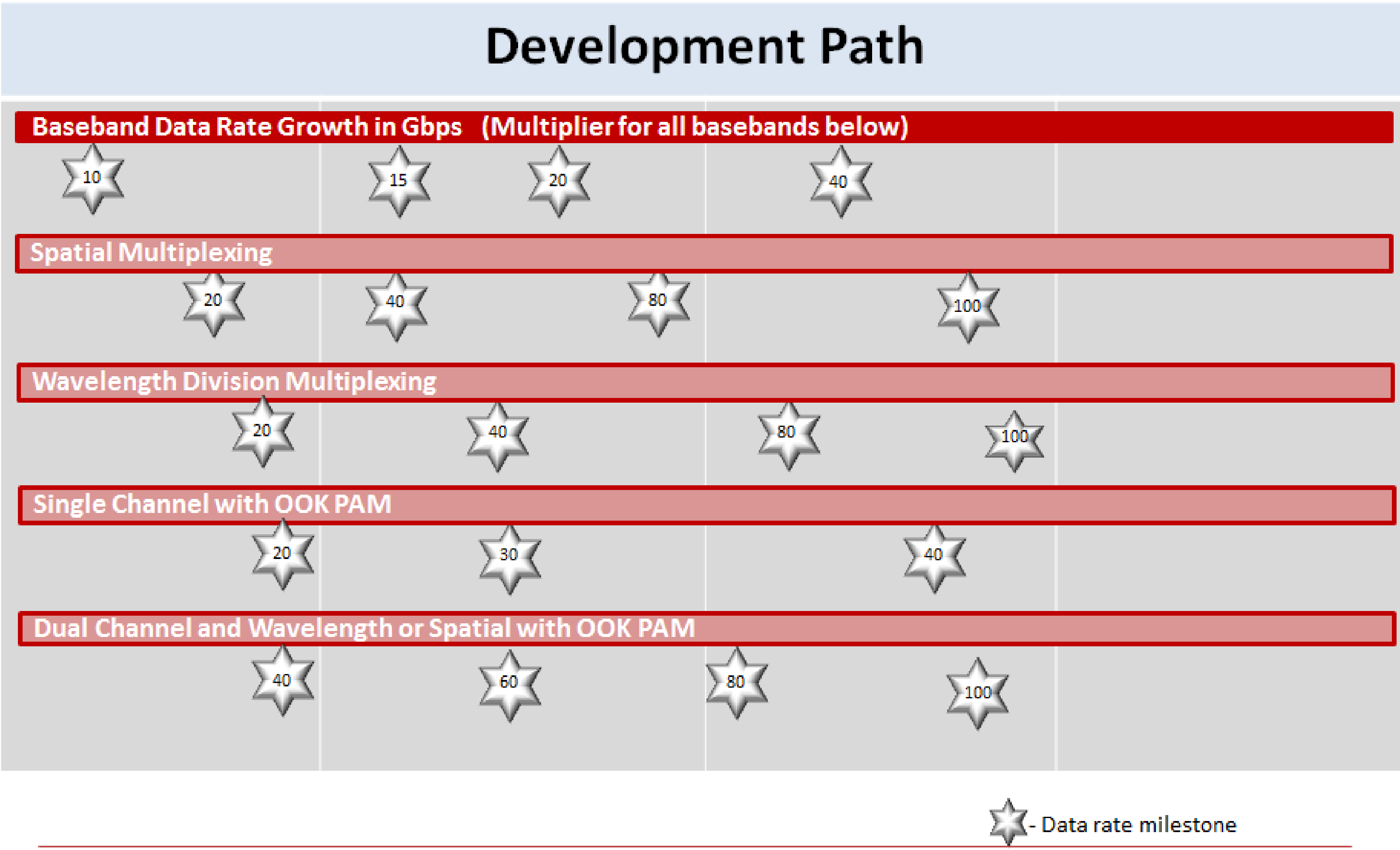
- Example of a PAM 2
- 20Gbps
- (4 - levels of detection)



- Example of a PAM 3 Emitter
- 30Gbps
- (8 - levels of detection)



Bandwidth Development Roadmap



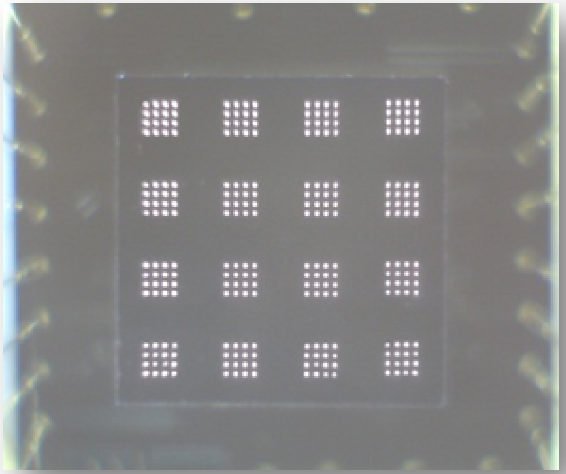
Eye Safety

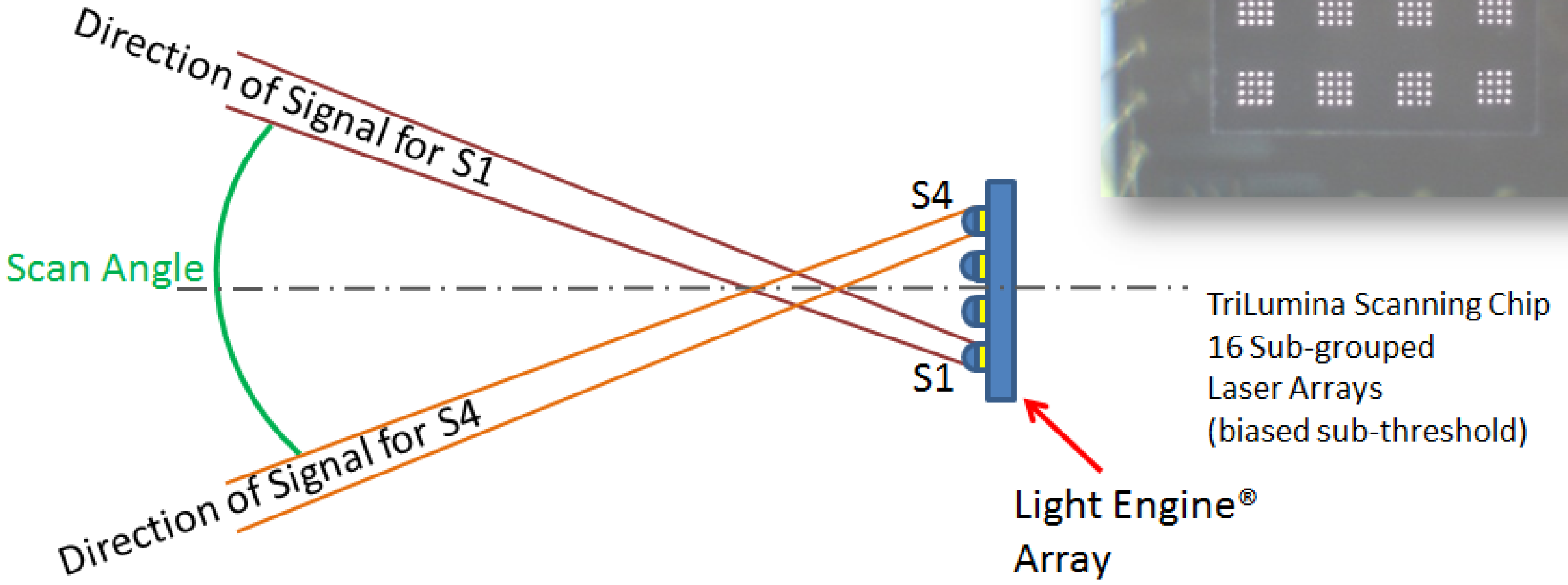
Eye Safety Factors for VCSEL Arrays

- Application (enclosed beam or open? Standards allow higher laser class in some situations)
- Extended Source Properties
- Array of Point Sources
- Incoherent Beam
- Modal Properties
- Power output
- Duty cycle
- Collimated Beam Size
- Longer Wavelengths (progressing to >1200nm)

Solid State Scanning - Auto Alignment

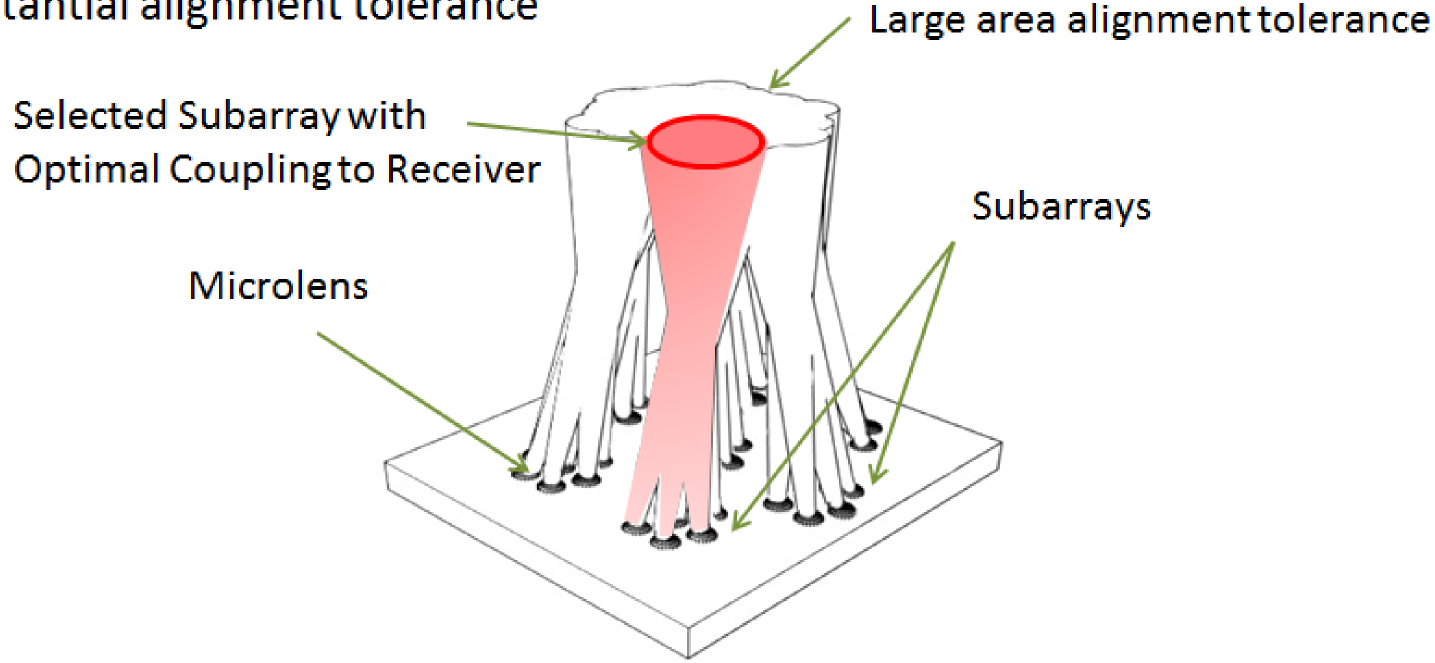
- Each sub-array contains multiple lasers
- Offers redundancy in case of single laser failure
- Permits scanning - Dynamic Link Management





Dynamic Link Management - Auto Alignment

Sequenced illumination through subarrays
Directed beam for scanning alignment with receiver
Substantial alignment tolerance

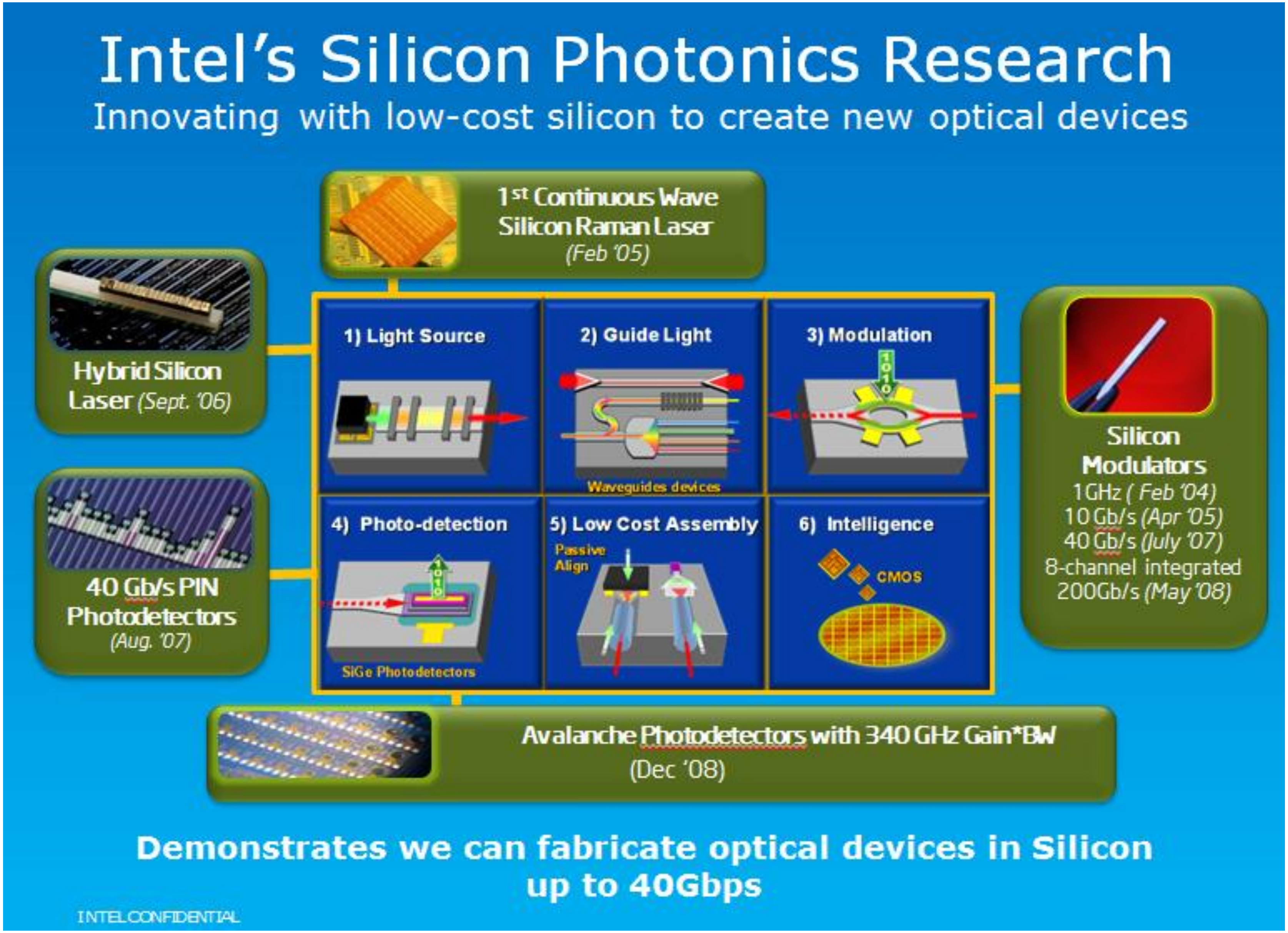


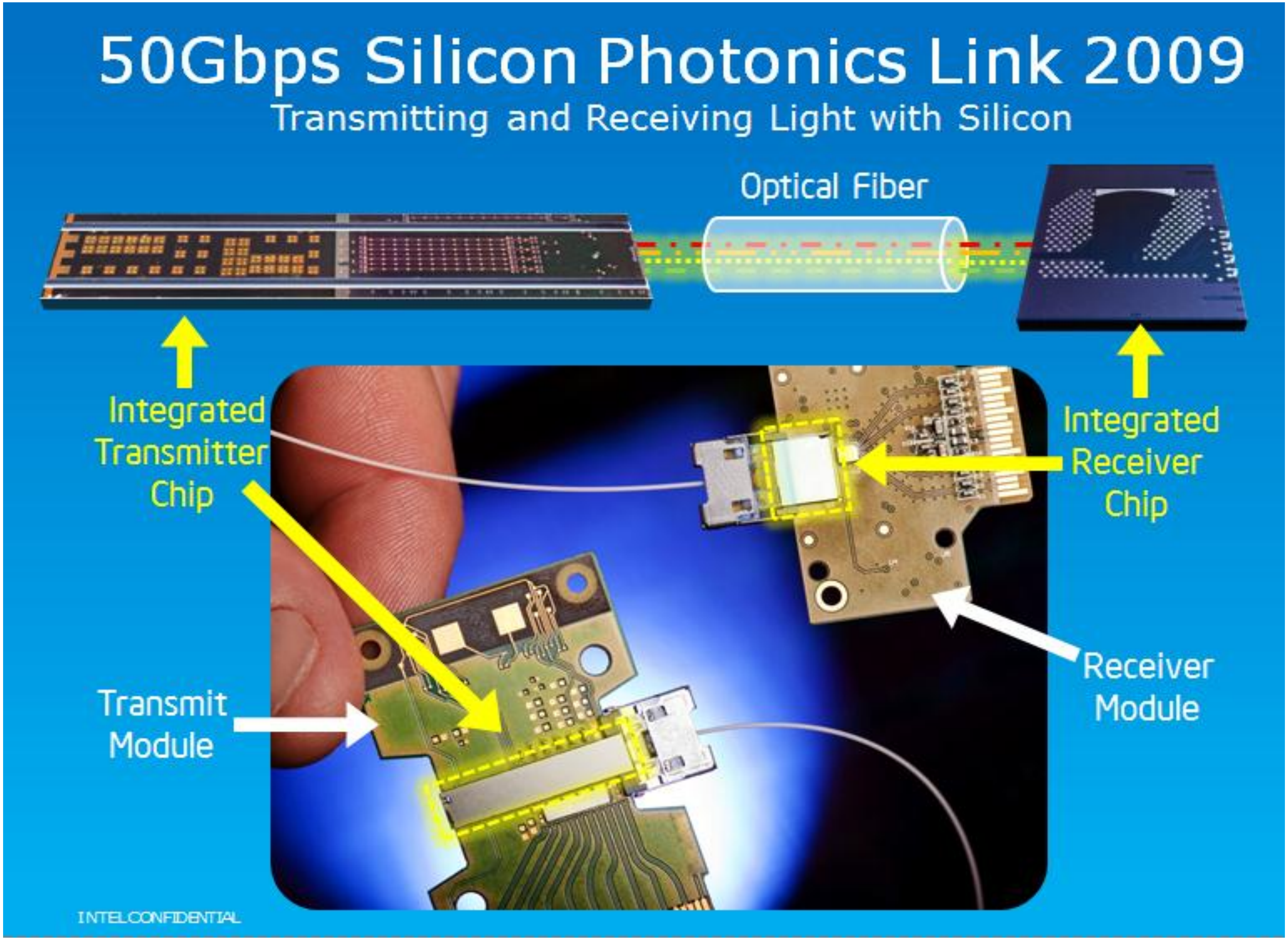
Subarrays not contributing to the link can be powered down

