Polymer Wave Guide Optical Interconnect Manufacturing

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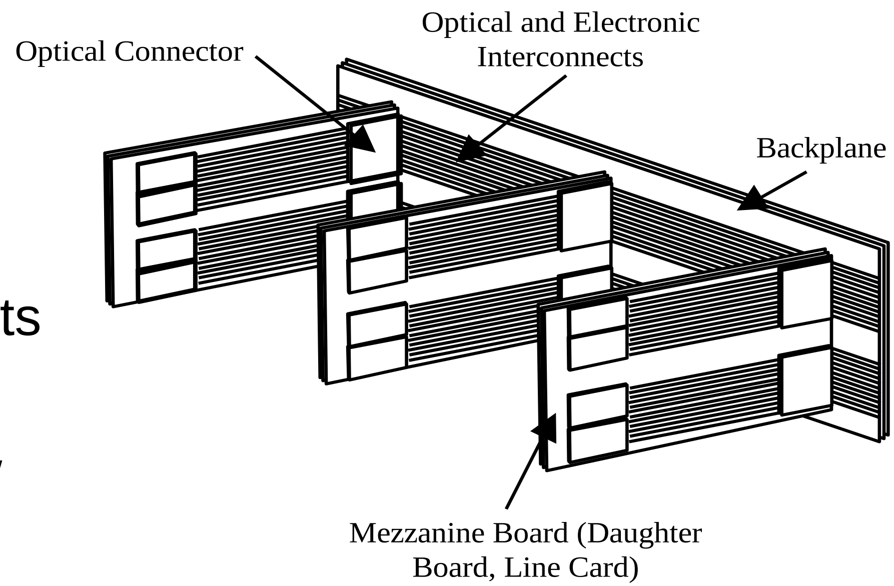
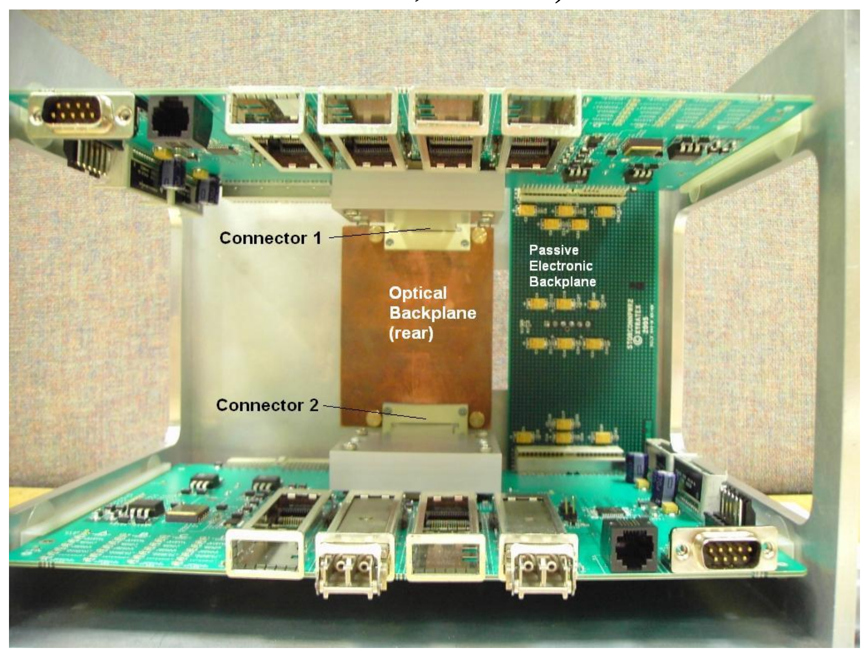
Outline

- Electronic versus Optical interconnects
- The OPCB project
- OPCB University Research Overview
  - Heriot Watt
  - Loughborough
  - UCL
- System Demonstrator





Copper Tracks versus Optical Waveguides for High Bit Rate Interconnects

- Copper Track
  - EMI Crosstalk
  - Loss
  - Impedance control to minimize back reflections, additional equalisation, costly board material

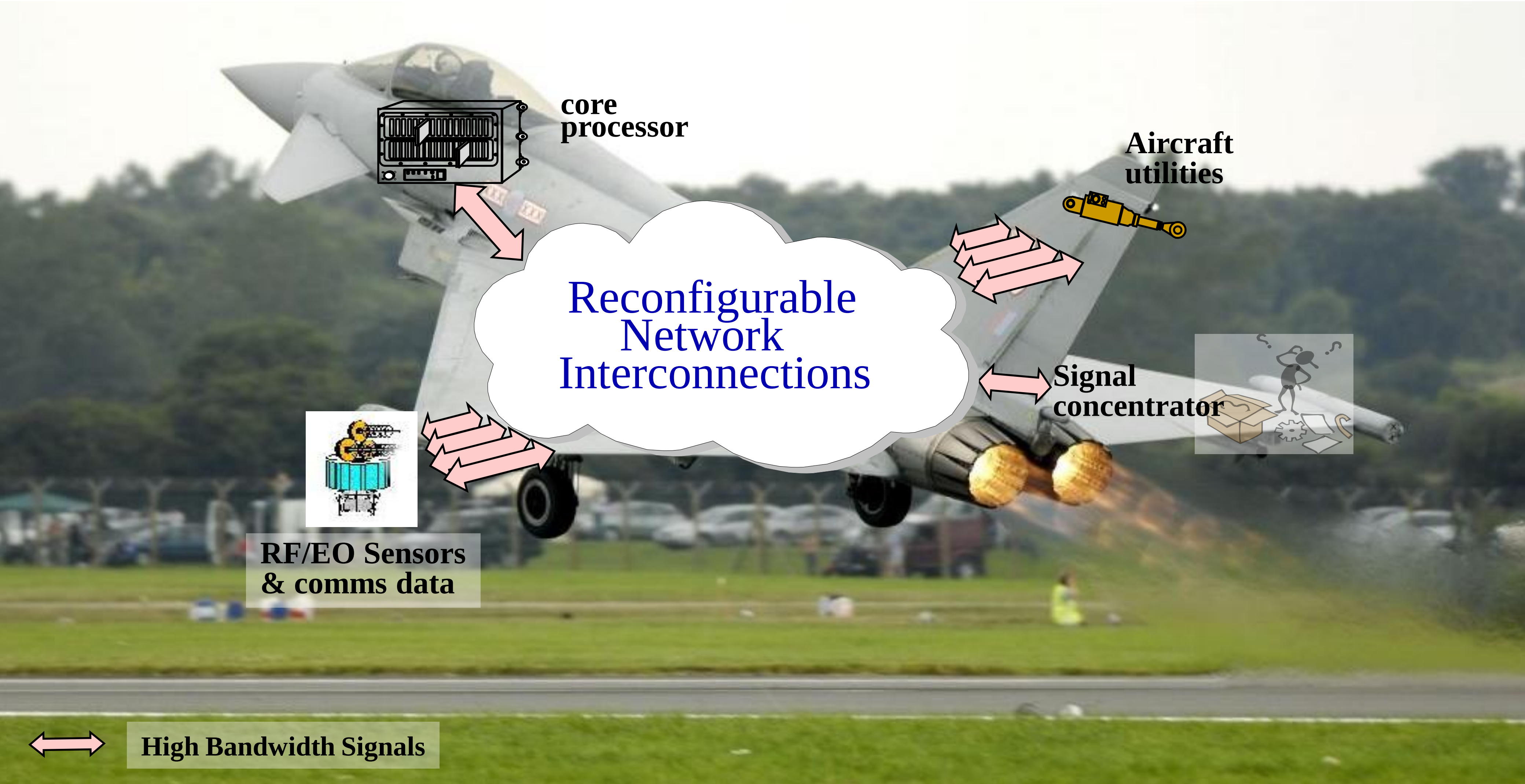
- Optical Waveguides
  - Low loss
  - Low cost
  - Low power consumption
  - Low crosstalk
  - Low clock skew
  - WDM gives higher aggregate bit rate
  - Cannot transmit electrical power

On-board Platform Applications

BAE SYSTEMS

On-board Platform Applications

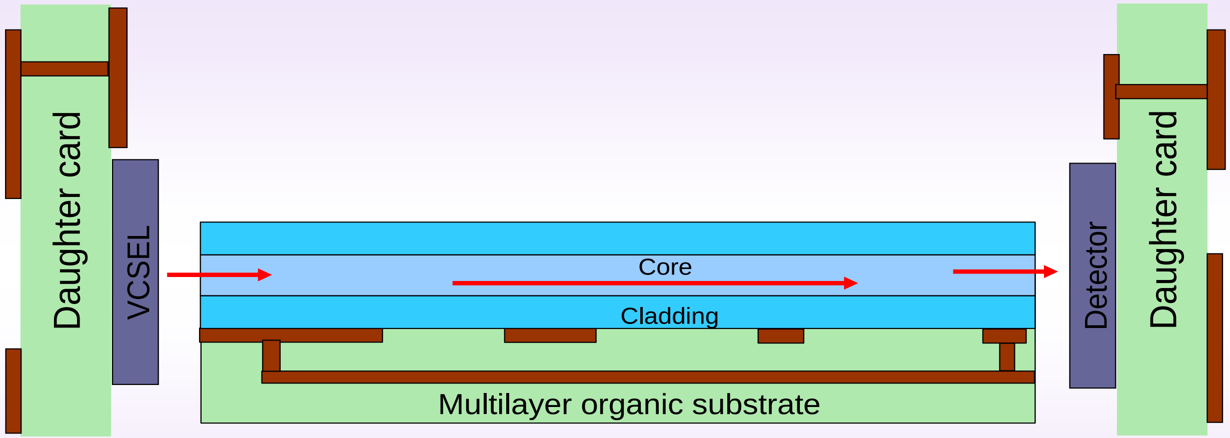
BAE SYSTEMS



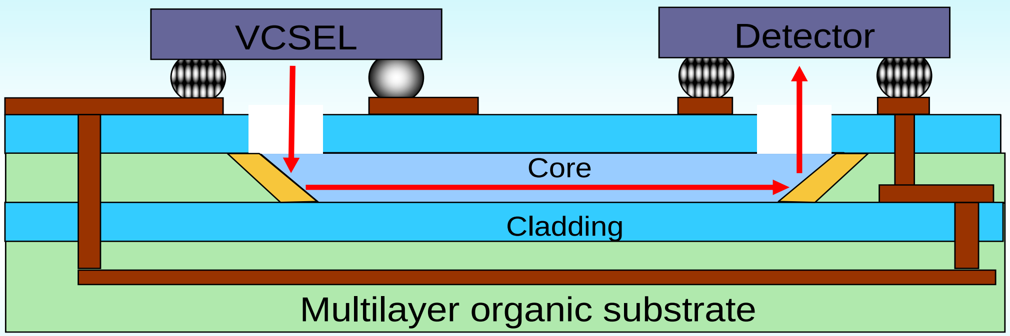
The Integrated Optical and Electronic Interconnect PCB Manufacturing (OPCB) project

- Hybrid Optical and Electronic PCB Manufacturing Techniques
- 8 Industrial and 3 University Partners led by industry end user
- Multimode waveguides at 10 Gb/s on a 19 inch PCB
- Project funded by UK Engineering and Physical Sciences Research Council (EPSRC) via the Innovative Electronics Manufacturing Research Centre (IeMRC) as a Flagship Project
- 3 year, £1.6 million project, half direct and indirect contributions from industry

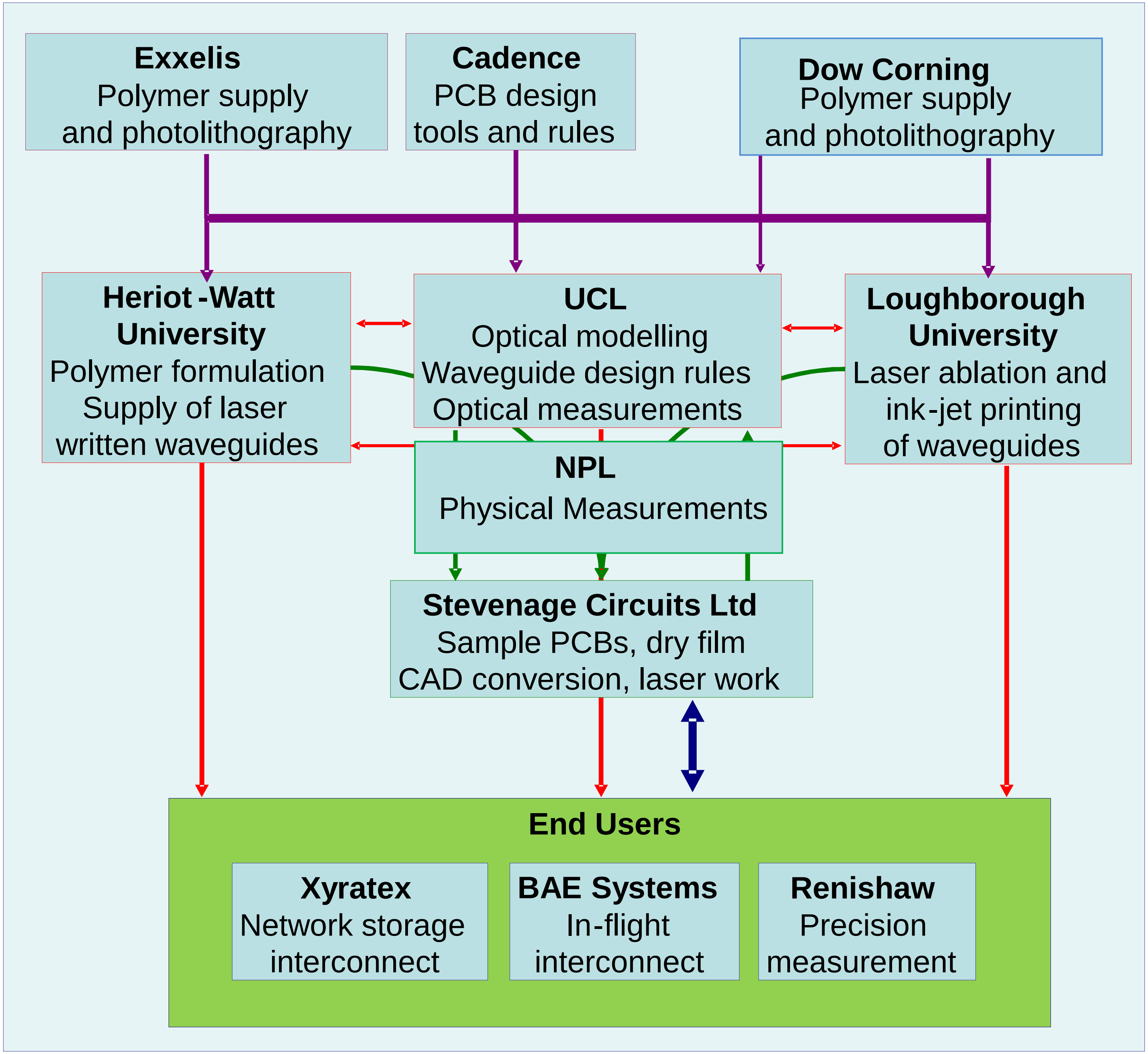
Integration of Optics and Electronics



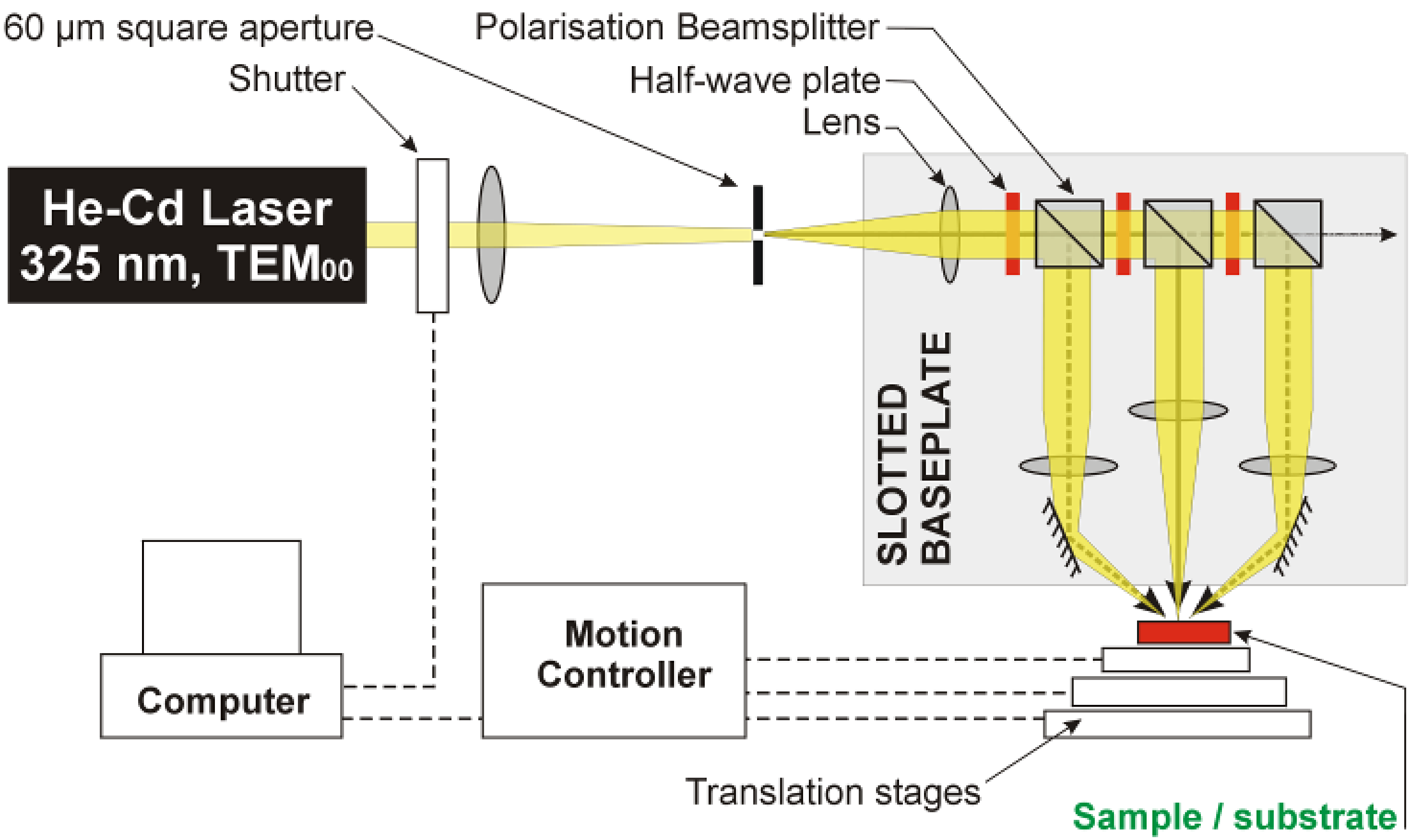
- Backplanes
  - Butt connection of "plug-in" daughter cards
  - In-plane interconnection
- Focus of OPCB project

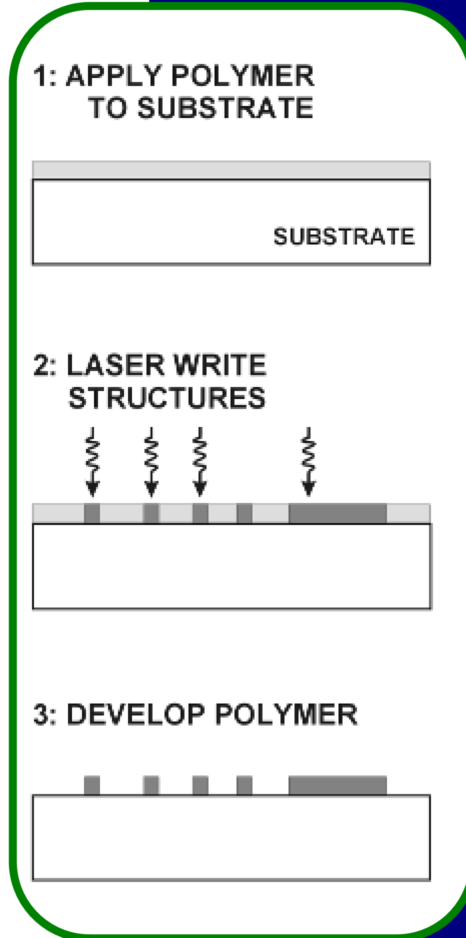


- Out-of-plane connection
  - 45 mirrors
  - Chip to chip connection possible


Exxelis
Polymer supply
and photolithography
Cadence
PCB design
tools and rules
Dow Corning
Polymer supply
and photolithography
Heriot -Watt
University
Polymer formulation
Supply of laser
written waveguides
UCL
Optical modelling
Waveguide design rules
Optical measurements
Loughborough
University
Laser ablation and
ink-jet printing
of waveguides
NPL
Physical Measurements
Stevenage Circuits Ltd
Sample PCBs, dry film
CAD conversion, laser work
End Users
Xyratex
Network storage
interconnect
BAE Systems
In-flight
interconnect
Renishaw
Precision
measurement