Part 3 – Historical Optical modem technology (Juthika Basak, Intel Labs)

Part 3
Optical Interconnect Technology
Silicon Photonics @ Intel

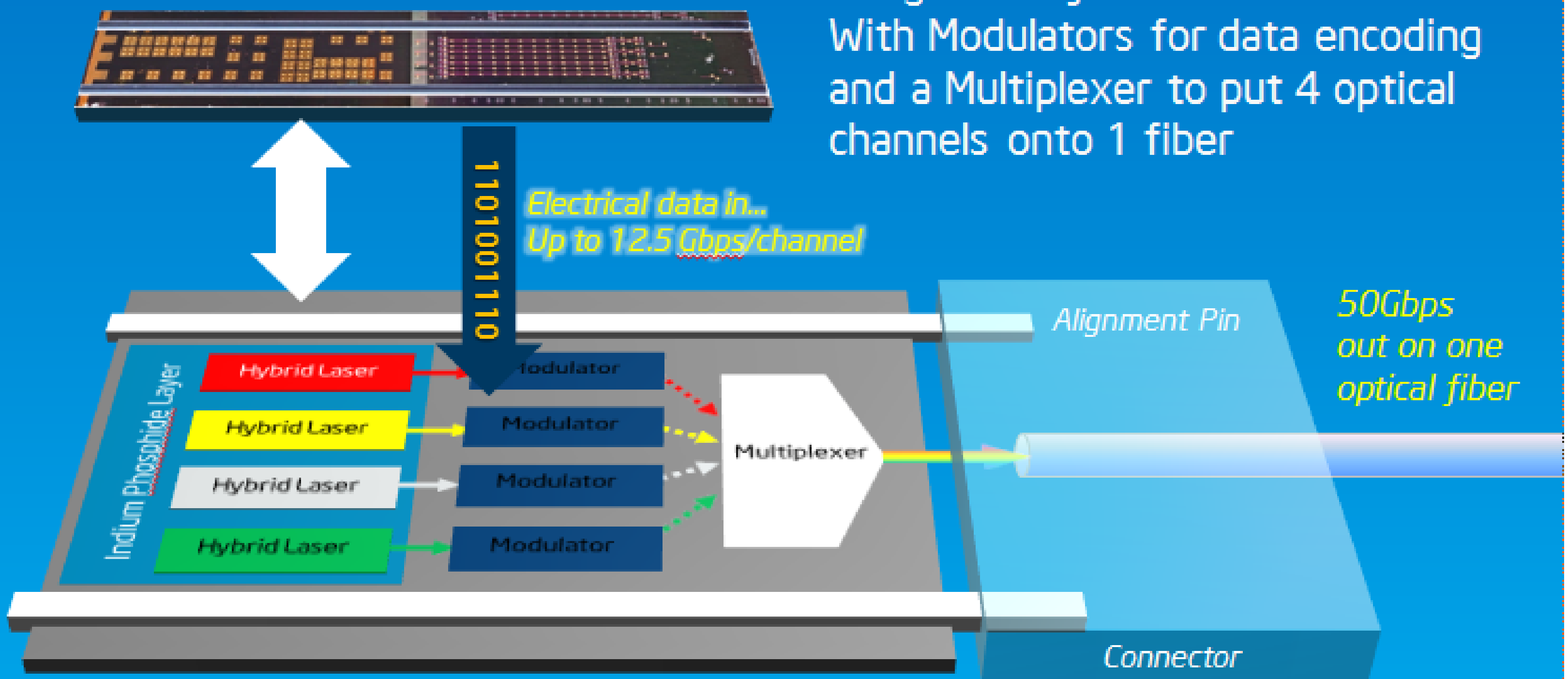
Contributor: Juthika Basak


Intel's Silicon Photonics Research
Innovating with low-cost silicon to create new optical devices
1st Continuous Wave Silicon Raman Laser (Feb '05)
Hybrid Silicon Laser (Sept. '06)
40 Gb/s PIN Photodetectors (Aug. '07)
1) Light Source
2) Guide Light
Waveguides devices
3) Modulation
4) Photo-detection
SiGe Photodetectors
5) Low Cost Assembly
Passive Align
6) Intelligence
CMOS
Silicon Modulators
1GHz (Feb '04)
10 Gb/s (Apr '05)
40 Gb/s (July '07)
8-channel integrated
200Gb/s (May '08)
Avalanche Photodetectors with 340 GHz Gain*BW (Dec '08)
Demonstrates we can fabricate optical devices in Silicon up to 40Gbps
INTEL CONFIDENTIAL


50Gbps Silicon Photonics Link 2009
Transmitting and Receiving Light with Silicon
Optical Fiber
Integrated Transmitter Chip
Integrated Receiver Chip
Transmit Module
Receiver Module
INTEL CONFIDENTIAL

Integrated Transmitter Chip

Integrates Hybrid Silicon Lasers With Modulators for data encoding and a Multiplexer to put 4 optical channels onto 1 fiber

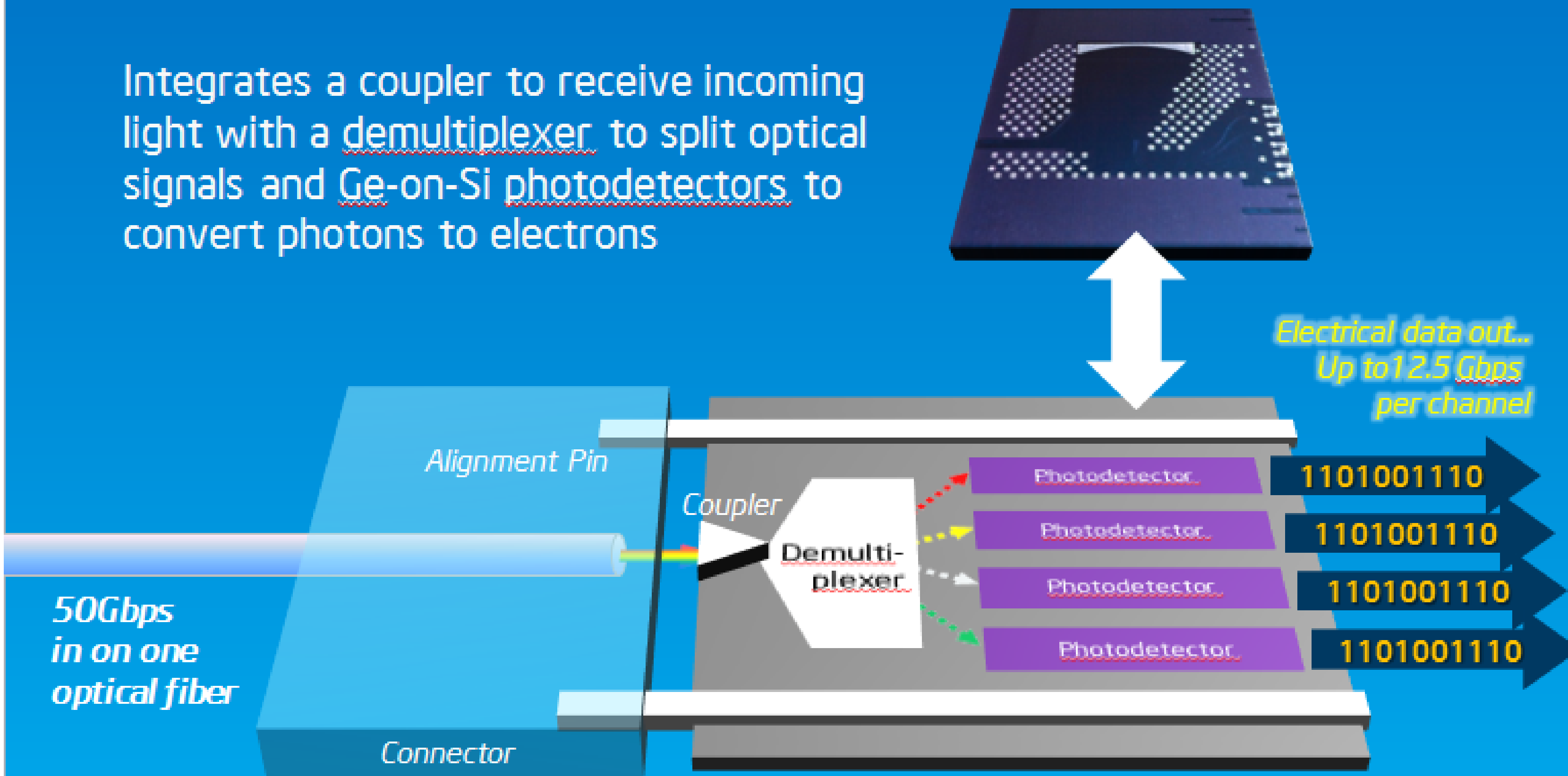


Parallel channels are key to scaling bandwidths at low costs

INTEL CONFIDENTIAL

Integrated Receiver Chip

Integrates a coupler to receive incoming light with a demultiplexer to split optical signals and Ge-on-Si photodetectors to convert photons to electrons



Receives 4 optical channels at 12.5Gbps and converts to electrical data

Intel's Challenge for Corning

#1 in computing

intel

#1 in optical communications

CORNING

"We need:"

1. A new fiber that is:
   - Multimode but with tight bends
   - Optimized for Silicon Photonics
   - Longer reach
2. A new connector that is:
   - Higher BW, more rugged AND smaller, less cost

"We like challenges and we will take this one on!"

Intel Corporation - Corning Incorporated

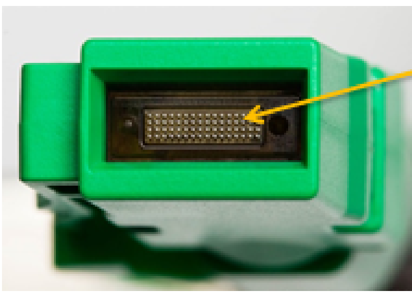
ClearCurve Fiber

Photons bounce off fiber "walls" as they travel
But they take different paths, distorting the data
Eventually the data becomes unreadable
ClearCurve fiber minimizes distortion & allows 300m distances

intel
Intel Corporation - Corning Incorporated
CORNING

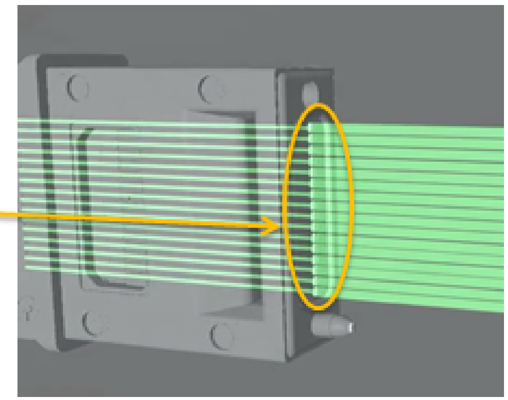
Connector: Dealing with Dust

Dust: #1 cause of failure for optical cabling in datacenters

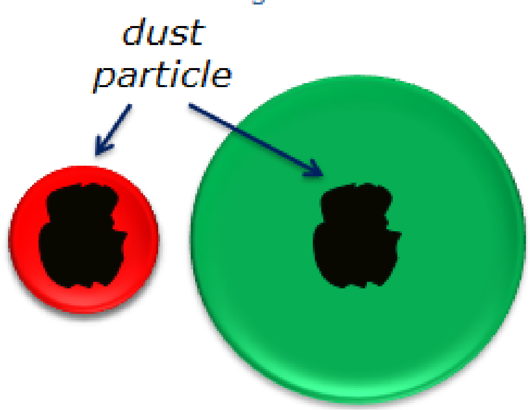


Recessed Integrated beam Expander

Recessed give better dust immunity and protection from physical damage



Tradition fiber core
50um diameter
Area = πr^2
Area = ~$2000 um^2$



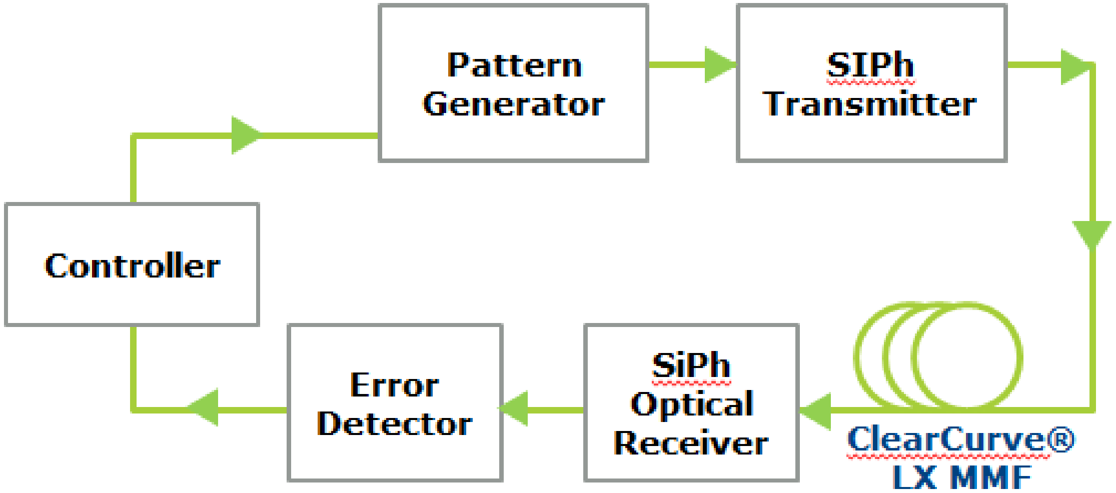
MXC with Beam Expander
180 um diameter
Area = $25,000 um^2$

10x Better Dust Immunity

CORNING

System testing of Fiber design :

25Gb/s with an Intel® Silicon Photonics Module

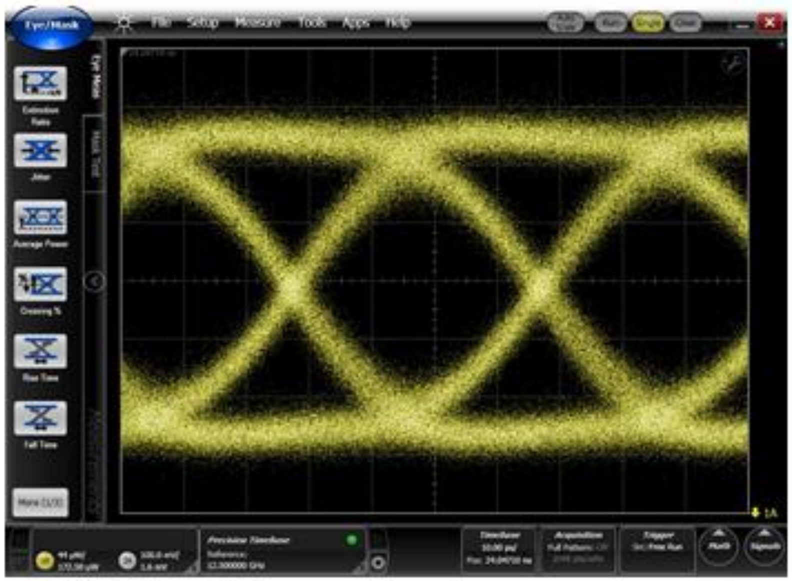


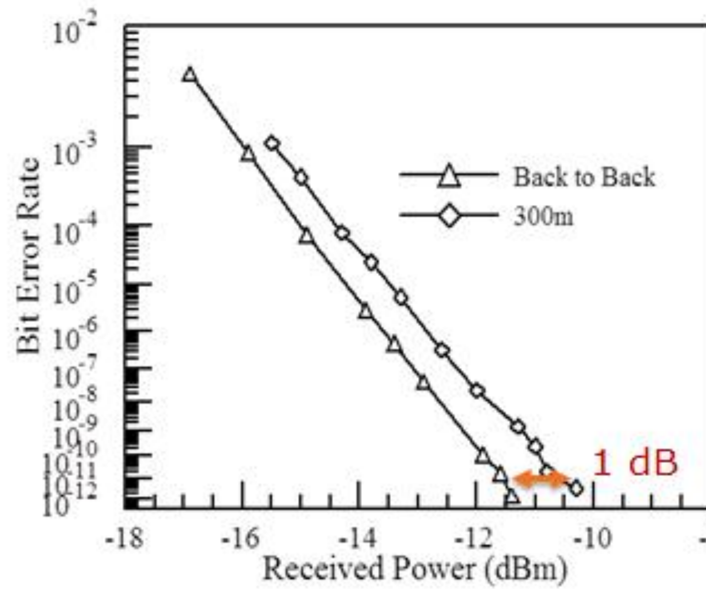
- The pattern generator encodes the data onto the laser signal from the transmitter
- The signal is transmitted through 300 m of ClearCurve® LX Multimode Fiber
- The optical receiver detects the signal and feeds it to a bit error rate (BER) detector

IDF13

Record 25Gbps transmission over 300m

- Eye diagram shows little degradation compared to back-to-back
- The total penalty was only ~1 dB after 300m
- Error-free transmission for >40 minutes