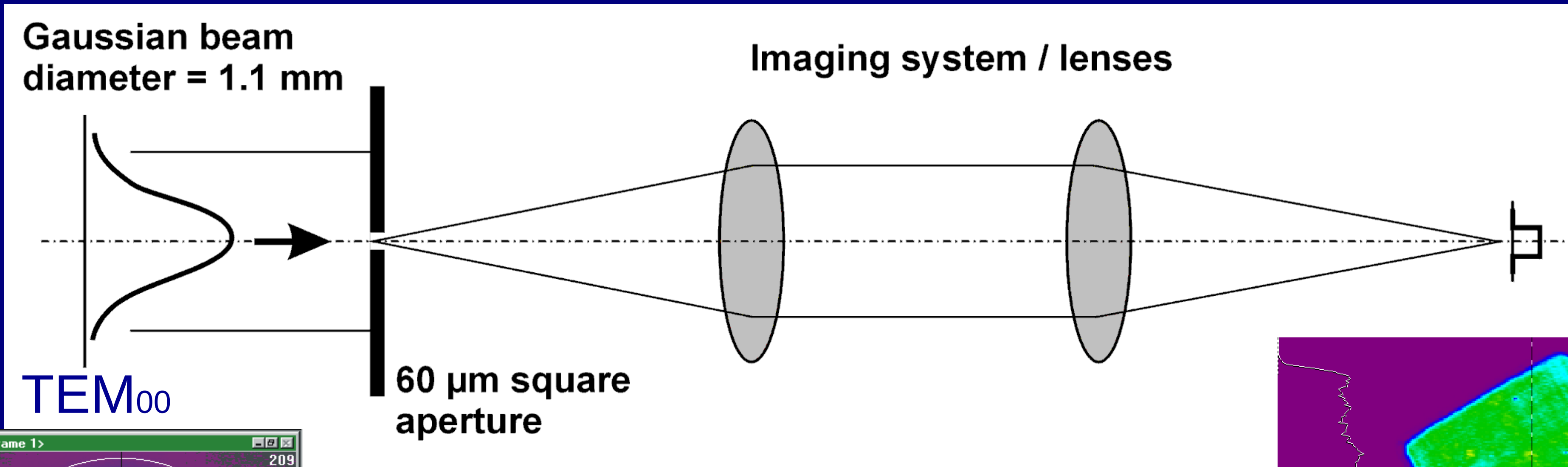
Direct Laser-writing Setup: Schematic

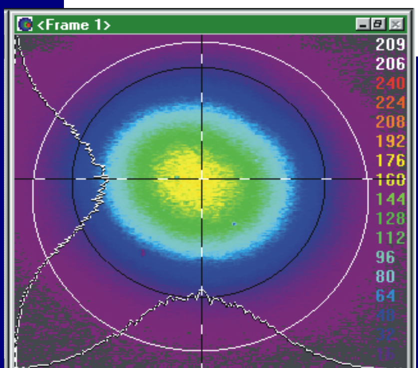


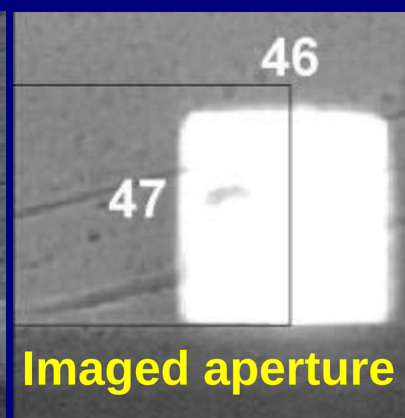


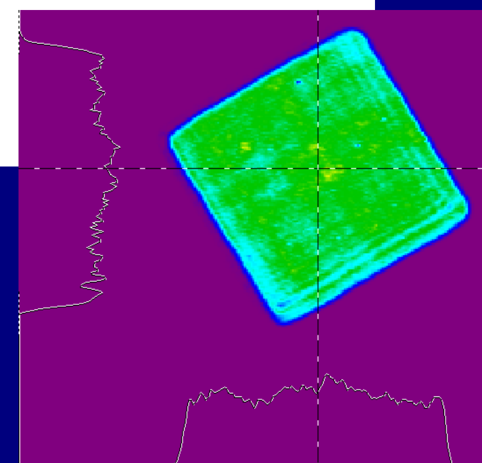
- **Slotted baseplate** mounted vertically over translation, rotation & vertical stages; components held in place with magnets
- By using two opposing 45º beams we minimise the amount of substrate rotation needed

Writing sharply defined features
– flat-top, rectangular laser spot







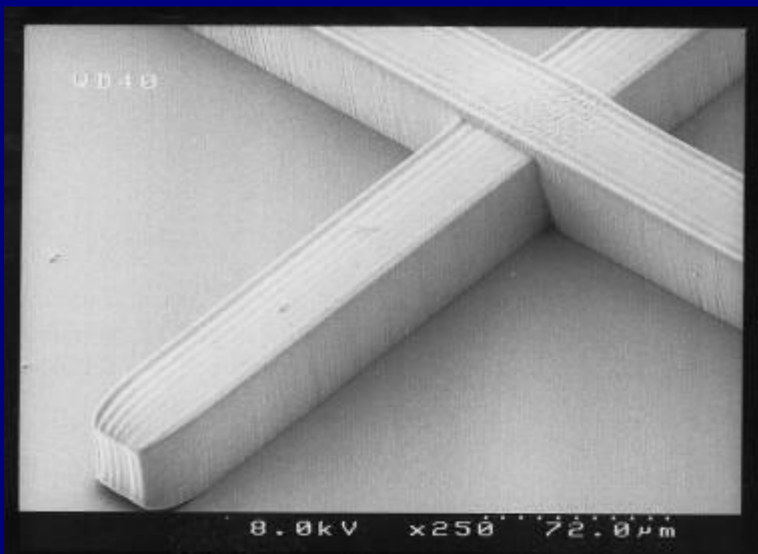


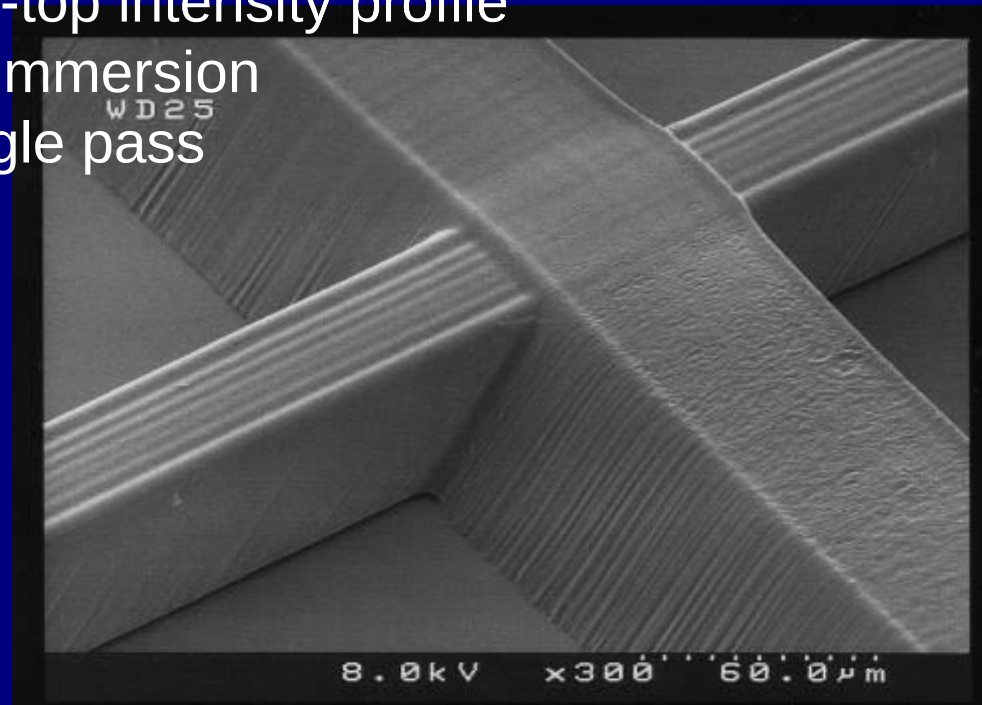
Images of the resulting waveguide
core cross-sections

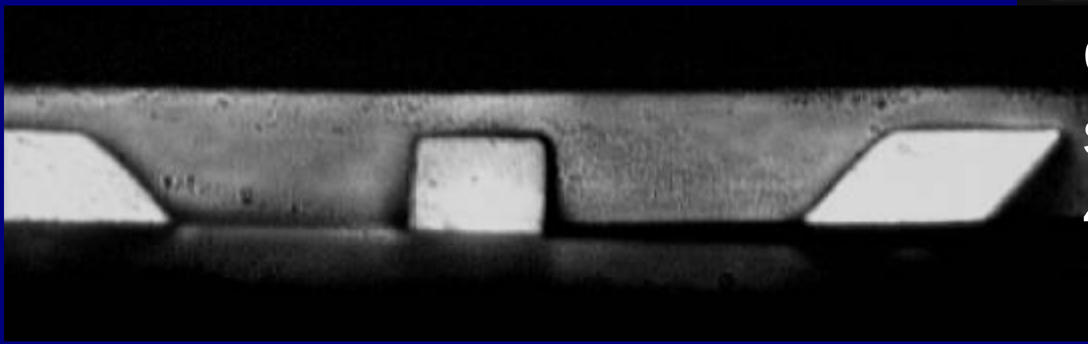
Laser written polymer structures

SEM images of polymer structures written using imaged 50 µm square aperture (chrome on glass)

- Writing speed: ~75 µm / s
- Optical power: ~100 µW
- Flat-top intensity profile
- Oil immersion
- Single pass