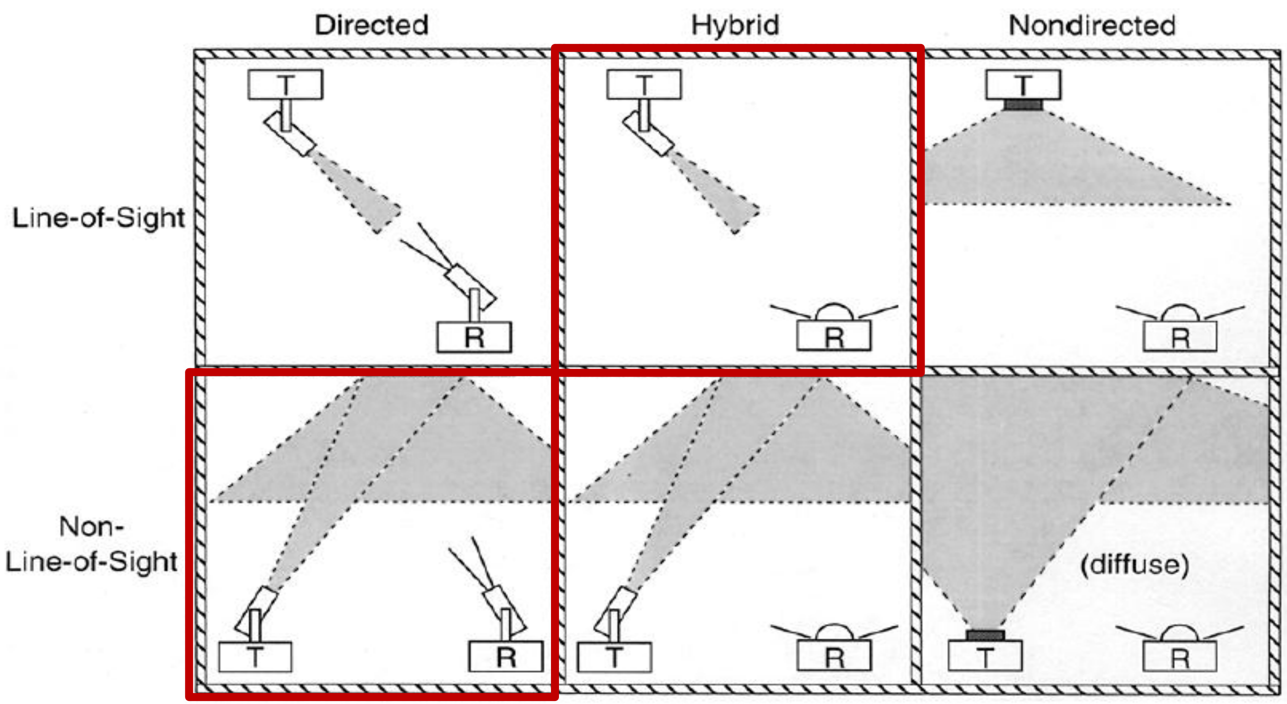




Optical Wireless Demonstrations relevant to Data Center Applications

A Literature Survey

Overall physical architectures



Better power efficiency
Lower path distortion

Better link robustness
Allows operation over barriers

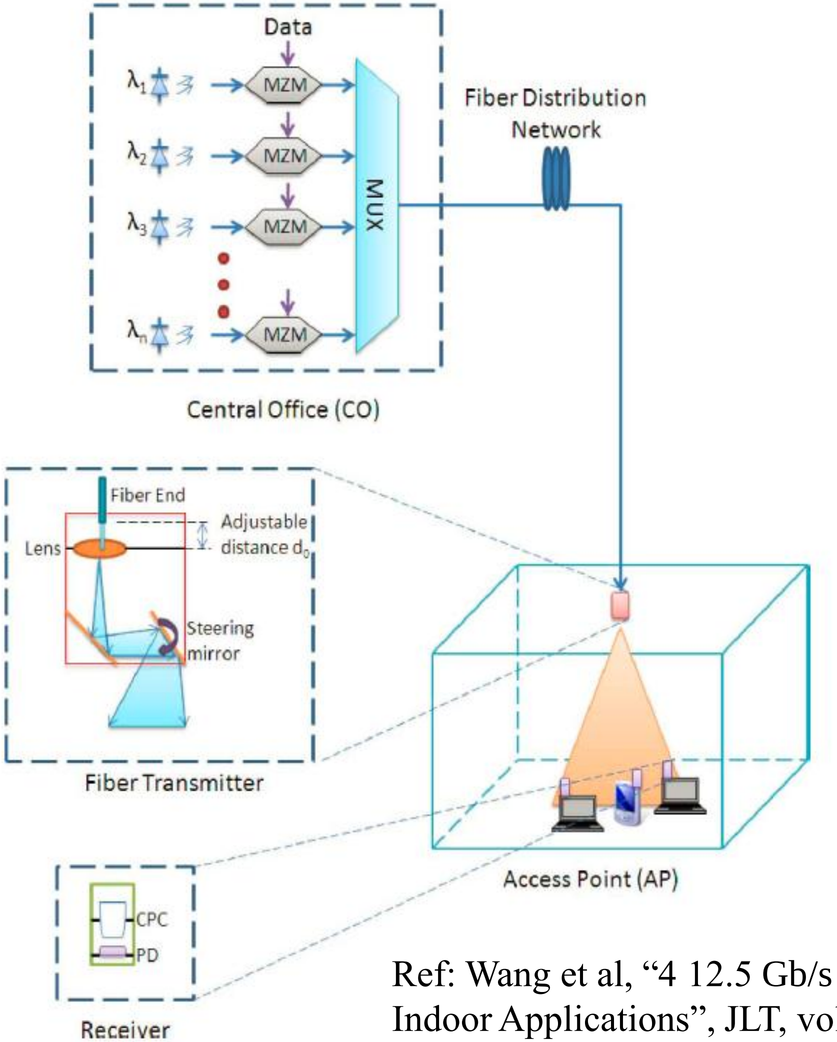
Better power efficiency

Better for mobility

Fig. 1. Classification of simple infrared links according to the degree of directionality of the transmitter and receiver and whether the link relies upon the existence of a LOS path between them.

Ref: J. M. Kahn et al, “Wireless Infrared Communications”, PROCEEDINGS OF THE IEEE, VOL. 85, NO. 2, FEBRUARY 1997

4x12.5 Gb/s WDM system



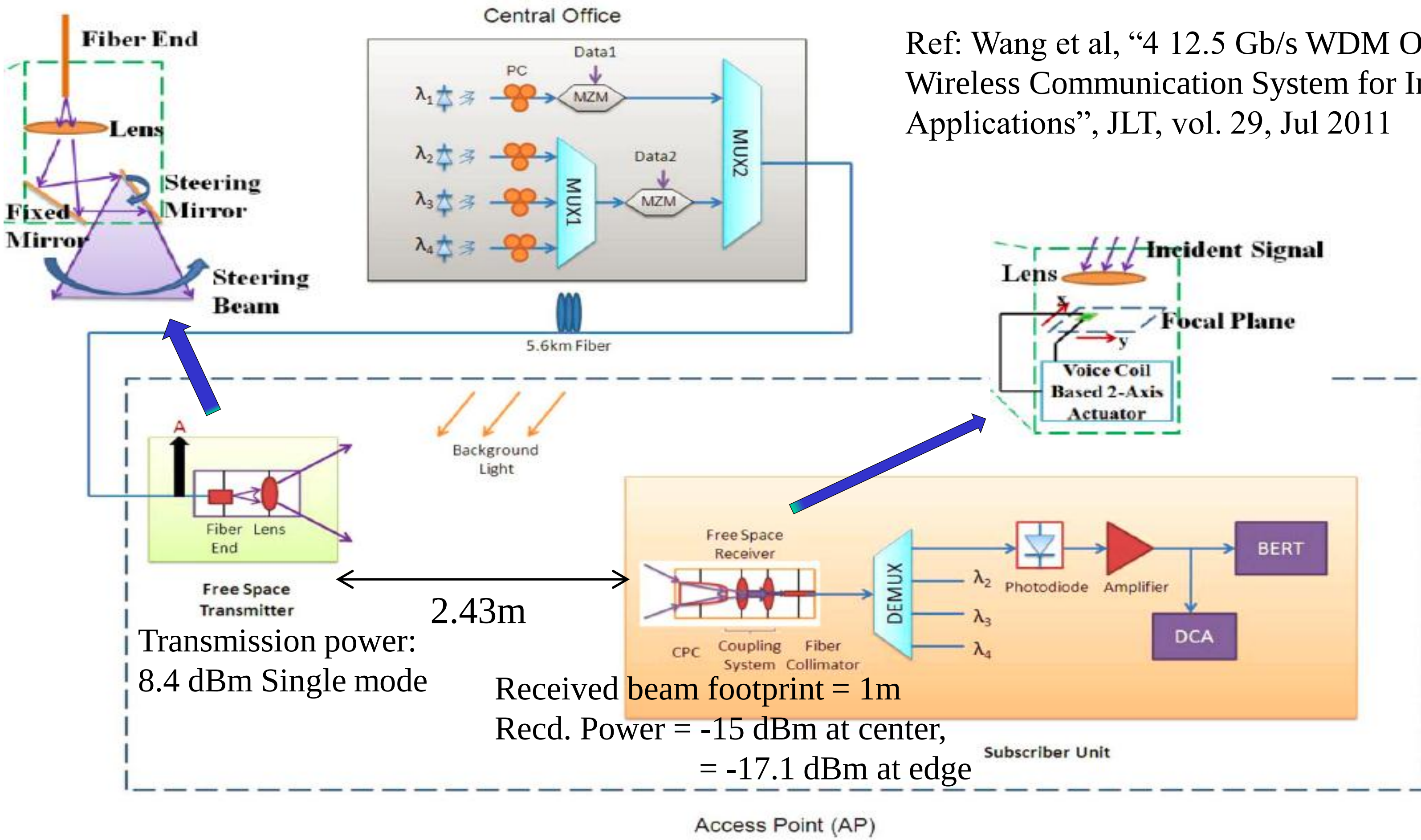
- Active transmitter in Central Office
- Access point Tx consists only of lens and steering mirror attached to ceiling
- Rx: Compound Parabolic Concentrator, Tx beam at mobile Rx adjusts adaptively by changing fiber to lens distance
- Localization system is “request” + “search and scan”

Ref: Wang et al, “4 12.5 Gb/s WDM Optical Wireless Communication System for Indoor Applications”, JLT, vol. 29, Jul 2011

4x12.5 Gb/s WDM System

Experimental setup

Ref: Wang et al, “4 12.5 Gb/s WDM Optical Wireless Communication System for Indoor Applications”, JLT, vol. 29, Jul 2011



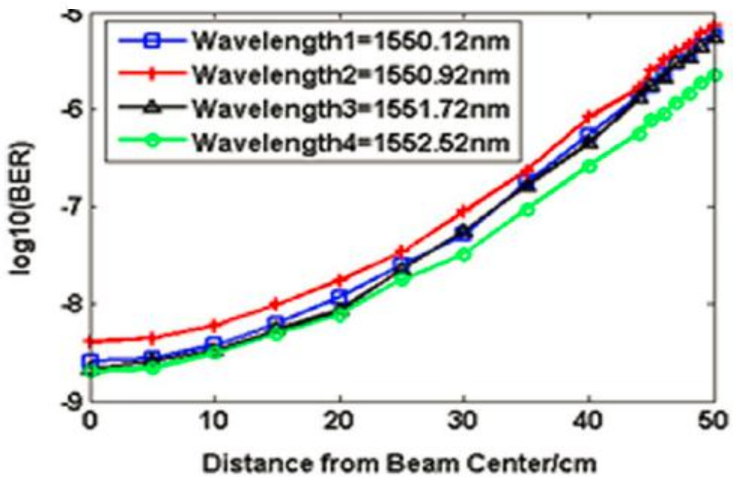
2.43m

Transmission power:
8.4 dBm Single mode

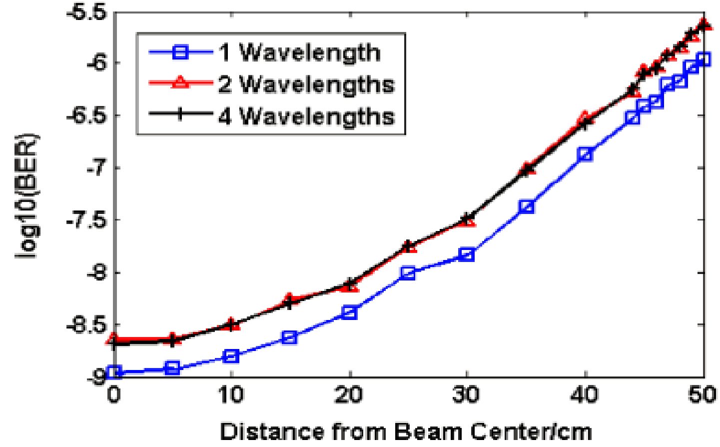
Received beam footprint = 1m
Recd. Power = -15 dBm at center,
= -17.1 dBm at edge

4x12.5 Gb/s WDM System Results

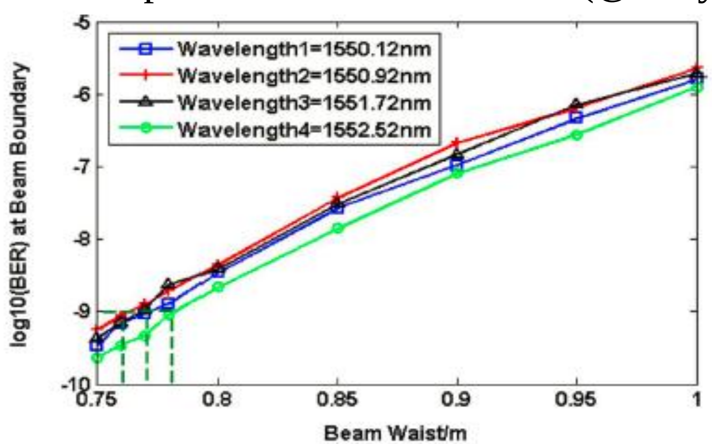
Penalty of distance from beam center



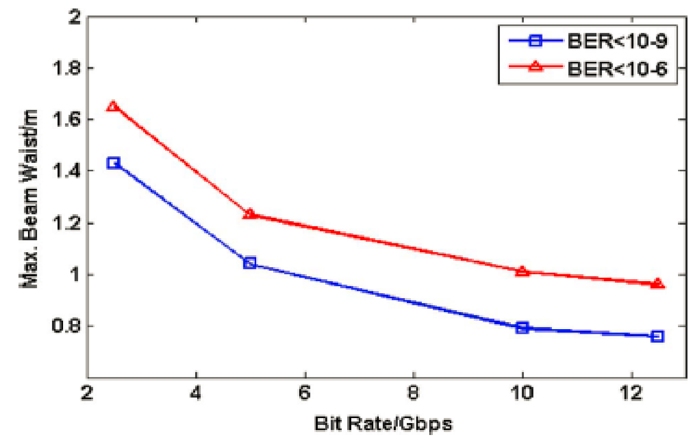
Penalty from channel crosstalk



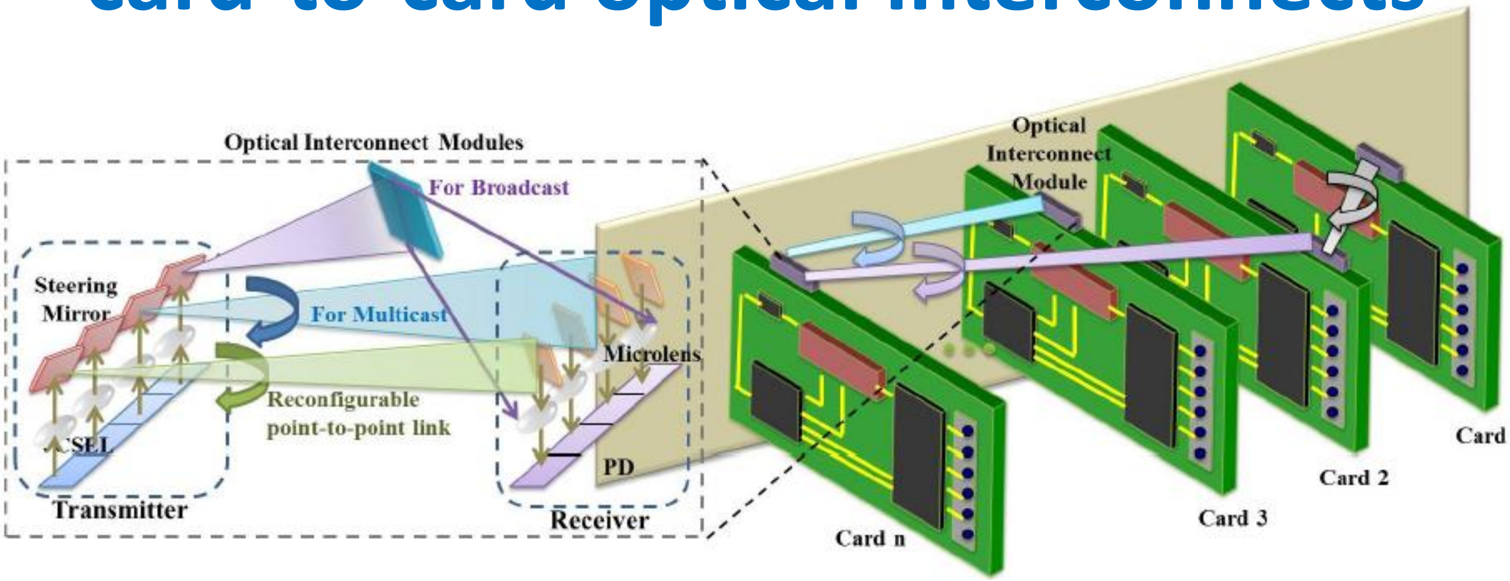
Dependence on Beam waist (@Bdry)



Beam waist reqd for different bit rates



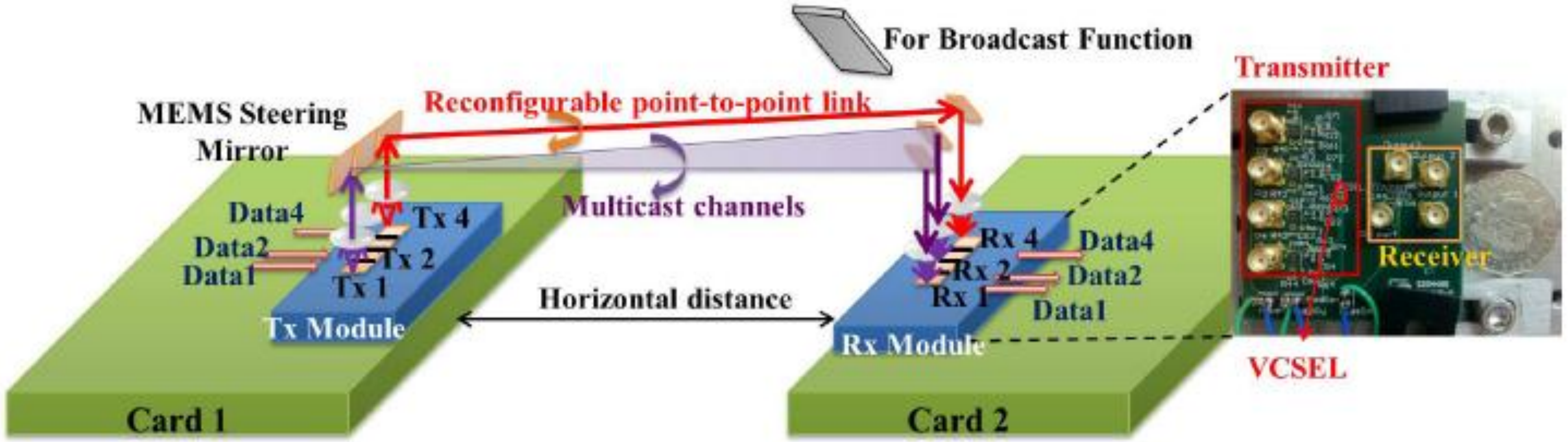
Free-space based reconfigurable card-to-card optical interconnects



- 1×4 **VCSEL** array (~17° divergent angle, 850 nm, 250 µm pitch, 1 mm overall dimension)
- 1 × 4 PD array (60 µm active diameter, 250 µm pitch, ~0.6 A/W responsivity at 850 nm, and 1 mm overall dimension)
- Micro-lens array with ~236 µm clear aperture and 250 µm pitch aligned to VCSEL and the PD arrays for collimation

Reference: Nirmalathas, et al, "High-speed free-space based reconfigurable card-to-card optical interconnects with broadcast capability", Optics Express, 15395, Jun 2013.

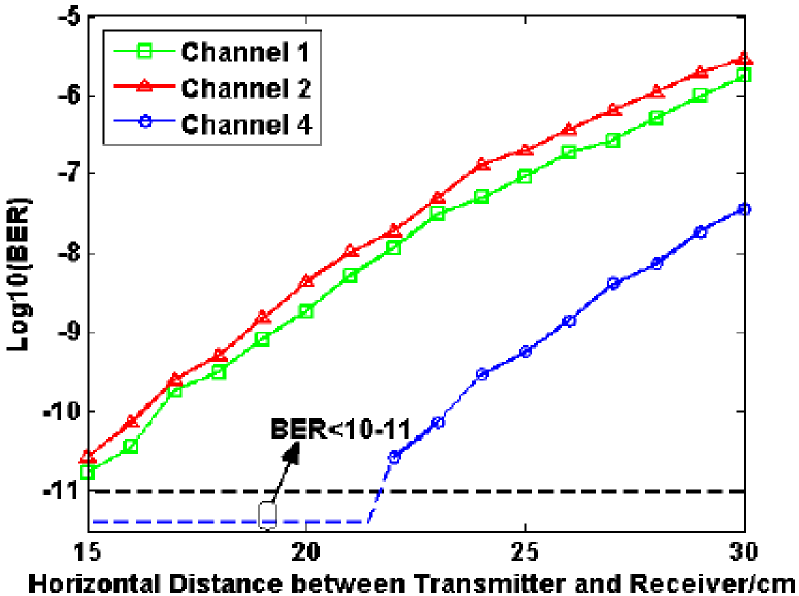
Reconfigurable Optical Interconnect
Experimental Setup



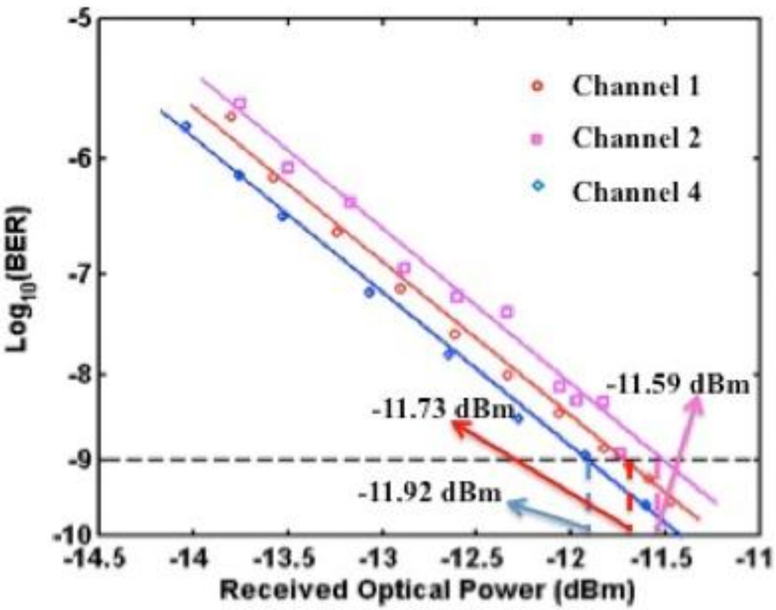
Reference: Nirmalathas, et al, "High-speed free-space based reconfigurable card-to-card optical interconnects with broadcast capability", Optics Express, 15395, Jun 2013.

Reconfigurable Optical Interconnect
10 Gbps Performance

VCSEL power = 2mW



Distance = 30cm



- VCSEL 1 is the transmitter in all cases
- Channel 4 is best since least susceptible to crosstalk induced by channels 1 and 2
- Channel 2 is worse than Channel 1 due to slightly longer distance
- Also showed multicast/broadcast: Broadcast does not suffer from crosstalk

Questions to Resolve

1. Single mode or Multimode
2. Wavelength of operation
3. Directed or Diffused System
4. Wavelength Division Multiplexing vs. Spatial Division Multiplexing

- All Interdependent factors
- In addition, the answer will depend on:

• Interconnect distance
• Air quality and Turbulence
• Line of sight violations

Part 4 - Media Access
802.15.3 full duplex possibility
(Rick Roberts, Intel Labs)

An 802.15.3 piconet consists of at least one DEV which assumes the role of coordinator (PNC) which provides basic timing and manages quality of service (QoS).

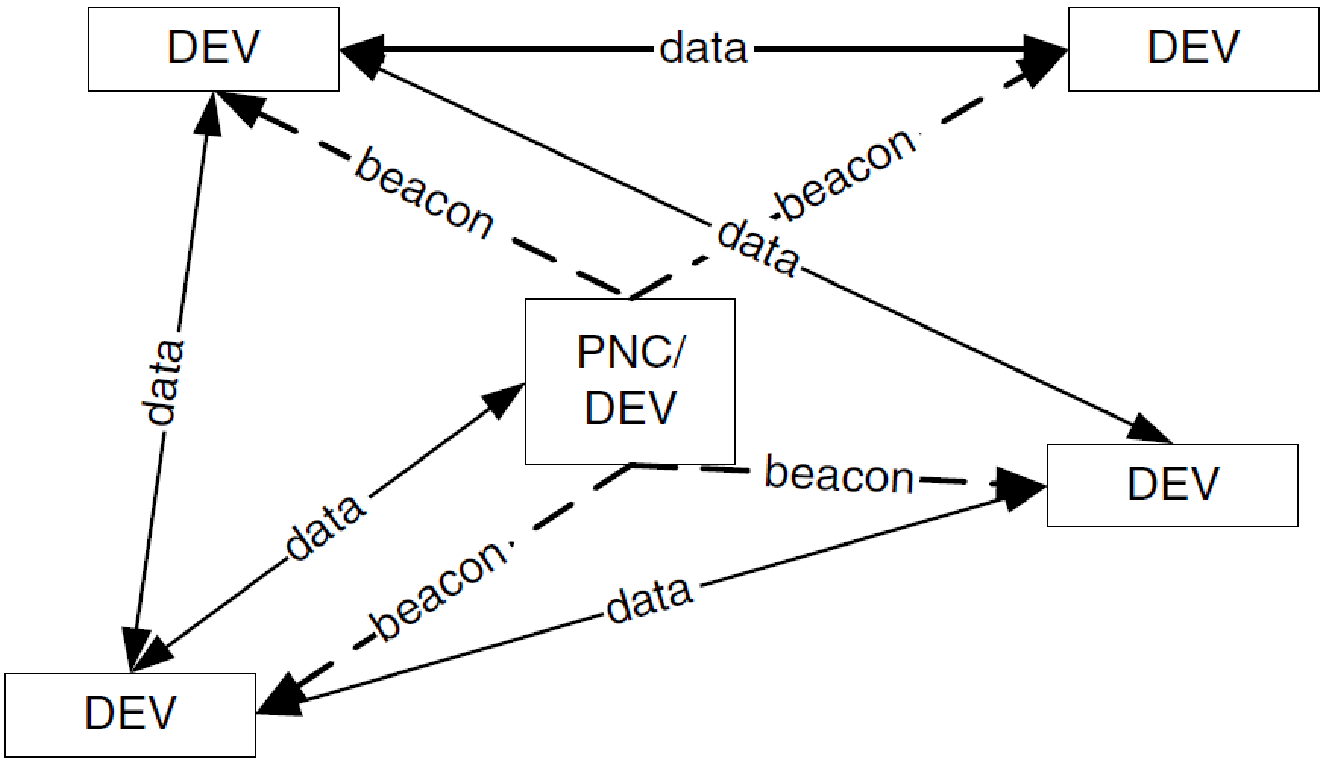


Figure 1—802.15.3 piconet elements

Superframe Structure and Error Control

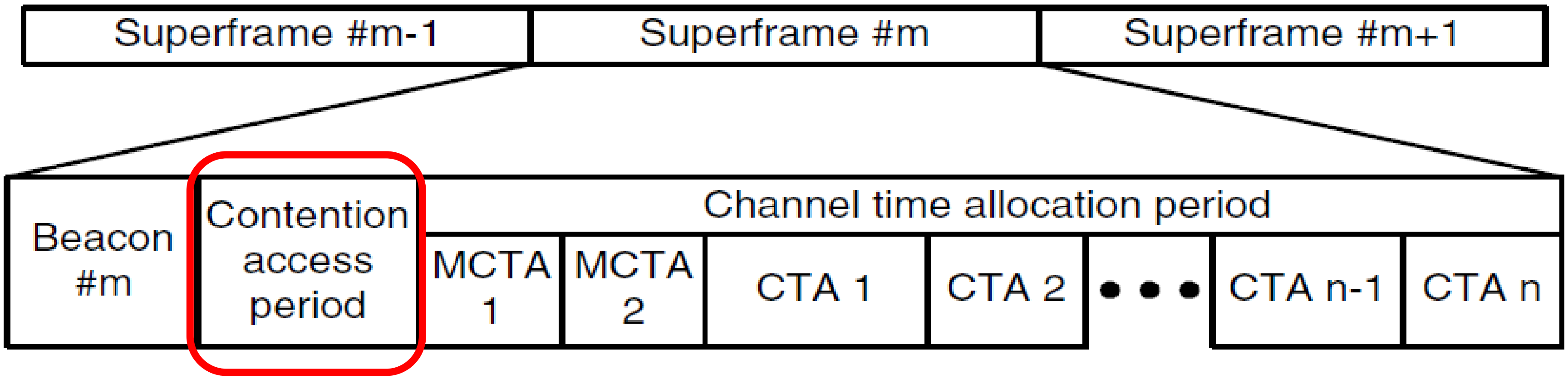
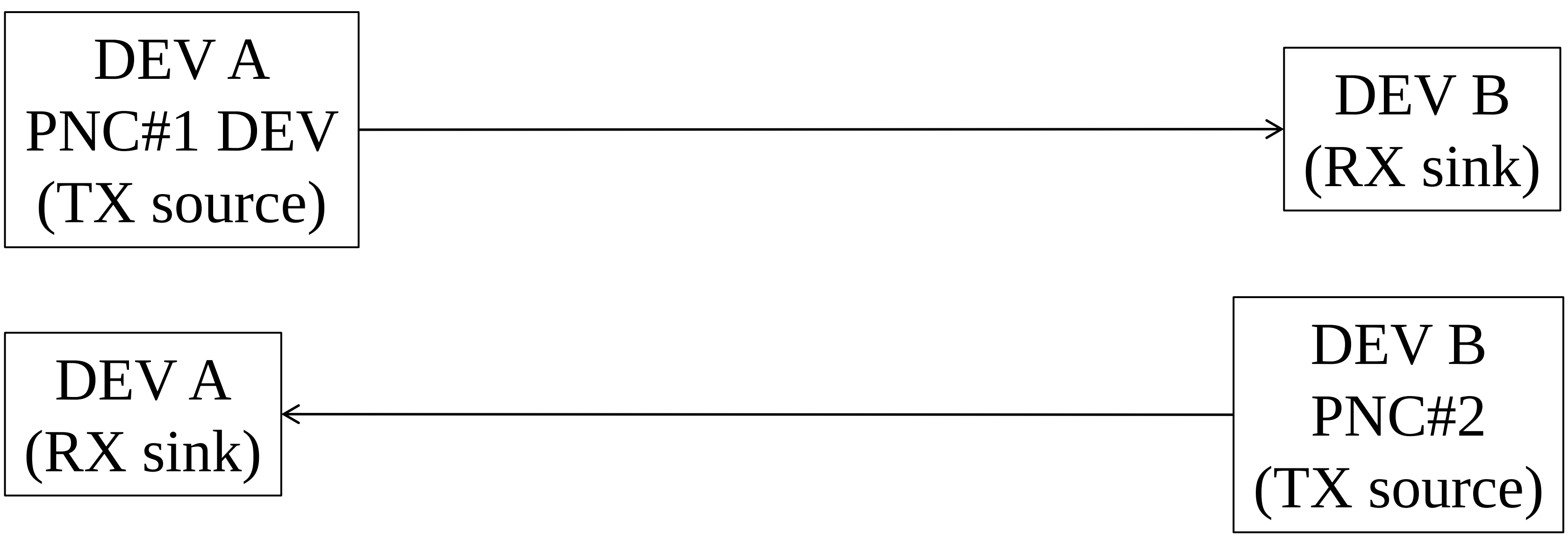


Figure 2—802.15.3 piconet superframe

Since this is a point-to-point full-duplex link, and there is really no contention, the whole superframe can be allocated as a contention access period.

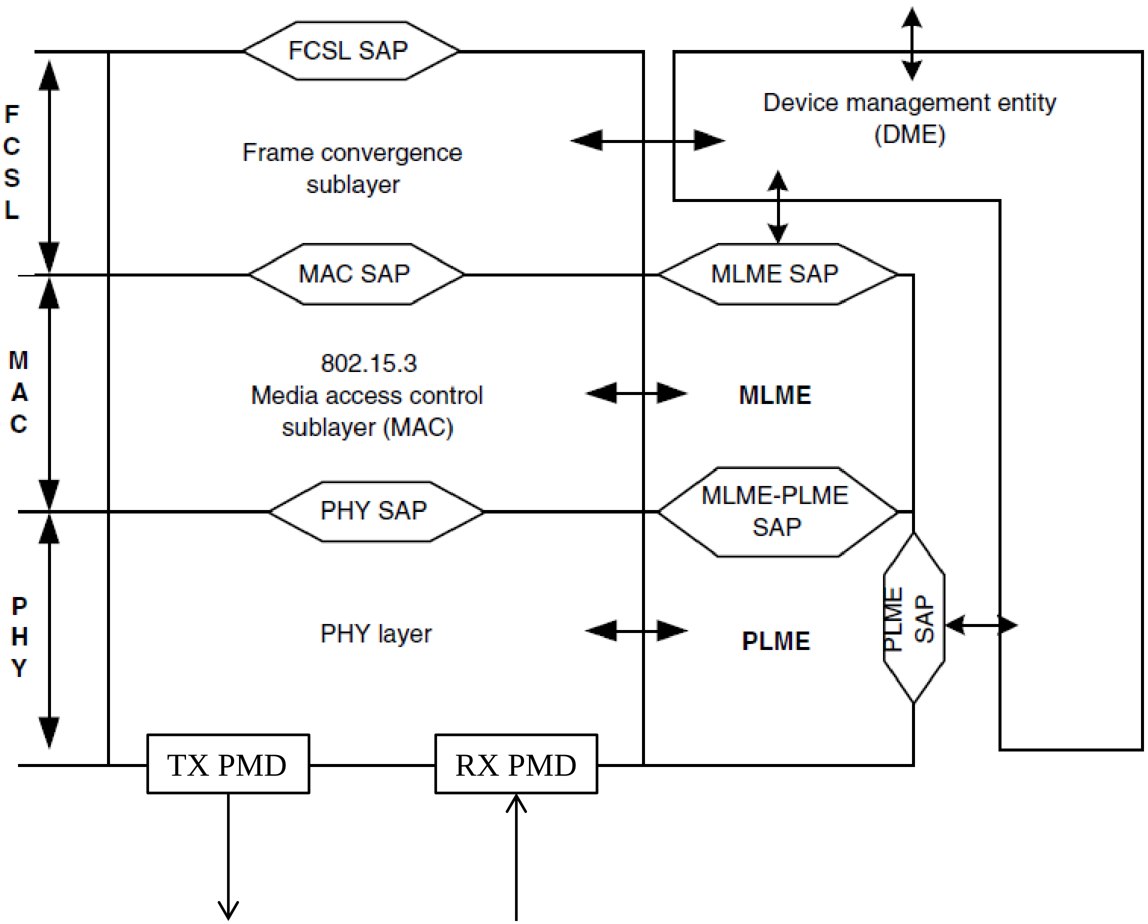
It is not clear that beaconing is necessary after link establishment, so the beacon can probably be turned off.

For the switched point-to-point, full-duplex application the network topology is greatly simplified and is known before the link establishment.



There are two PNCs established, both unidirectional.

Each device has a spatially separated TX and RX.



Conceptually TX on one "antenna" and RX on another.

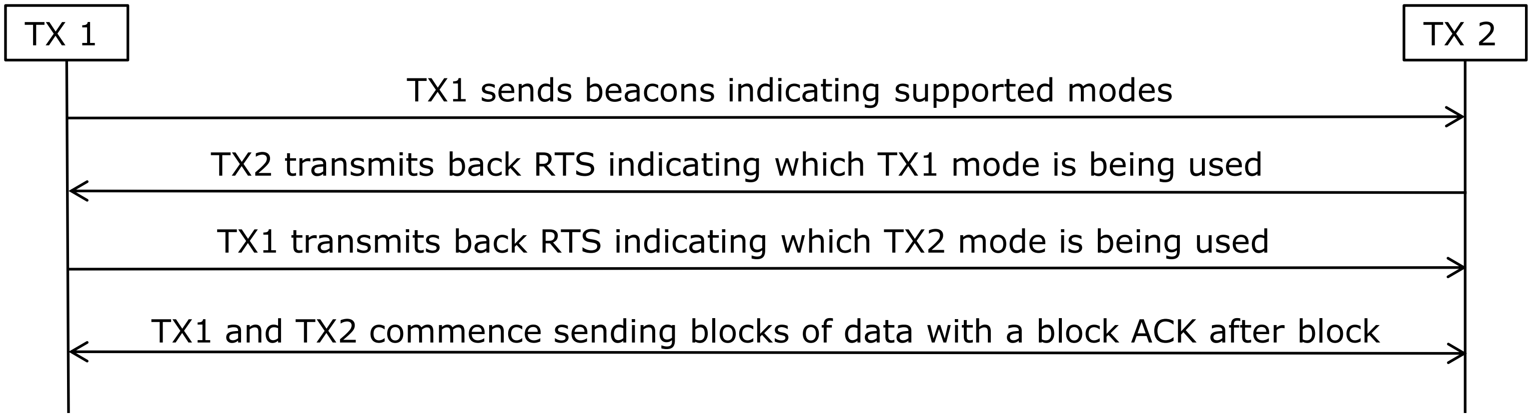
To start the full-duplex link, each PNC is switched to the appropriate beam and each PNC starts beaconing.