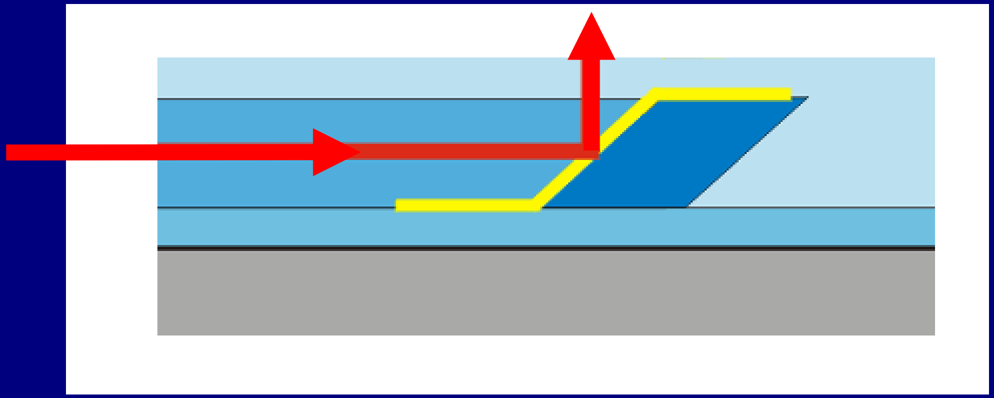


Optical microscope image showing end on view of the 45º surfaces

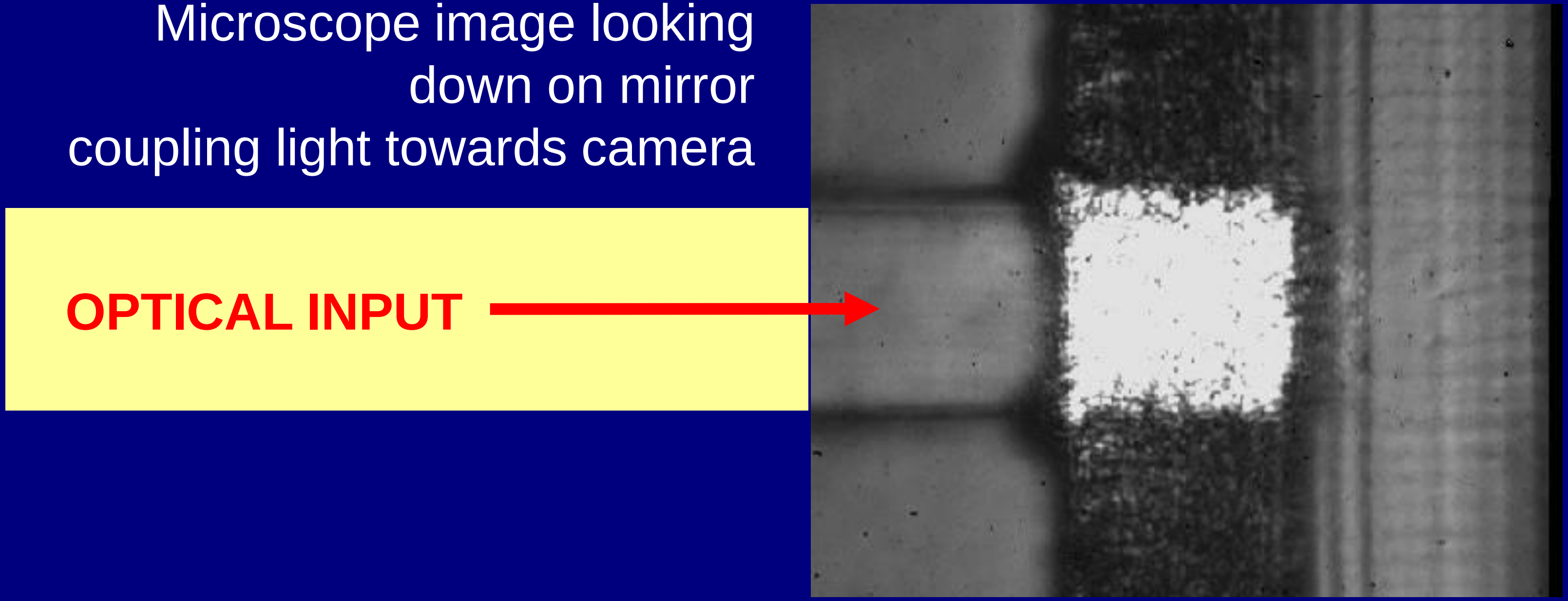
Waveguide terminated with 45-deg mirror

Out-of-plane coupling,

using 45-deg mirror (silver)



Microscope image looking down on mirror coupling light towards camera



Current Results

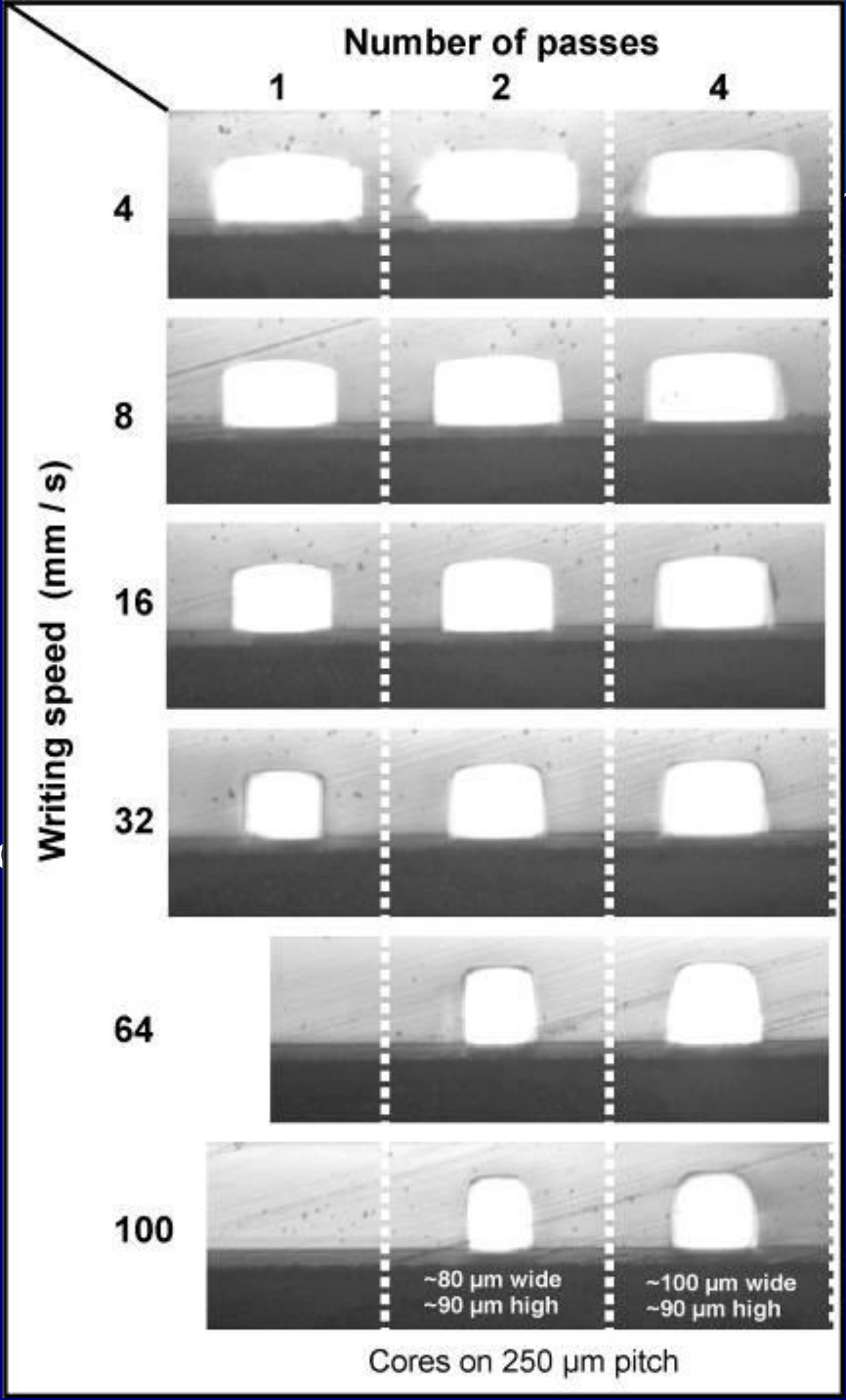
Laser-writing Parameters:

- Intensity profile: Gaussian
- Optical power: ~8 mW
- Cores written in oil

Polymer:

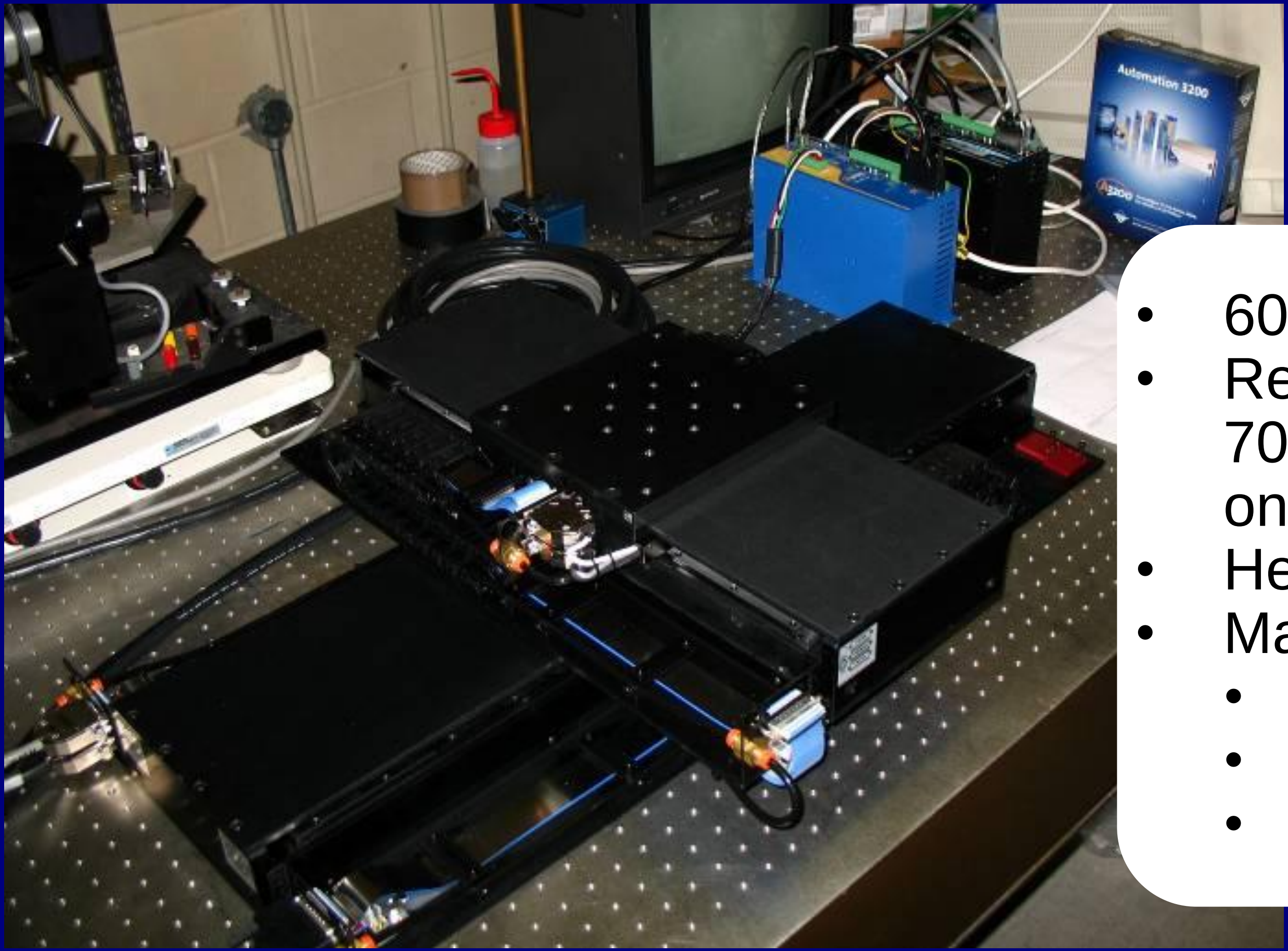
- Custom multifunctional acrylate photo-polymer
- Fastest "effective" writing speed to date: 50 mm/s

(Substrate: FR4 with polymer undercladding)