Between TX beacons, the PNC listens on the RX PMD.

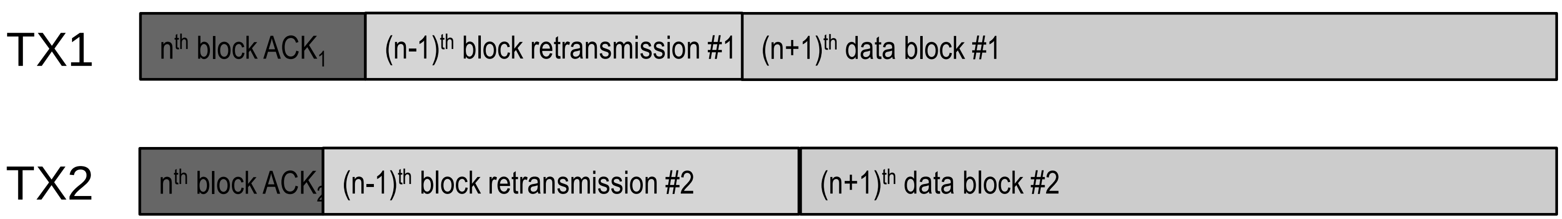
When the other PNC's beacons are heard on the RX PMD then the originating PNC knows the other DEV is present, reconfigures the superframe (turns off the beacon) and starts sending a RTS.

The receipt of a RTS is followed by a CTS and packet transmissions commences using a block ACK protocol.

Outline of Full-duplex link establishment MSC



Asynchronous full-duplex superframes



Issues to be addressed

- flow control if the selected modes don’t have equal data rate
- should synchronized beaconing be used?

MAC system issues (lots of issues)

1. Are beacons really needed; and if so, should they be synchronized?

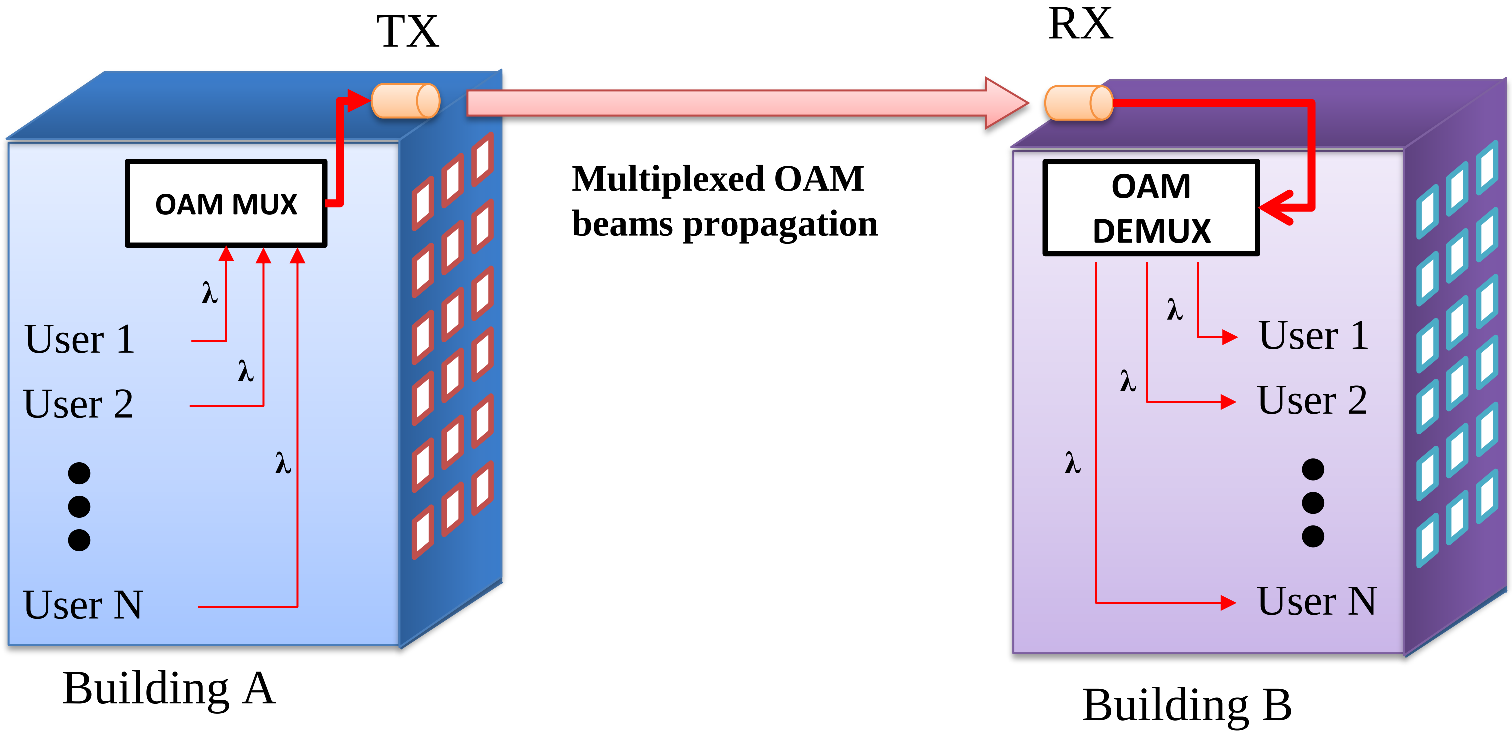
2. Need to define PPDU/MPDU header/trailer fields.
   - Preamble
   - PHY header fields
   - MAC header fields

3. Need specifics on needed modifications to IEEE802.15.3.
   - Frame definitions
   - Superframe modifications
   - Other issues!

Believe MAC modifications are readily doable given the anticipated exclusive channel usage.

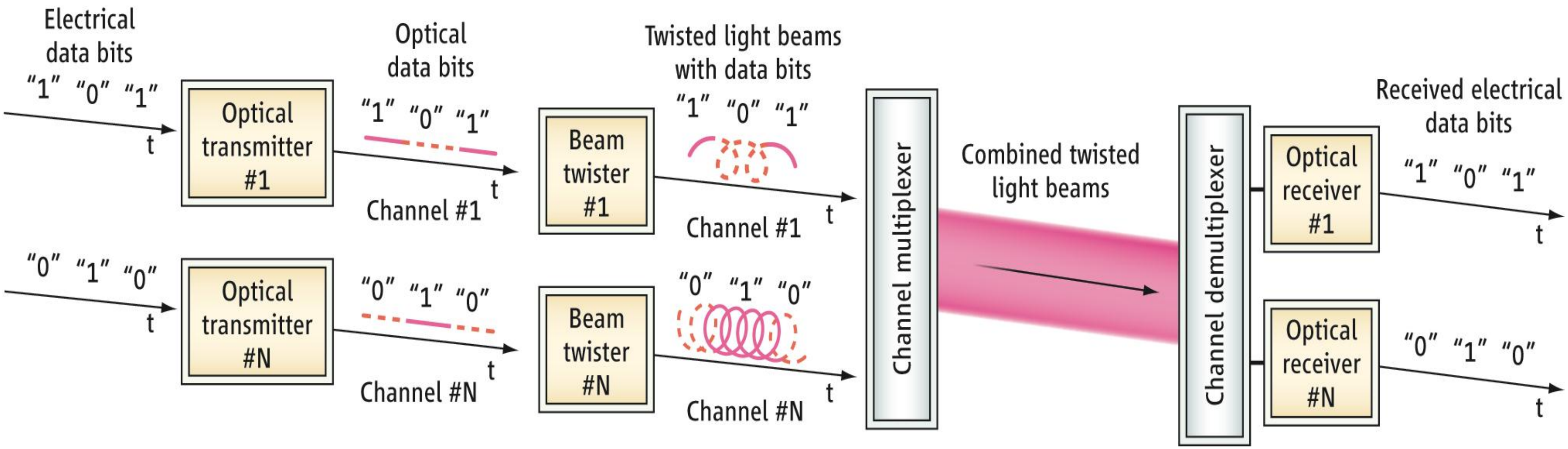
Part 5 – QAM Multiplexing
Orbital Angular Momentum Multiplexing
(Alan Willner, University of California - San Diego)

Conceptual deployment of OWC using OAM multiplexing



- The same wavelength can be used by multiple users.
- Each channel is converted to an OAM beam with a different vortex charge.
- Multiple channels are spatially multiplexed and sent out using a single transmitter.

Data transmission system using multiple OAM beams



A. Willner, Science, 8/2012

OAM value = +4

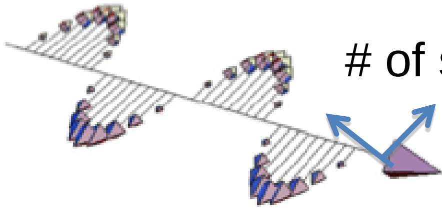
OAM value = +8

OAM value = –8

OAM value = +16

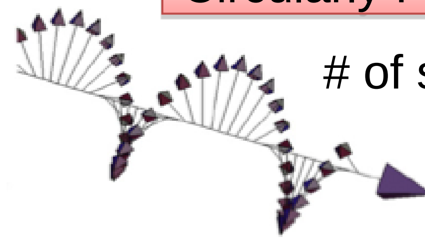
Orbital Angular Momentum (OAM): Concept

Linear Polarized Light



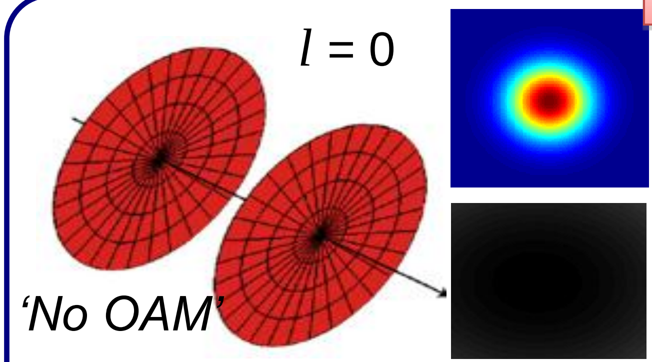
# of states possible = 2

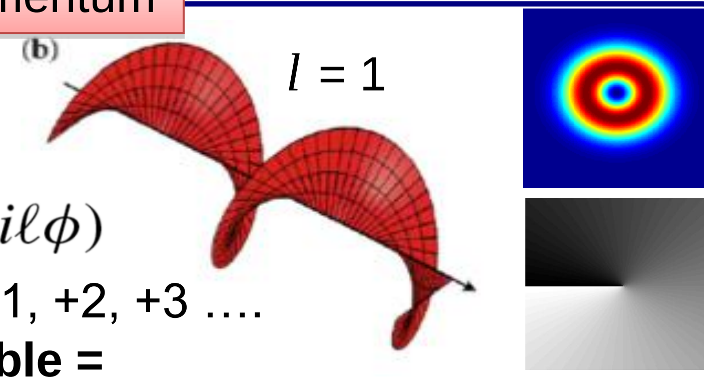
Circularly Polarized Light



# of states possible = 2

Orbital Angular Momentum

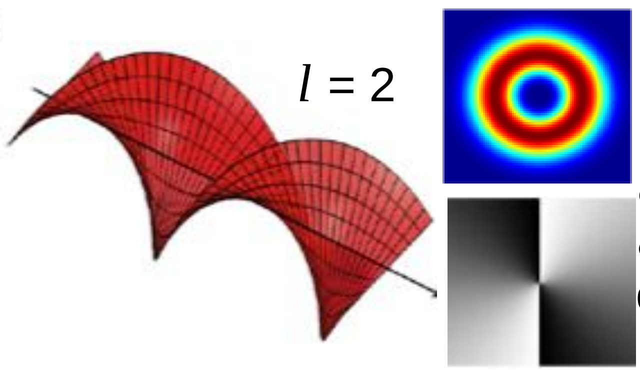


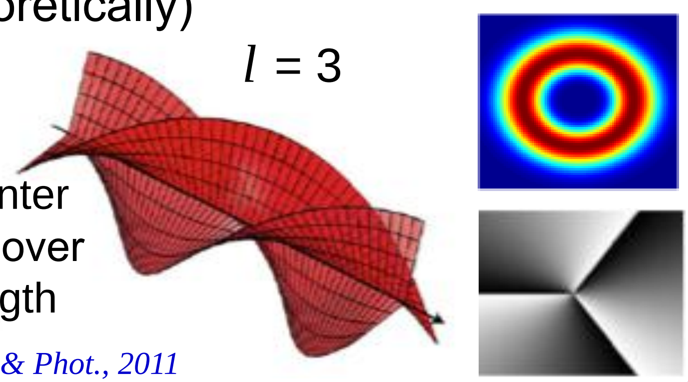


$$\phi(r,\phi) = \exp(i\ell\phi)$$

l = …. -3, -2, -1 ,+1, +2, +3 ….

# of states possible = infinite! , …. (theoretically)

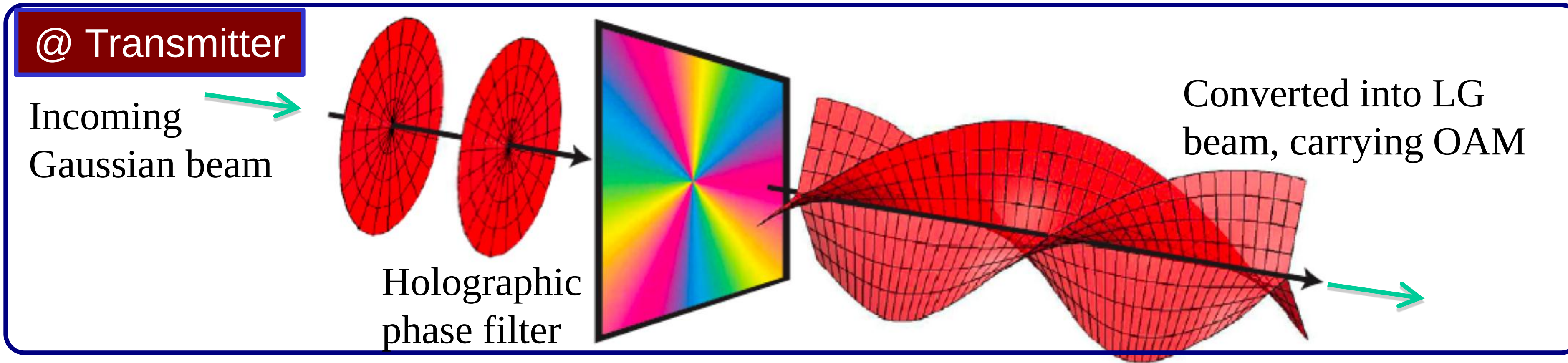


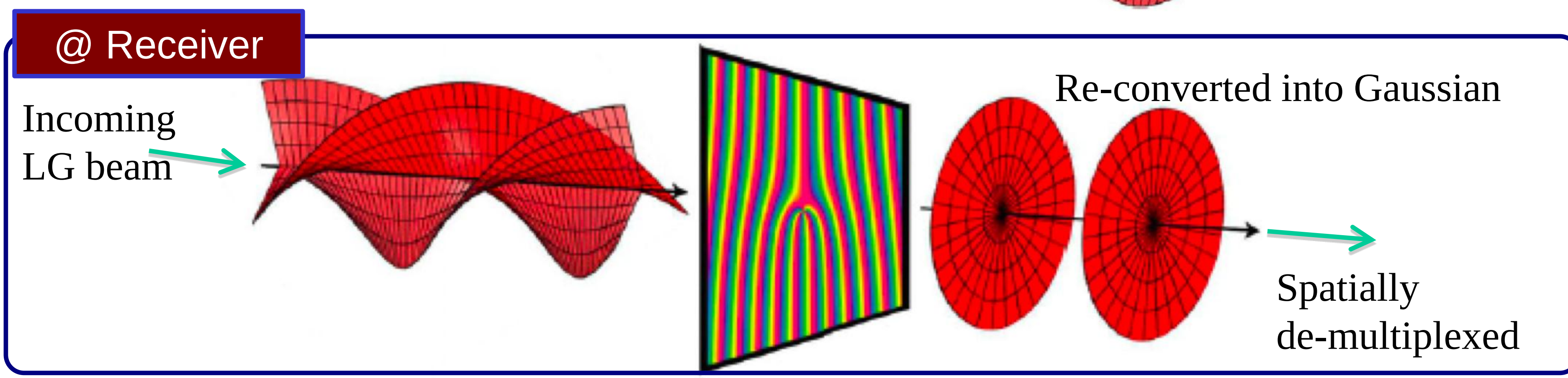


- Intensity null at the center
- Phase spirals '*l*' times over distance of one wavelength