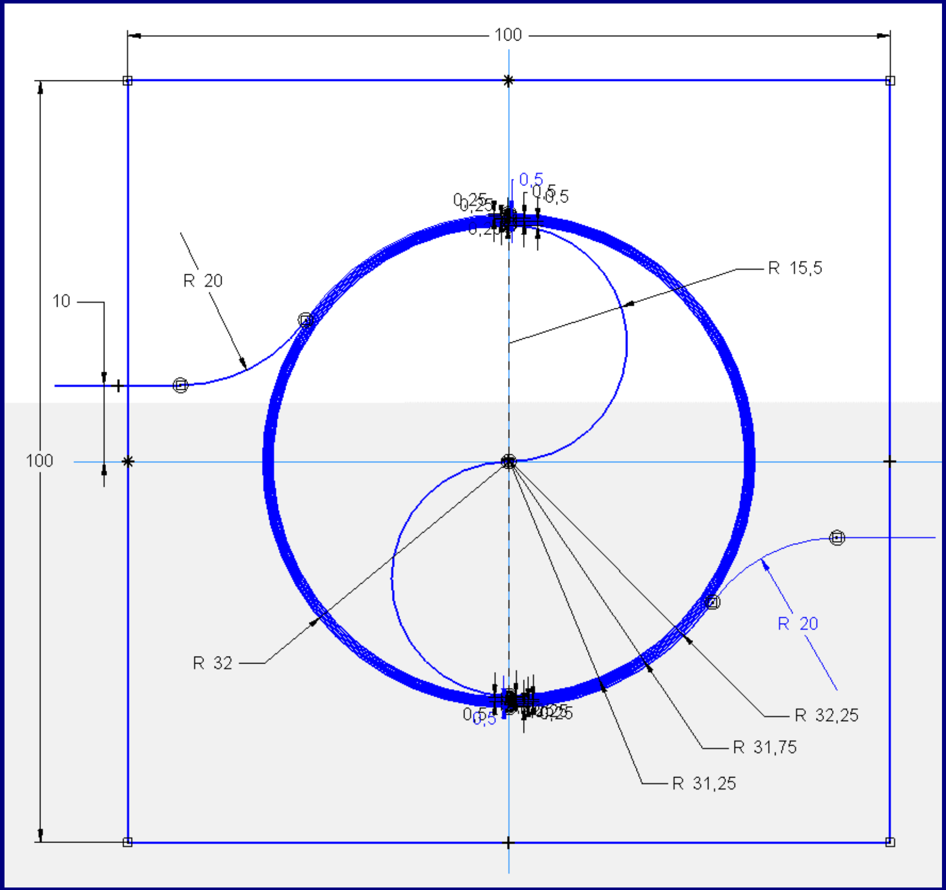
Large Board Processing: Writing

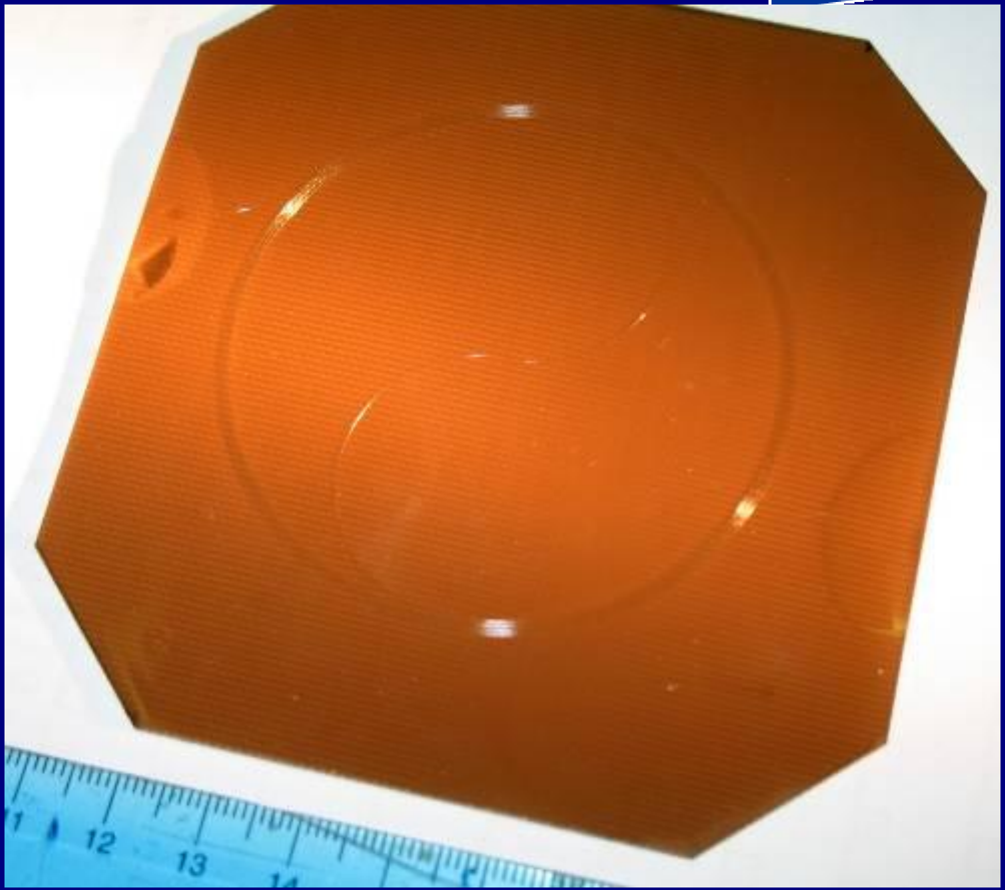
- Stationary "writing head" with board moved using Aerotech sub-µm precision stages
- Waveguide trajectories produced using CAD program



- 600 x 300 mm travel
- Requires a minimum of 700 x 1000 mm space on optical bench
- Height: ~250 mm
- Mass:
  - 300 mm: 21 kg
  - 600 mm: 33 kg
  - Vacuum tabletop

Large Board Processing: Writing



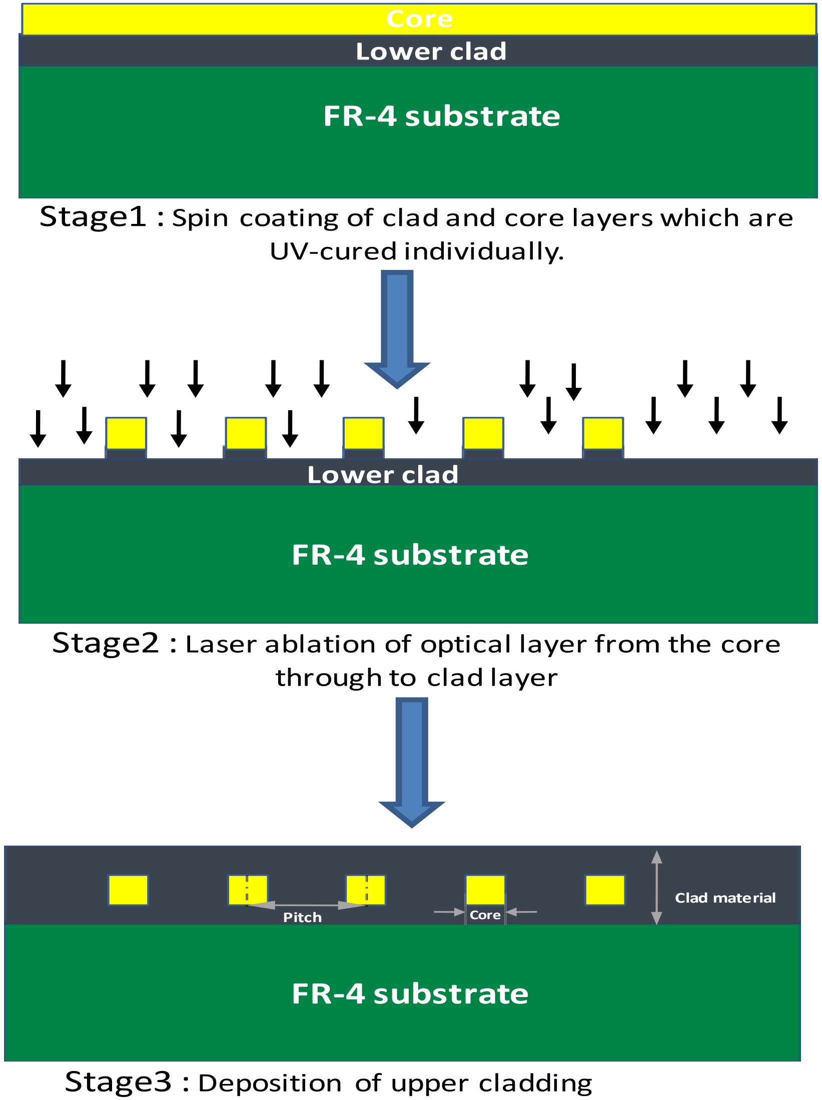


The spiral was fabricated using a Gaussian intensity profile at a writing speed of 2.5 mm/s on a 10 x 10 cm lower clad FR4 substrate. Total length of spiral waveguide is **~1.4 m**. The spiral was upper cladded at both ends for cutting.

Laser Ablation of Optical Waveguides

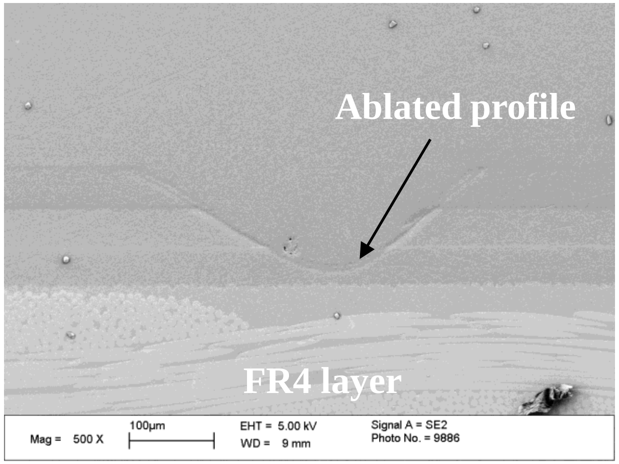
- Research
  - Straight waveguides
  - 2D & 3D integrated mirrors
- Approach
  - Excimer laser – Loughborough
  - CO_2 laser - Loughborough
  - UV Nd:YAG – Stevenage Circuits Ltd
- Optical polymer
  - Truemode® – Exxelis
  - Polysiloxane – Dow Corning

Schematic diagram (side view) showing stages in the fabrication of optical waveguides by laser ablation