Alison M. Yao, et al. Adv. in Opt. & Phot., 2011

OAM Generation and Detection

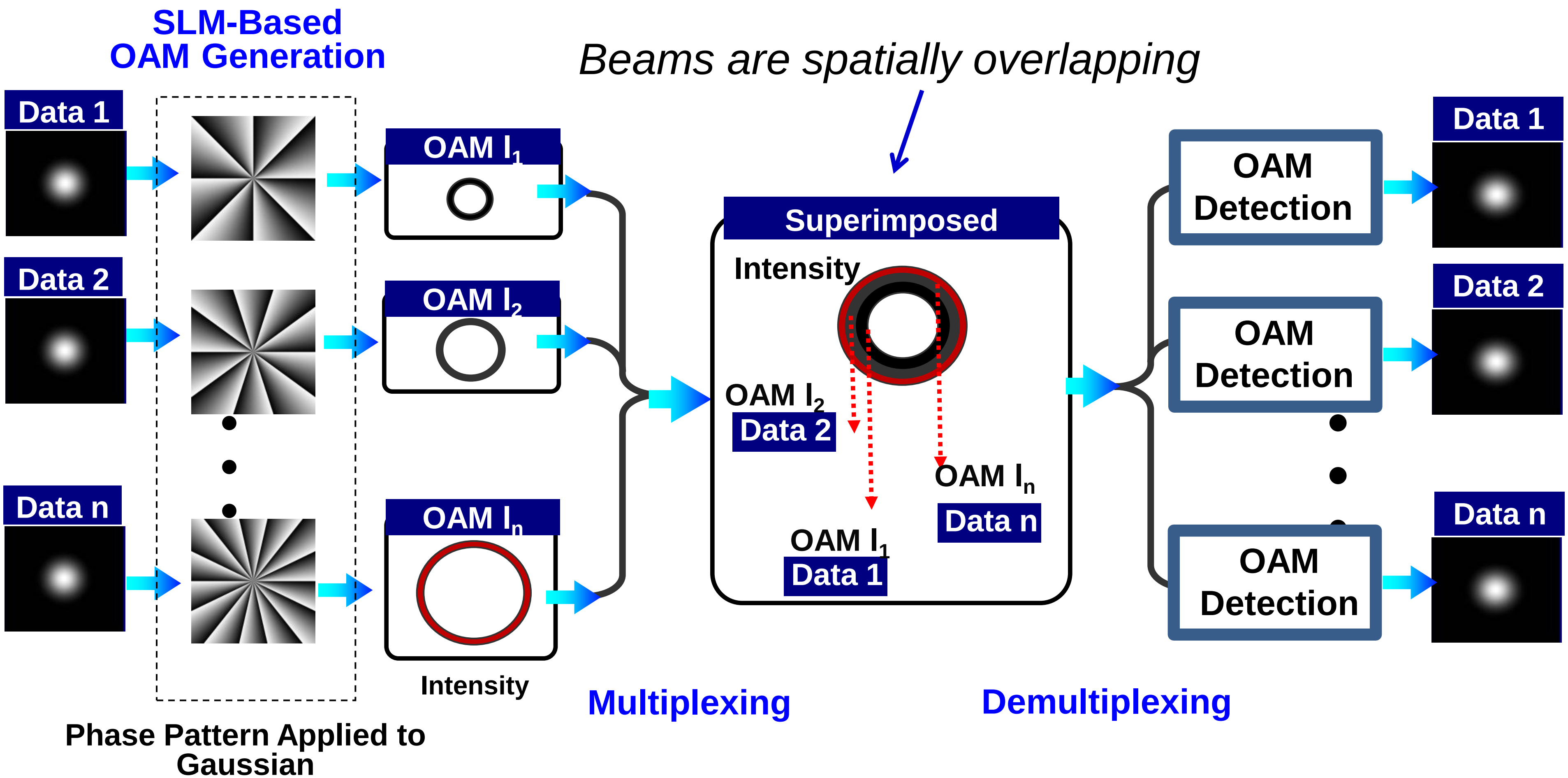




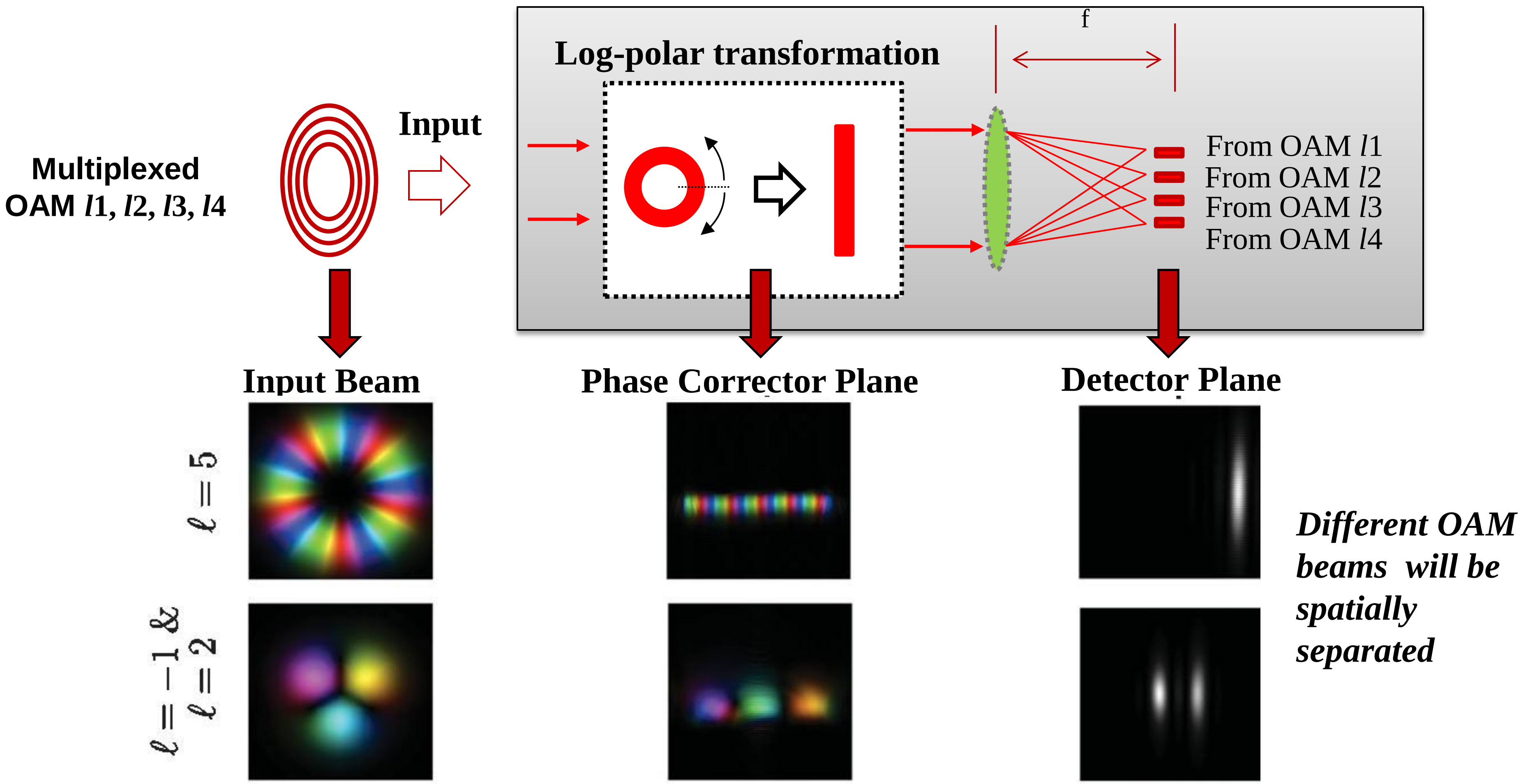
- ❑ The holographic phase filter could be spatial light modulator (SLM), q-plate or fixed hologram, etc.
- ❑ The OAM generation and detection could be also achieved by using integrated photonics devices.

Alison M. Yao, et al. Adv. in Opt. & Phot., 2011

OAM Multiplexing and Demultiplexing



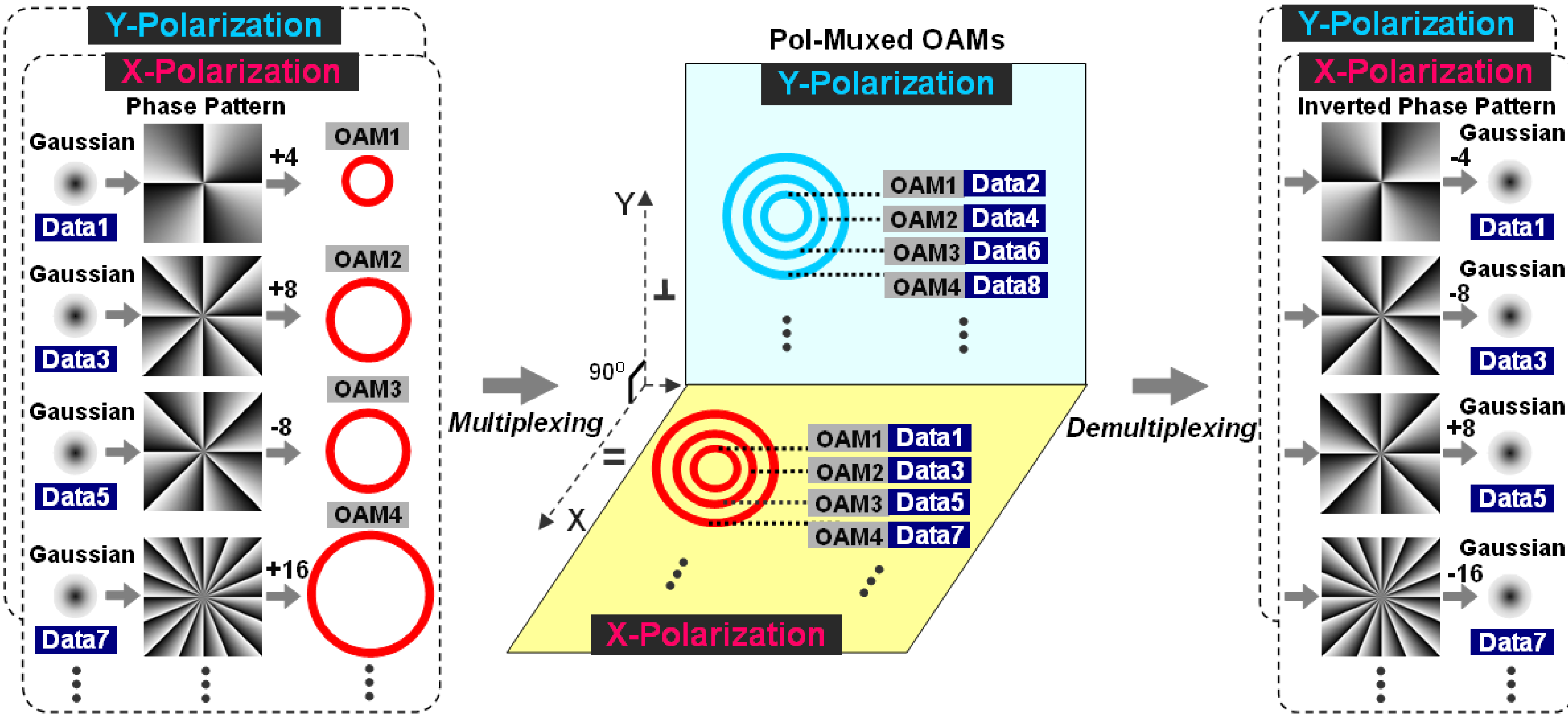
OAM Mode Sorter for OAM Multiplexing and Demultiplexing



❑ The geometric transformation based OAM mode sorter could be used in both OAM multiplexing and demultiplxing.

G. Berkhout et al., Phys. Rev. Lett. 105, 153601 (2010) *M. Lavery et al., Opt. Express 20, 2110-2115 (2012)*

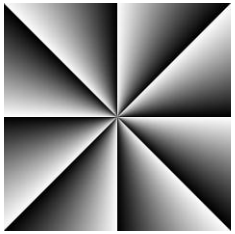
OAM Data Transmission – 2.56 Tbit/s Link Using 32 OAM Beams



- ❑ Spatial light modulators (SLM) convert input Gaussian mode to OAM modes.
- ❑ Inverted phase pattern is used to demultiplex OAM modes.
- ❑ OAM_{+8} and OAM_{-8} have the same size of intensity profiles.

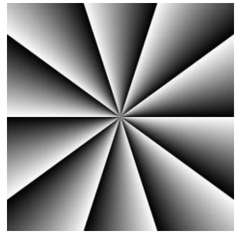
Phase Patterns Loaded to SLM1-SLM4

SLM1



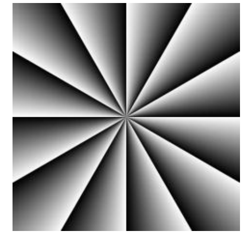
Charge “+8”

SLM2



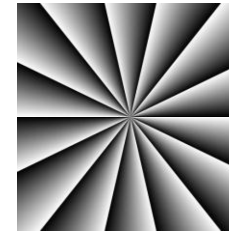
Charge “+10”

SLM3



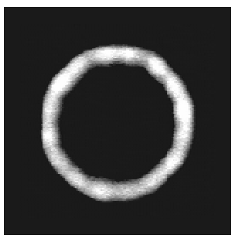
Charge “+12”

SLM4

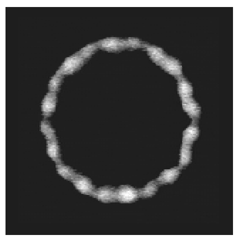


Charge “+14”

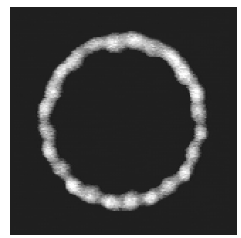
Intensity Profiles of OAM Modes



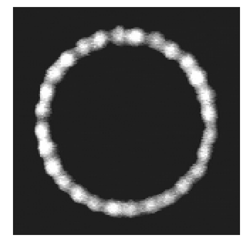
OAM (0,-8)



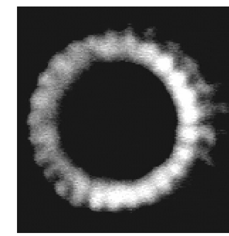
OAM (0,+10)



OAM (0,+12)

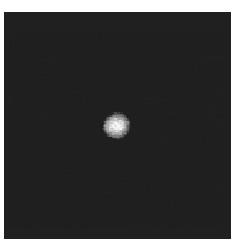


OAM (0,-14)

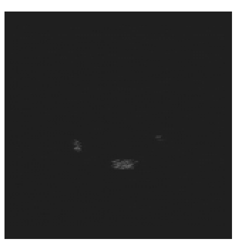


Superimposed Four OAM Modes

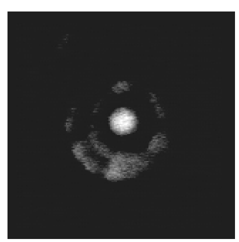
OAM(0,-8) Demultiplexing



Only SLM1 On
Without crosstalk

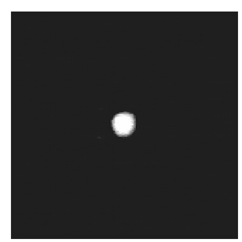


Only SLM1 Off
Crosstalk only

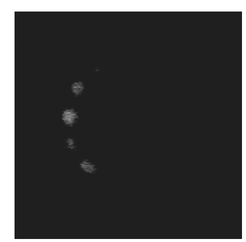


SLM1-4 On
With crosstalk

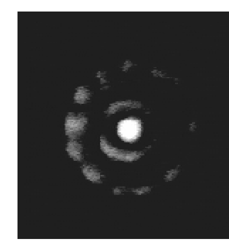
OAM(0,-14) Demultiplexing



Only SLM4 On
Without crosstalk

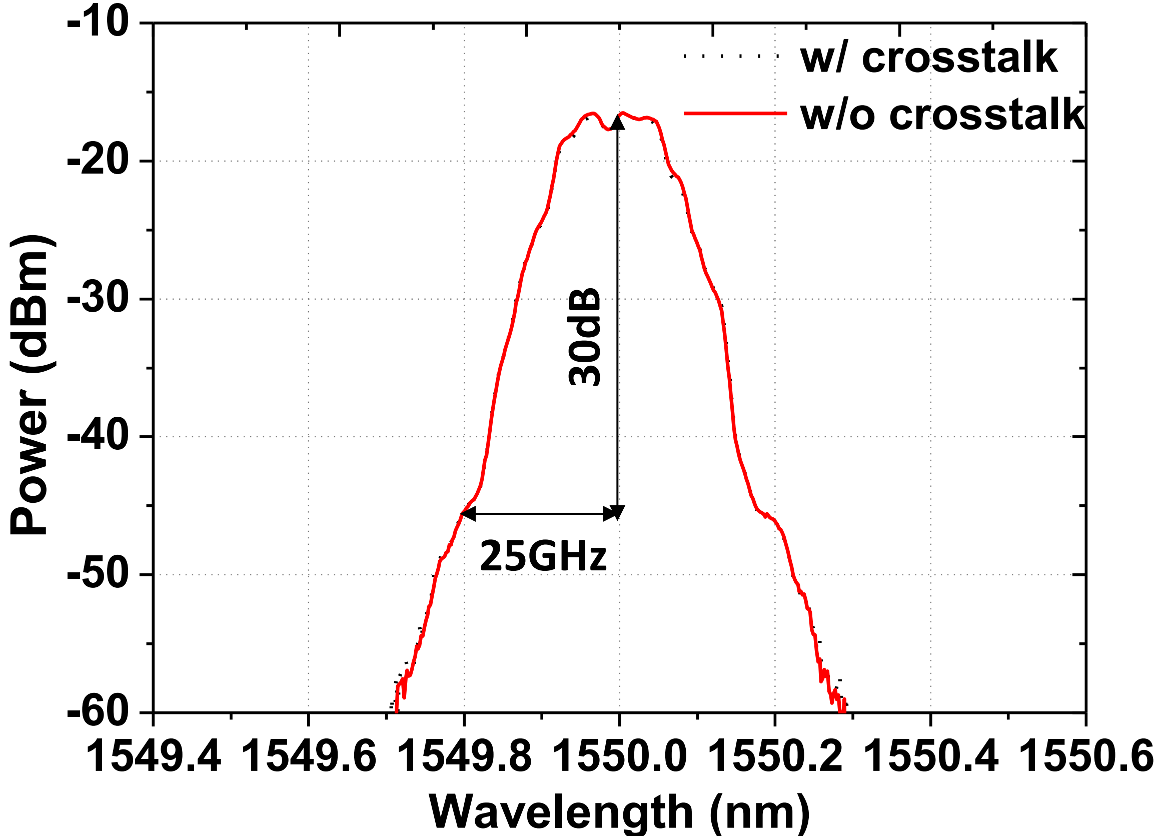


Only SLM4 Off
Crosstalk only



SLM1-4 On
With crosstalk

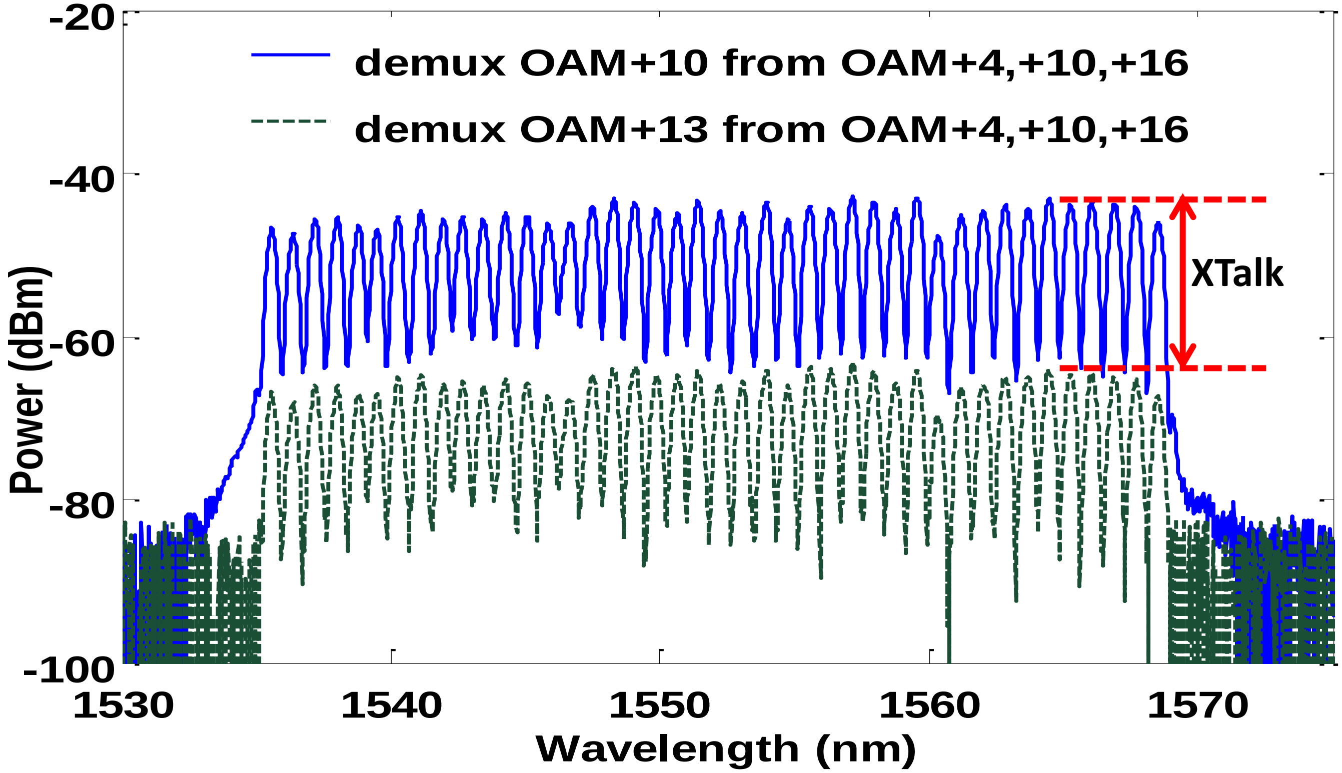
OAM Data Transmission – 2.56 Tbit/s Link Using 32 OAM Beams