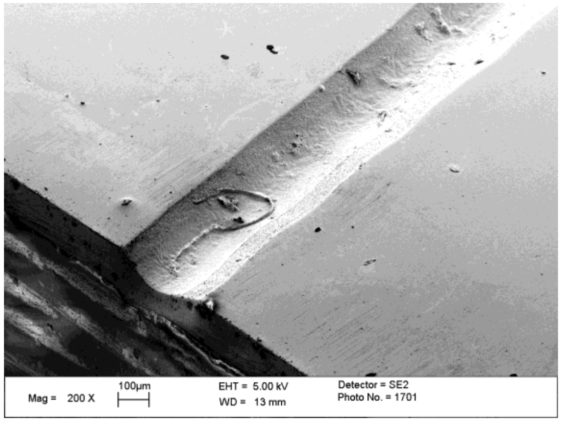


Machining of Optical Polymer with CO_2 Laser

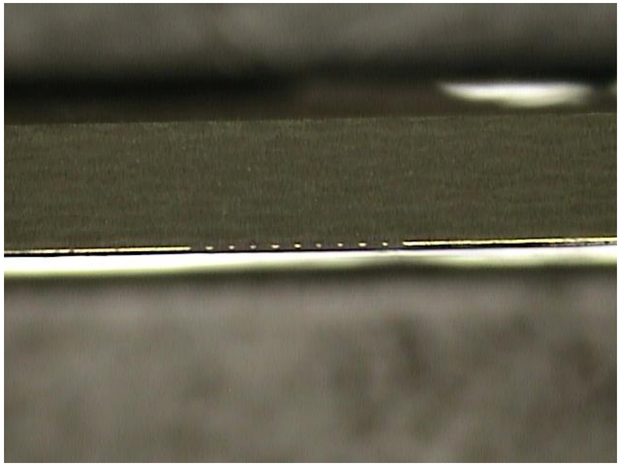
- System
  - 10 Watt(max.) power CW beam
  - Wavelength = 10.6 µm (infrared)
- Process
  - Thermally-dominated ablation process
- Machining quality
  - Curved profile
  - Waveguide fabrication underway



Side view of machined trench

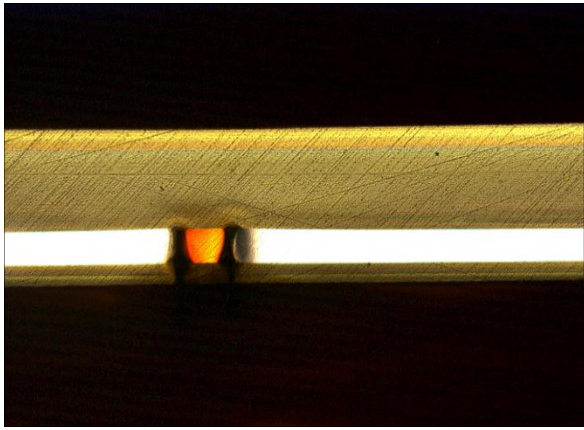


Machined trench

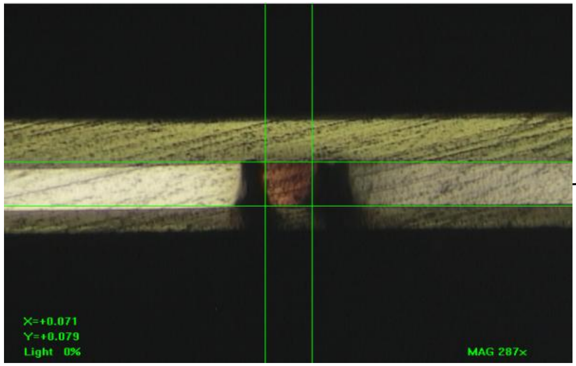


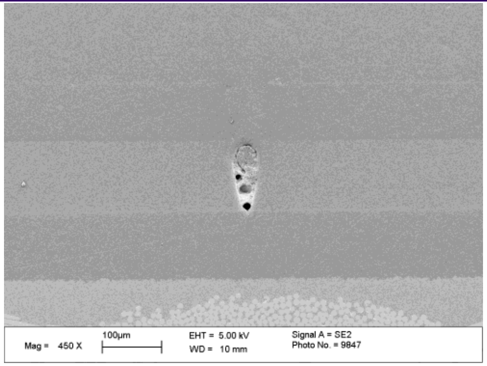
Waveguides (side view)

UV Nd:YAG machining in collaboration with Stevenage Circuits Ltd

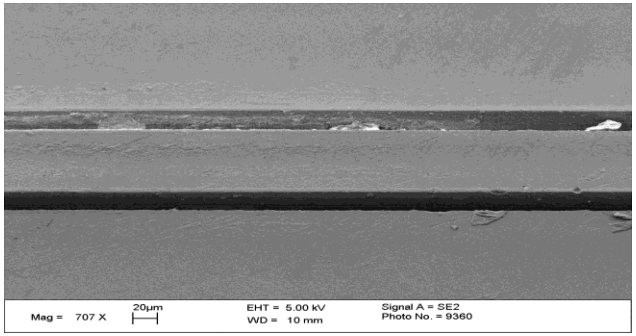


- **Waveguide of 71 µm x 79 µm fabricated using UV Nd:YAG**
- **Waveguide detected using back lighting**





Side view

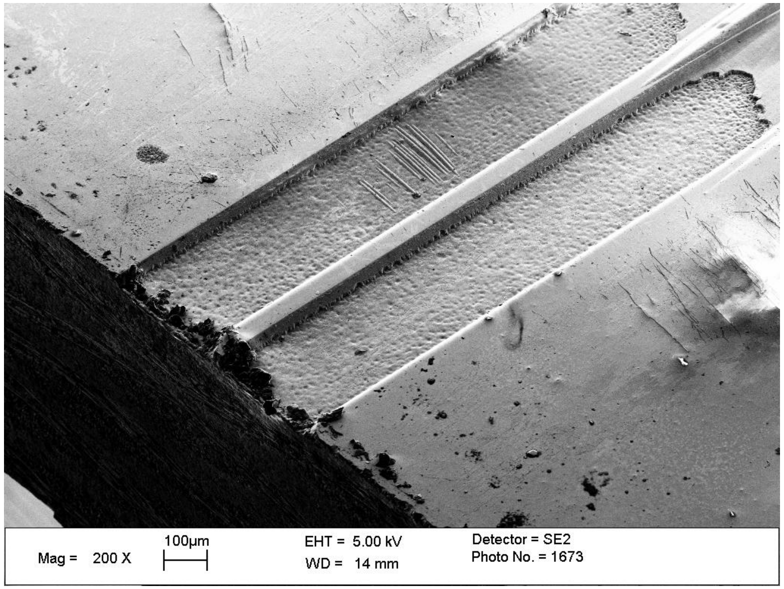


Plan view

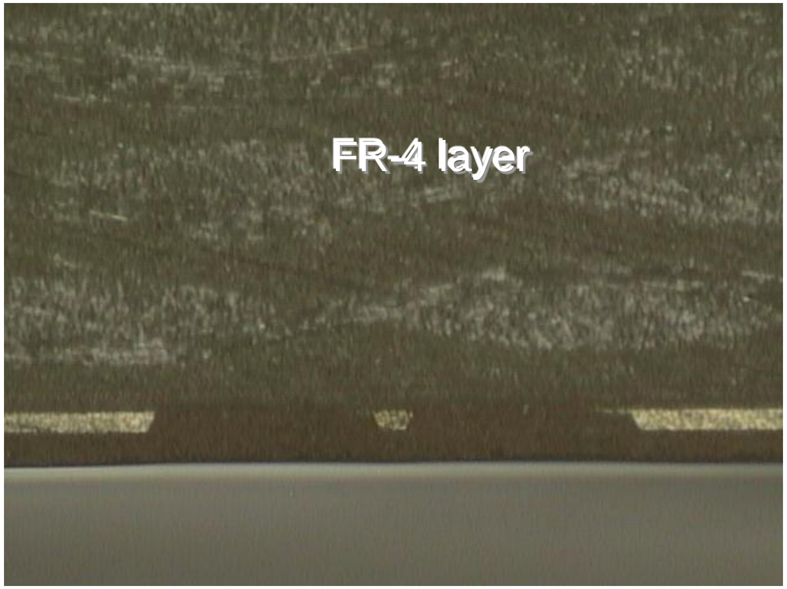
- System
  - 355 nm (UV) Pulsed laser with 60 ns pulse width and Gaussian beam (TEM_{00}) or “Tophat” profile at Stevenage Circuits Ltd.
- Process
  - Photochemically-dominated ablation process.
- Waveguide quality
  - Minimum Heat Affected Zone
  - Propagation loss measurement underway

Machining of Optical Polymer with Excimer Laser

- Straight structures machined in an optical polymer.
- Future work to investigate preparation of mirrors for in and out of plane bends.

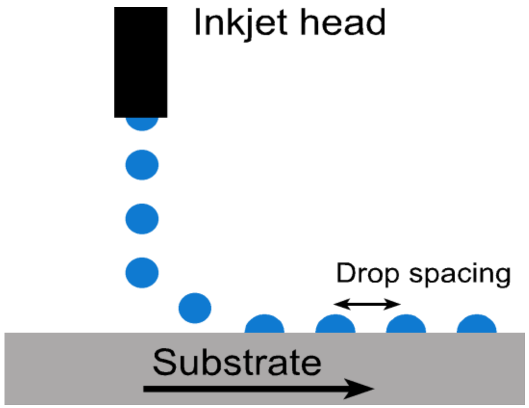


Machined trenches

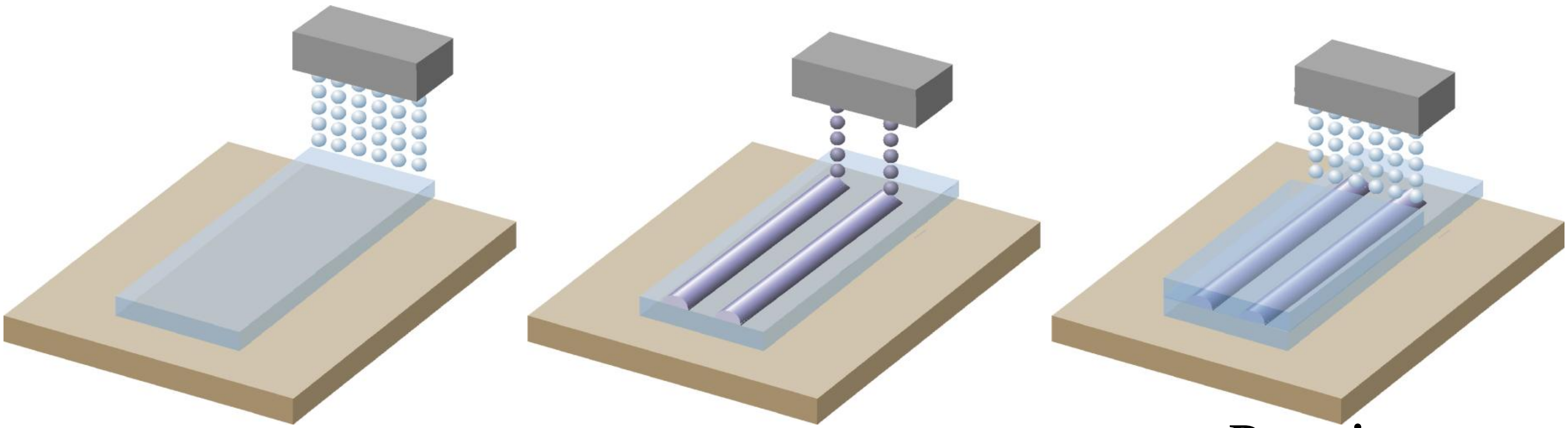


Waveguide structure

Inkjetting as a Route to Waveguide Deposition

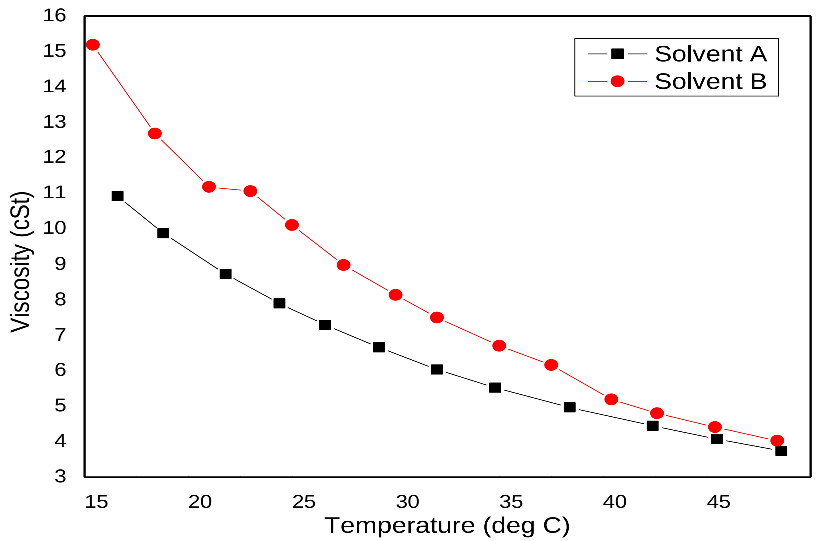


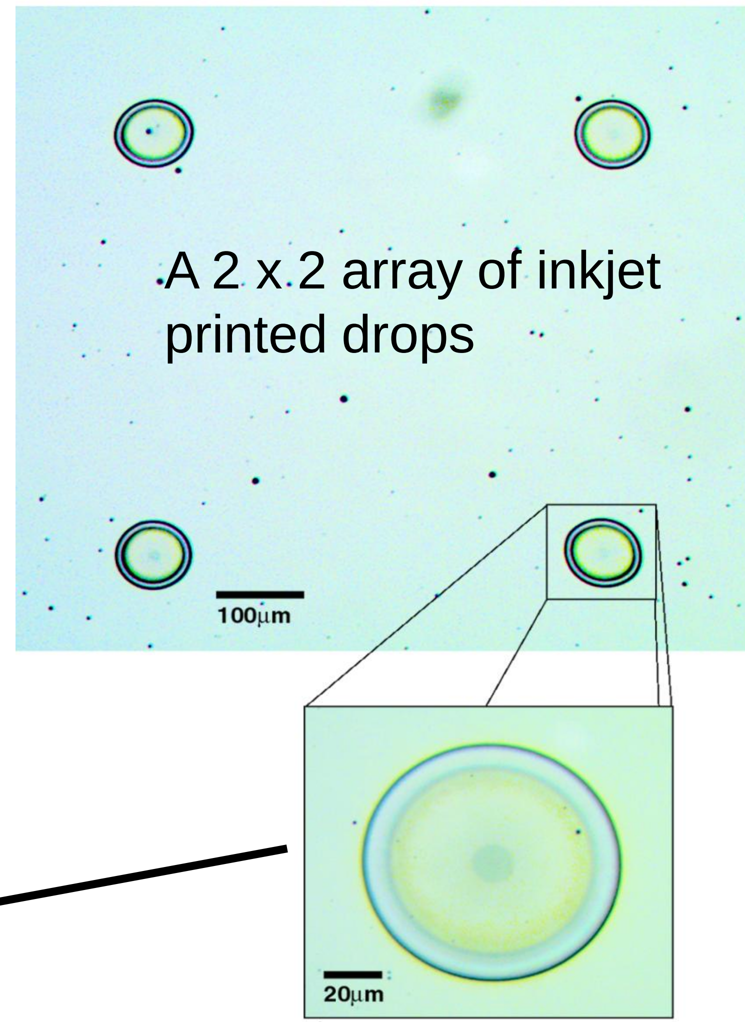
- Print polymer then UV cure
- Advantages:
  - controlled, selective deposition of core and clad
  - less wastage: picolitre volumes
  - large area printing
  - low cost



Challenges of Inkjet Deposition

- Viscosity tailored to inkjet head via addition of solvent
- “Coffee stain” effects

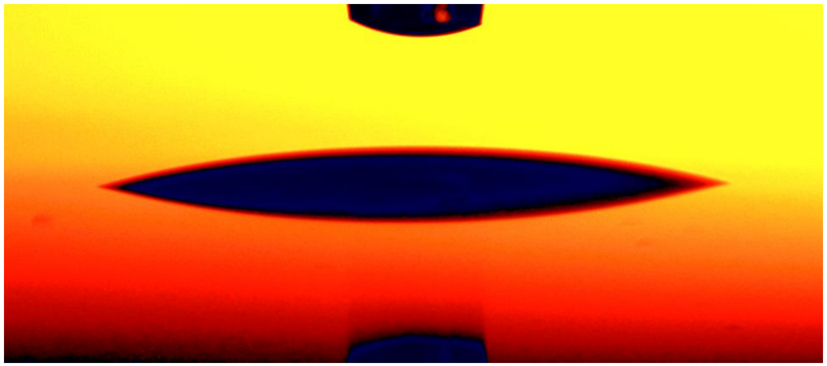




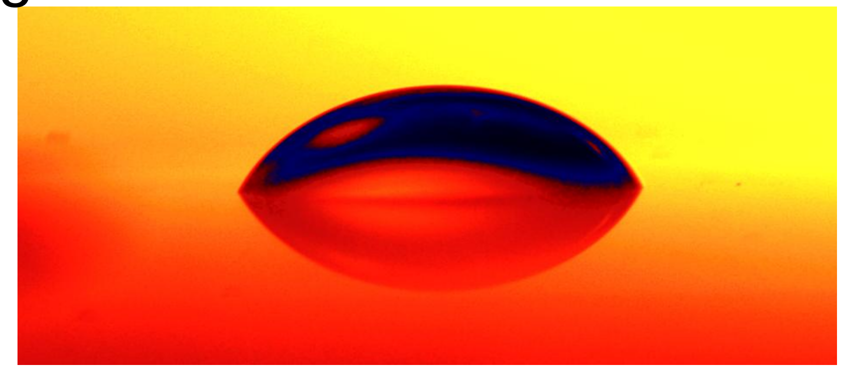
Cross-section of dried droplet “coffee-stain” effect

Changing Surface Wettability

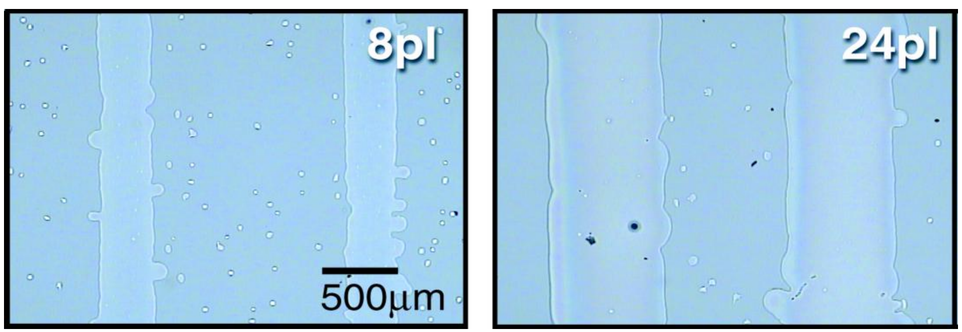
Contact Angles



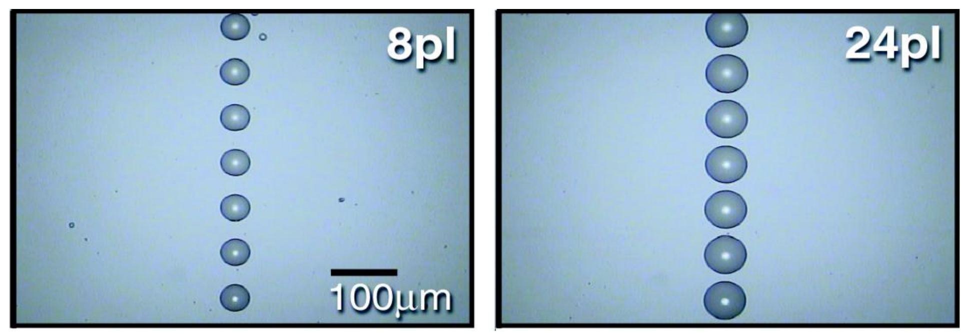
Core material on cladding



Core material on modified glass surface (hydrophobic)