J. Wang, et al., Nature Photon. 6, 488-496 (2012).

- **Considering 20Gbaud 16-QAM signal on 32 OAM channels with 7% FEC overhead, an aggregate SE of 95.7 bit/s/Hz (80*32/25/1.07) is achieved. (SE= 102.4 bit/s/Hz without considering 7% FEC overhead）**
- **Total capacity of 2.56Tbit/s on a single wavelength.**

100 Tbit/s Link Using OAM and WDM Multiplexing

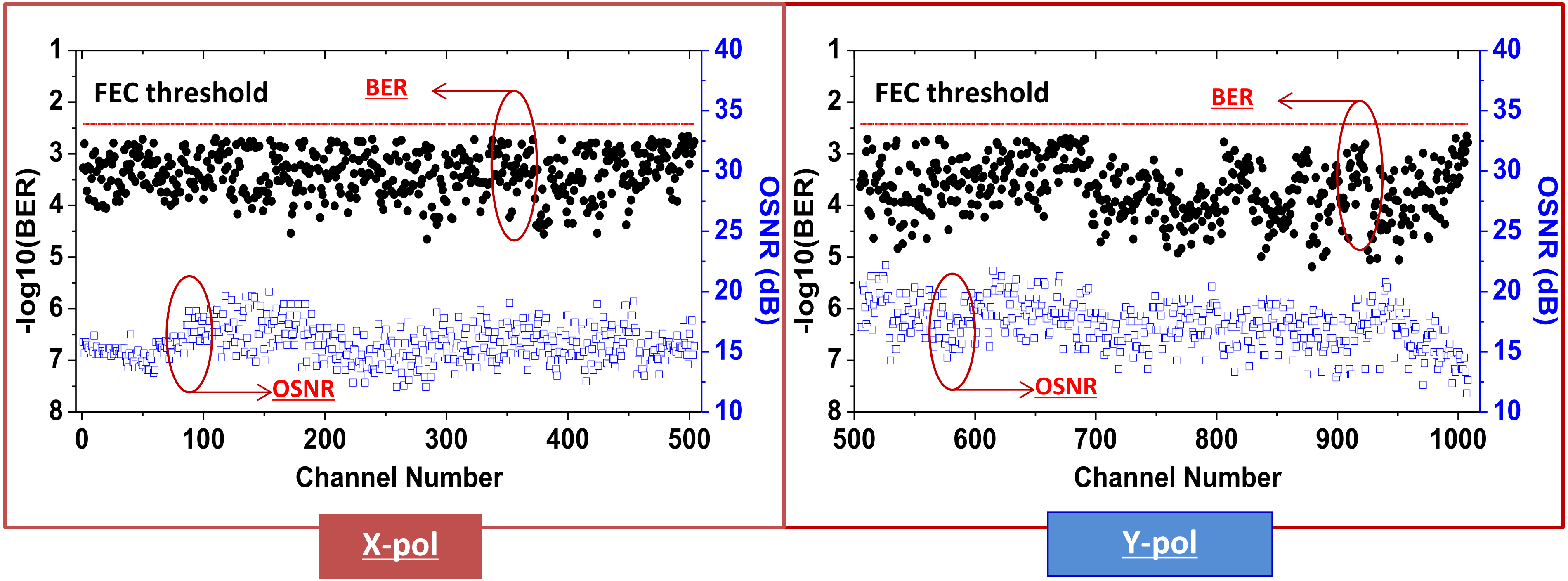


❑ The wavelength dependence for the crosstalk is very small over the wavelength range from 1530-1570 nm.

H. Huang et al, Optics Letters, 2013

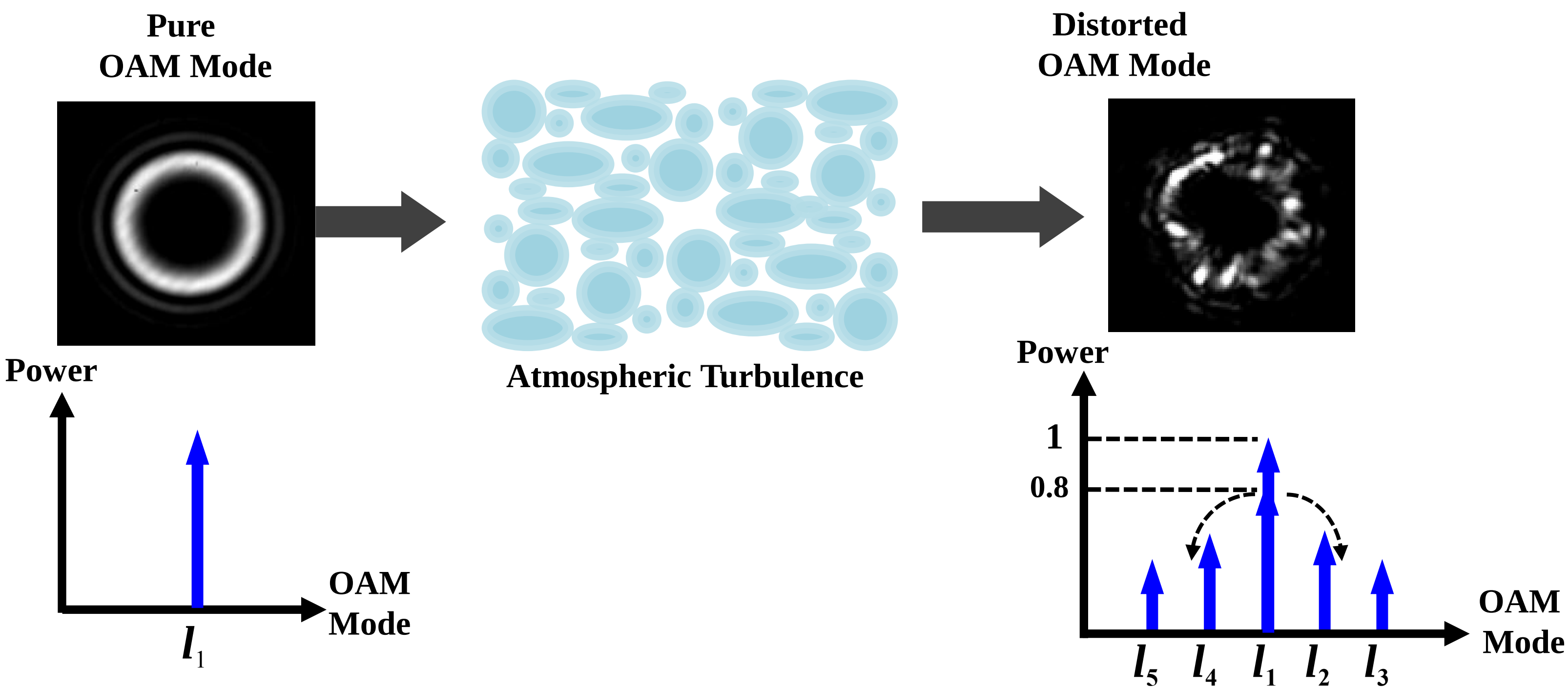
100 Tbit/s Link Using OAM and WDM Multiplexing

42 wavelengths, 12 OAM beams, 2 polarizations
(42 × 12 × 2=1008 channels)



- **Total capacity: 1008 × 100Gbit/s=100.8 Tbit/s.**
- **All of the channels can achieve a BER of < 3.8 × 10−3 (the limit for 7% overhead FEC)**

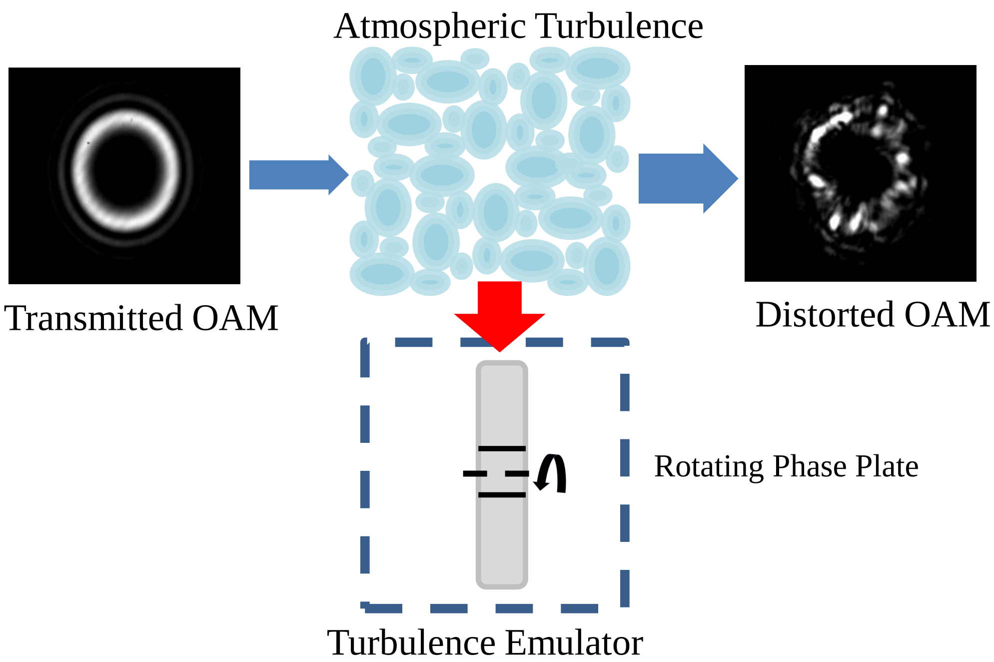
Atmospheric Turbulence Effects and Potential Solutions

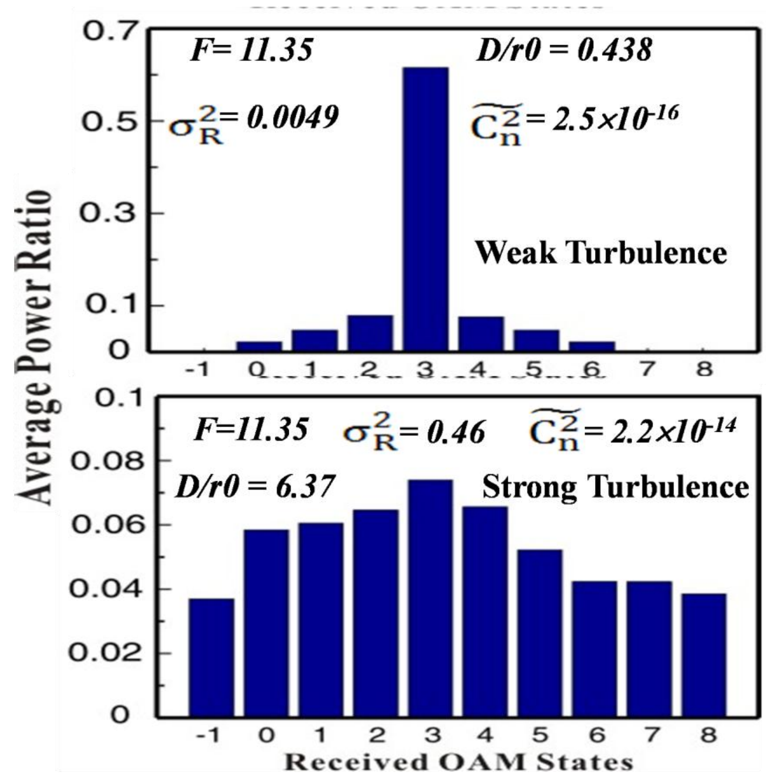


- Wavefront distortion may destroy the OAM beam and affect the orthogonality between OAM modes
  - ✓ The orthogonality of OAM modes are built on the integrity of their "helical" phase-fronts

J. Anguita et al, Appl. Optics 47, 2412 (2008). *G. Tyler et al, OL 34, 142 (2009)*

Atmospheric Turbulence Effects



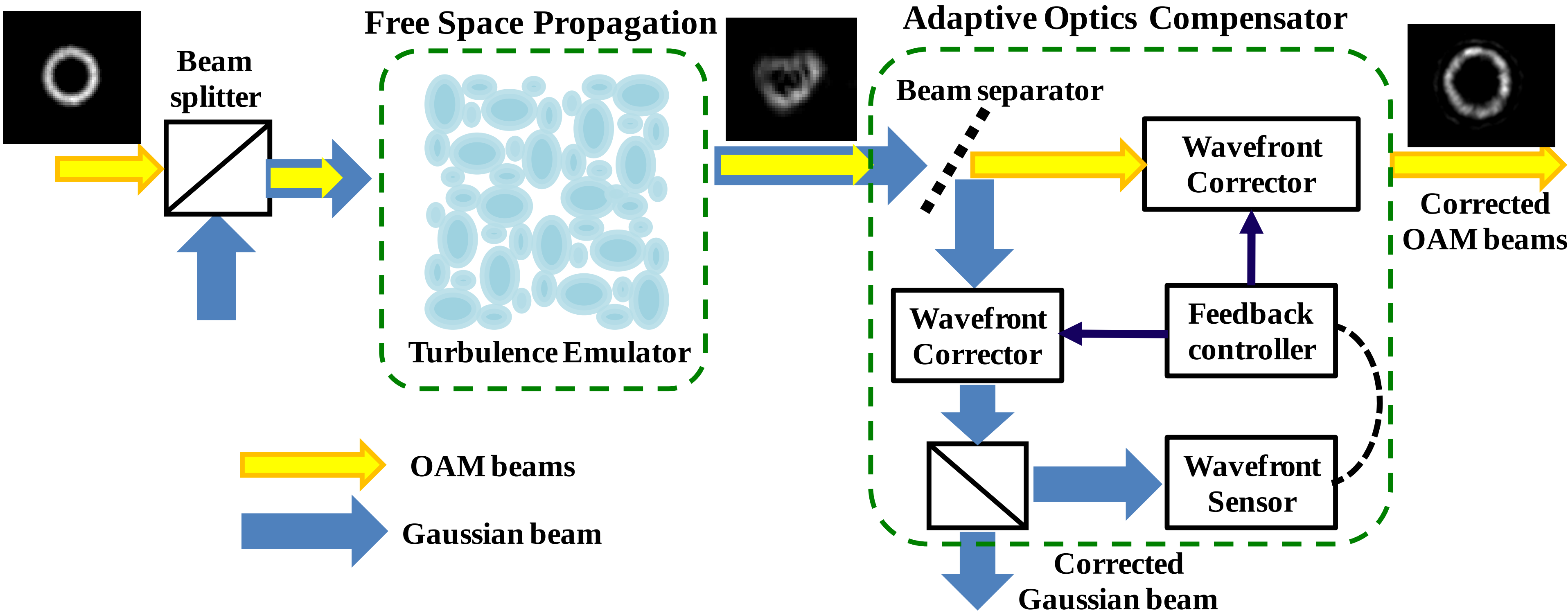


Y. Ren, CLEO2013, Invited

- ❑ OAM beam will experience turbulence-induced distortion, which will result in channel crosstalk and system power penalty.
- ❑ The atmospheric turbulence is emulated in the lab environment by using rotating phase plates, obeying Kolmogorov spectrum statistics.

Potential Solutions – Adaptive Optics Compensation

- *Conventional adaptive optics approach could not work for OAM beams.*

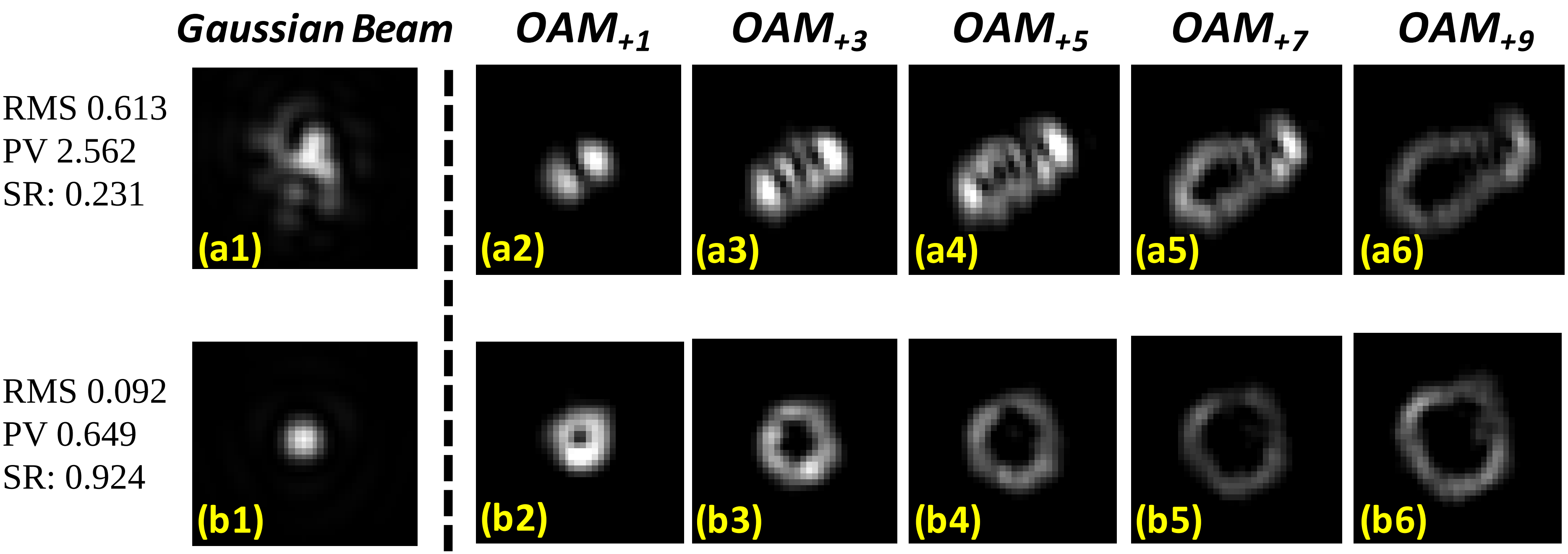


- *Use Gaussian beam as a pilot beam to detect wavefront distortion of Gaussian beam by using conversional WFS.*

Y. Ren et al, ECOC2013

Potential Solutions ─ Adaptive Optics Compensation

Far Field Images

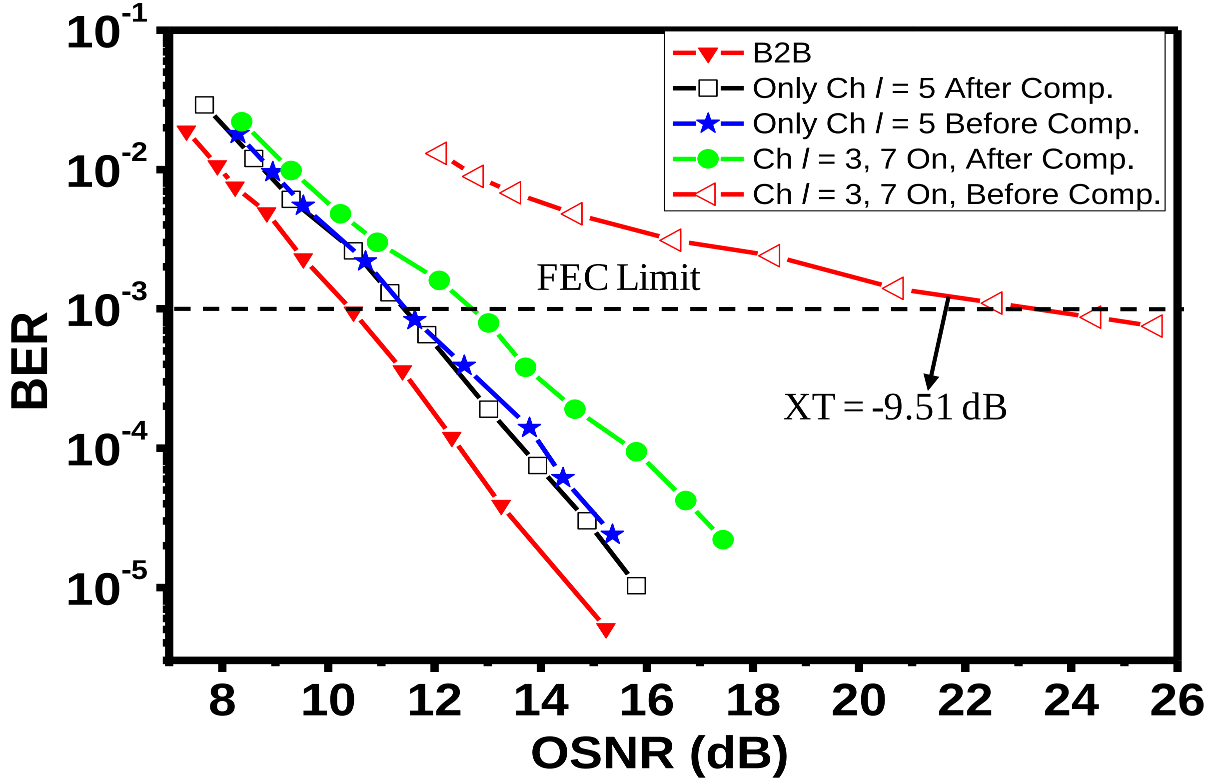


- ❑ By using the correction pattern obtained from Gaussian pilot beam in AO system, the distorted OAM beams up to OAM *l=9 are efficiently compensated.*

Y. Ren et al, ECOC2013

Potential Solutions — Adaptive Optics Compensation

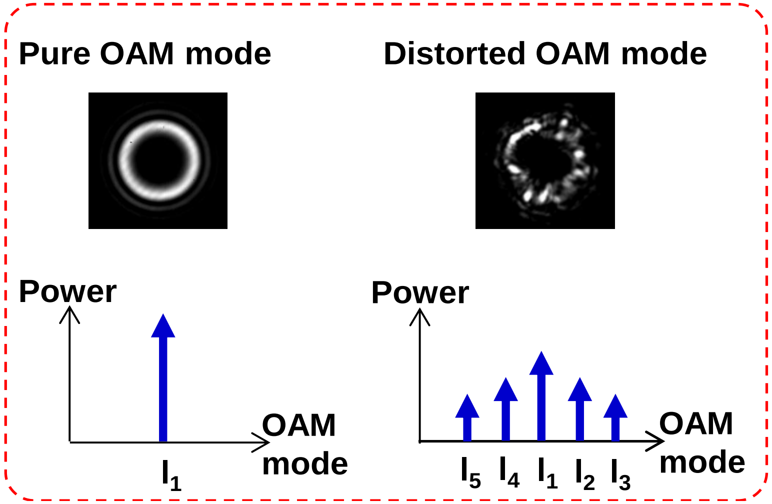
BER for channel OAM *l*=5

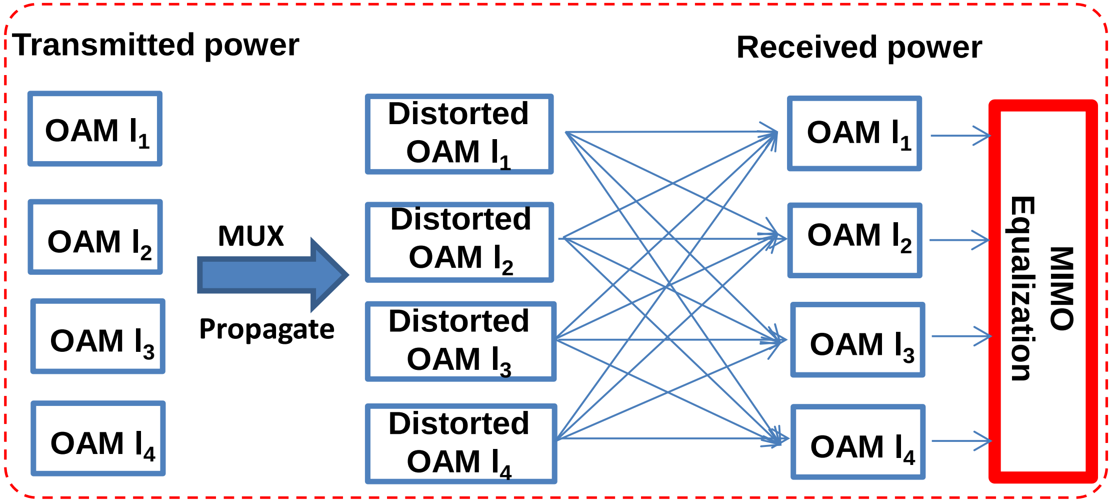


	With Comp.	W/o Comp.
Only l=5	-27.85 dBm	-35.00 dBm
Ch l=3,7 on	-47.80 dBm	-44.51 dBm

Y. Ren et al, ECOC2013

Potential Solutions ─ 4×4 MIMO Equalization

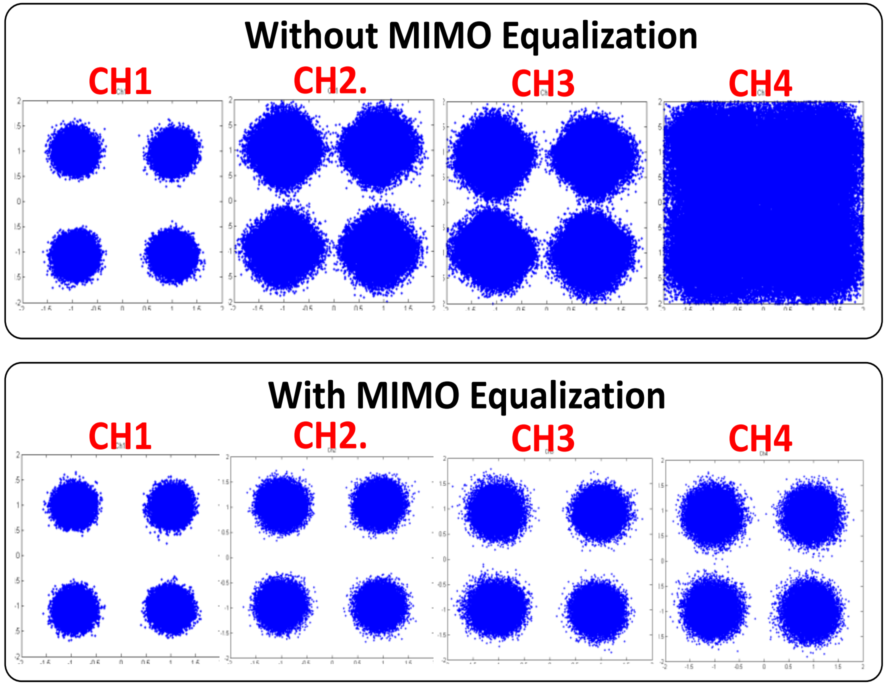




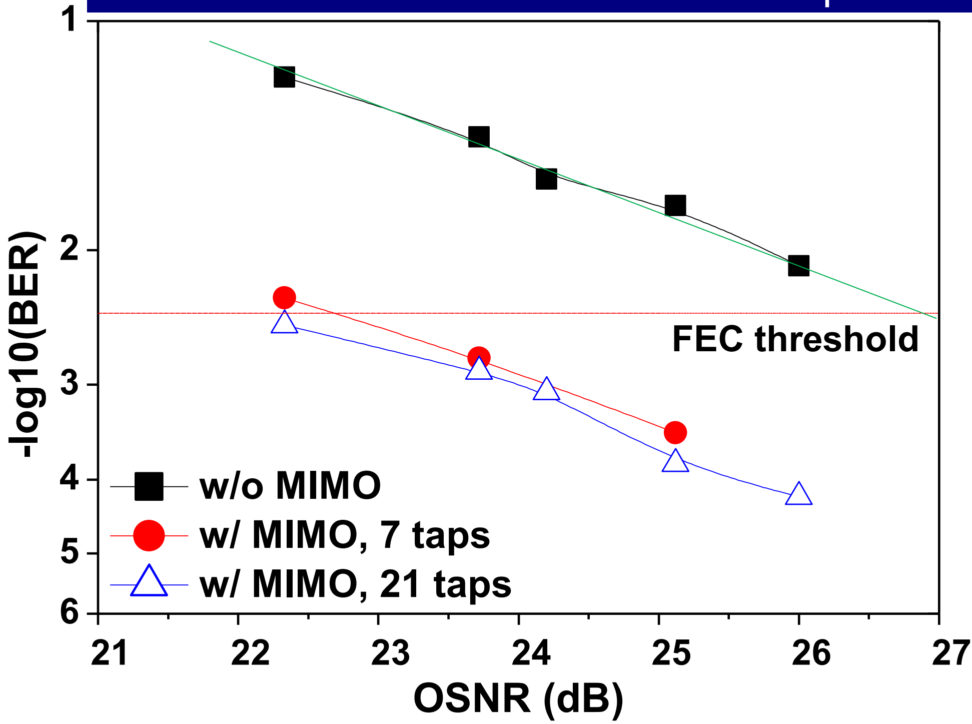
- ❑ Turbulence causes crosstalk among channels on each OAM beam.
- ❑ MIMO equalization could be used to undo the crosstalk between OAM modes.

Potential Solutions — 4×4 MIMO Equalization

Recovered constell. with and w/o MIMO



BER Vs. OSNR under different taps



- ❑ The crosstalk on each channel is ~-19 dB, ~-12 dB, ~-11dB and ~-7 dB.

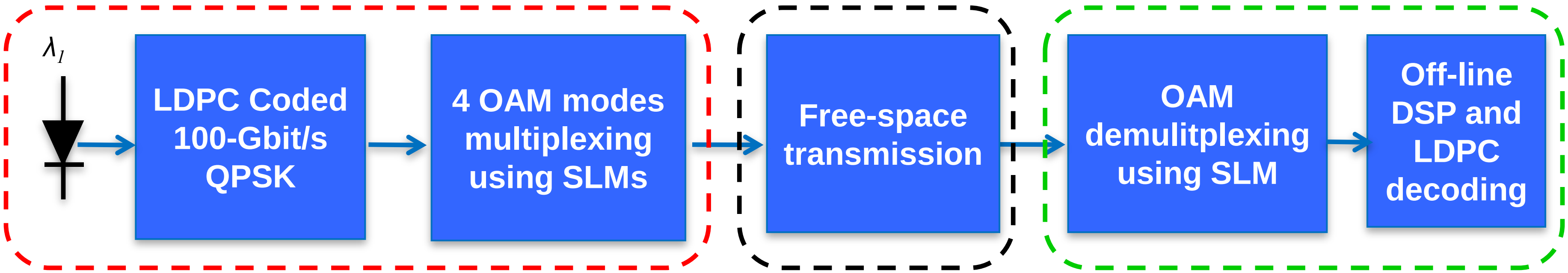
- ❑ Measured crosstalk for this channel is ~ 12.5 dB.

H. Hao et al, ECOC2013

Potential Solutions — Soft-decision LDPC Coding

➢ ***LDPC coding can help approach the theoretical quantum-limited capacity, has powerful error correction capability***

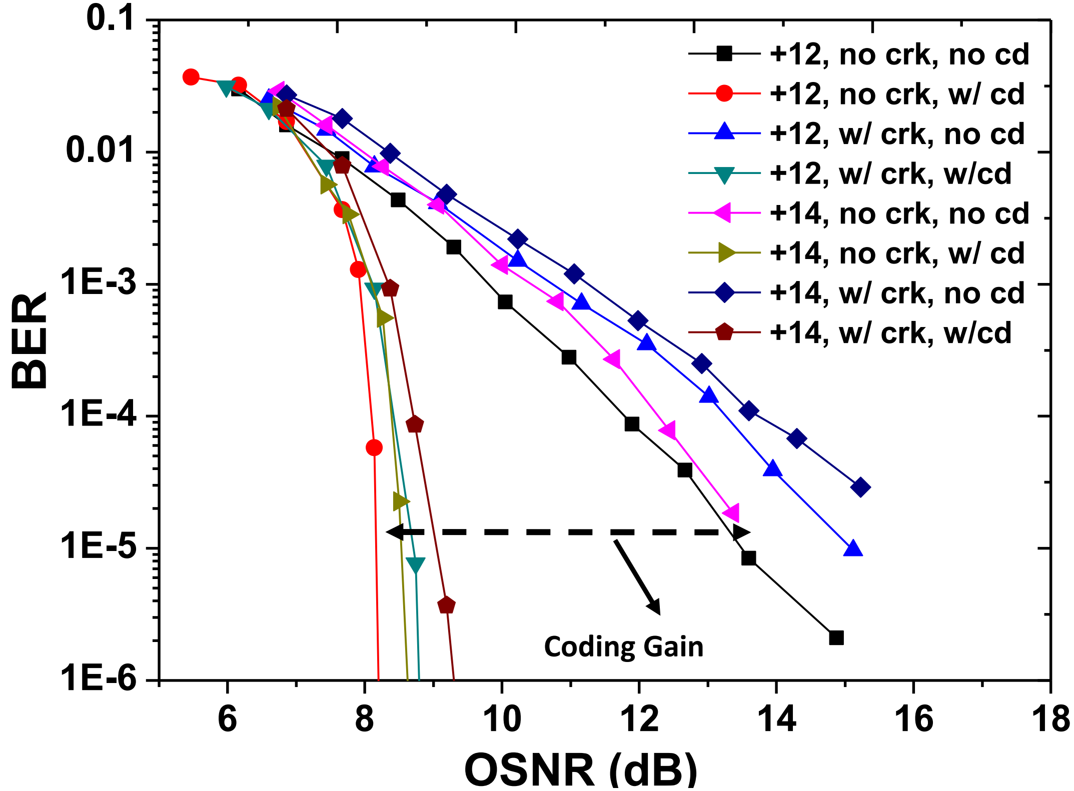
Experiment Block Diagram



- ❑ Data sequence is encoded through LDPC encoder and fed into 100-Gbit/s transmitter
- ❑ OAM multiplexing: 4 OAM modes are multiplexed using 4 SLMs
- ❑ Demultiplexing: An SLM converts one of the multiplexed OAM modes back to the Gaussian beam
- ❑ The converted Gaussian beam is coupled into fiber for detection and followed by off-lined processing and decoding

Potential Solutions ─ Soft-decision LDPC Coding

BER performance of LDPC coded 4 OAM Modes Multiplexed Links



- ❑ The BER performance for demuxed OAM_{+12}/OAM_{+14} with and without crosstalk.
- ❑ The coding gain of LDPC(8547, 6922) is about 5.8 dB, 7.0 dB/5.7 dB, 7.3 dB at BER= 10^{-5} for OAM_{+12} / OAM_{+14} without and with crosstalk.

Y. Ren et al, ECOC2012

Discussion: Other Potential Challenges

- *In addition to atmospheric turbulence, there are many other challenges for OAM multiplexing in OWC links:*

➢OAM Beam Spreading: The divergence of an OAM beam is directly related to $\sqrt{l+1}$. Higher-order OAM modes spread more significantly than lower-order OAM modes during propagation.

➢Transmitter/Receiver Aperture Design: Imposed by diffraction, the number of modes that could be accommodated could be determined by the link distance and transmitter/receiver aperture size.

Part 6 - Q&A (all)

The End
Thanks!