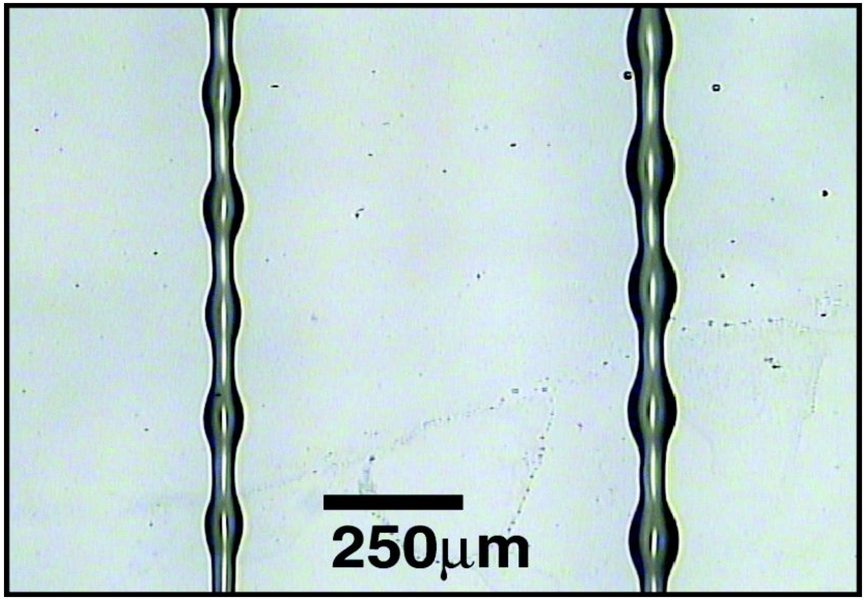
Large wetting - broad inkjetted lines



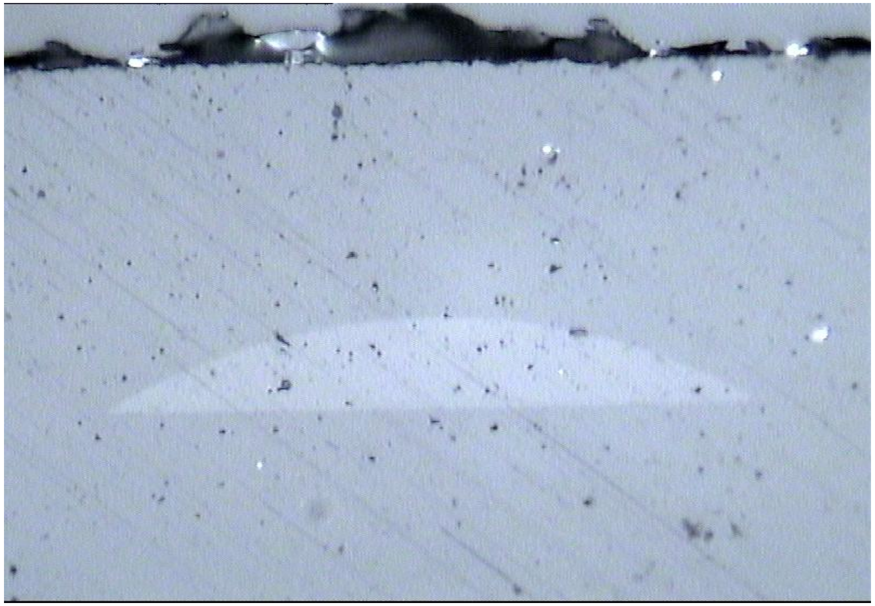
Reduced wetting – discrete droplets

Identical inkjetting conditions - spreading inhibited on modified surface

Towards Stable Structures



Stable line structures with periodic features

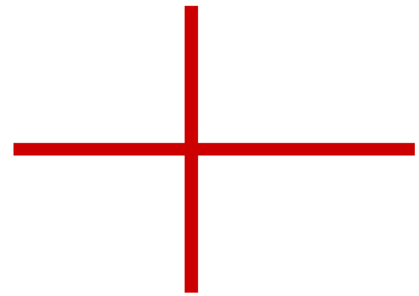


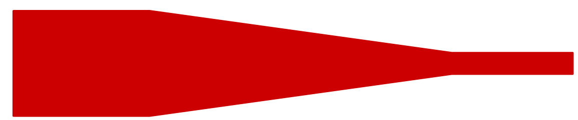
Cross section of inkjetted core material surrounded by cladding (width 80 microns)

A balance between wettability, line stability and adhesion

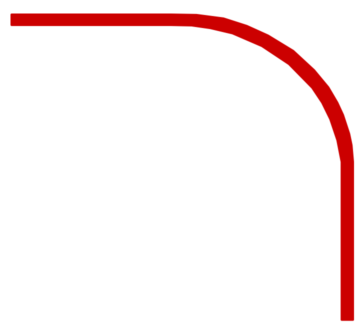
Waveguide components and measurements

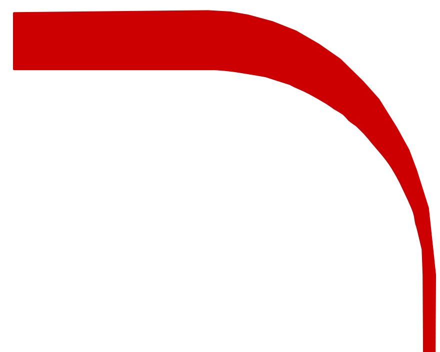
- Straight waveguides 480 mm x 70 µm x 70 µm
- Bends with a range of radii
- Crossings
- Spiral waveguides
- Tapered waveguides
- Bent tapered waveguides



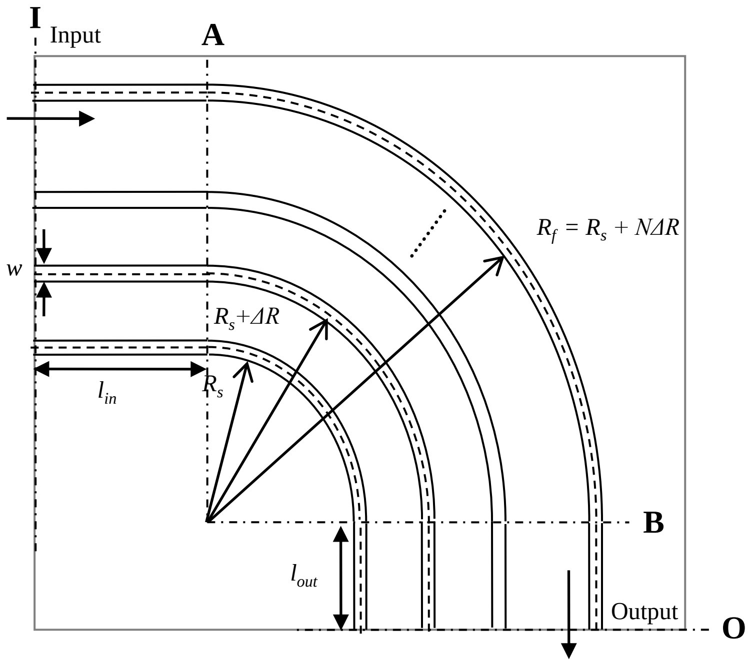


- Loss
- Crosstalk
- Misalignment tolerance
- Surface Roughness
- Bit Error Rate, Eye Diagram

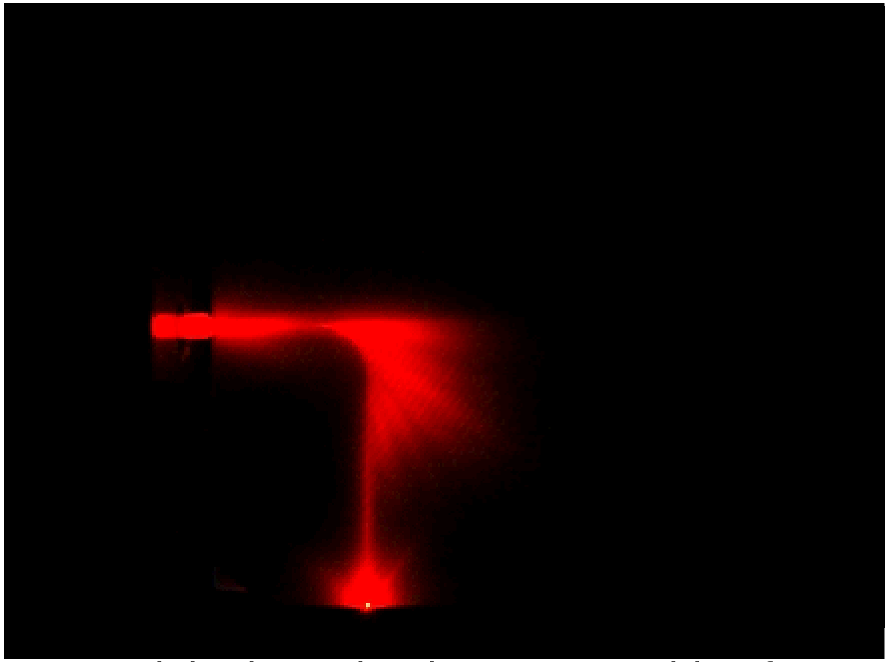




Optical Power Loss in 90 Waveguide Bends



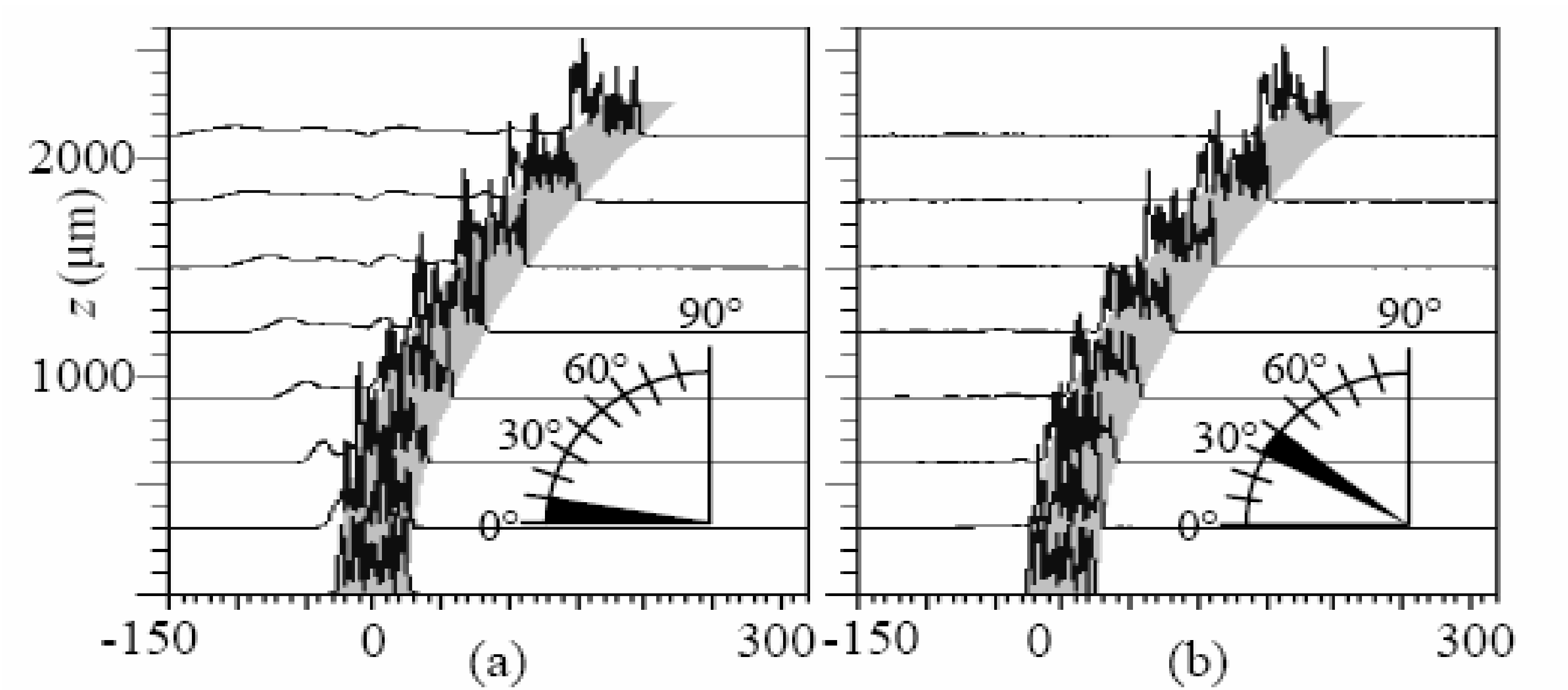
Schematic diagram of one set of curved waveguides.



Light through a bent waveguide of R = 5.5 mm – 34.5 mm

- Radius R, varied between 5.5 mm < R < 35 mm, ΔR = 1 mm
- Light lost due to scattering, transition loss, bend loss, reflection and back-scattering
- Illuminated by a MM fiber with a red-laser.

BPM, beam propagation method modeling of optical field in bend segments

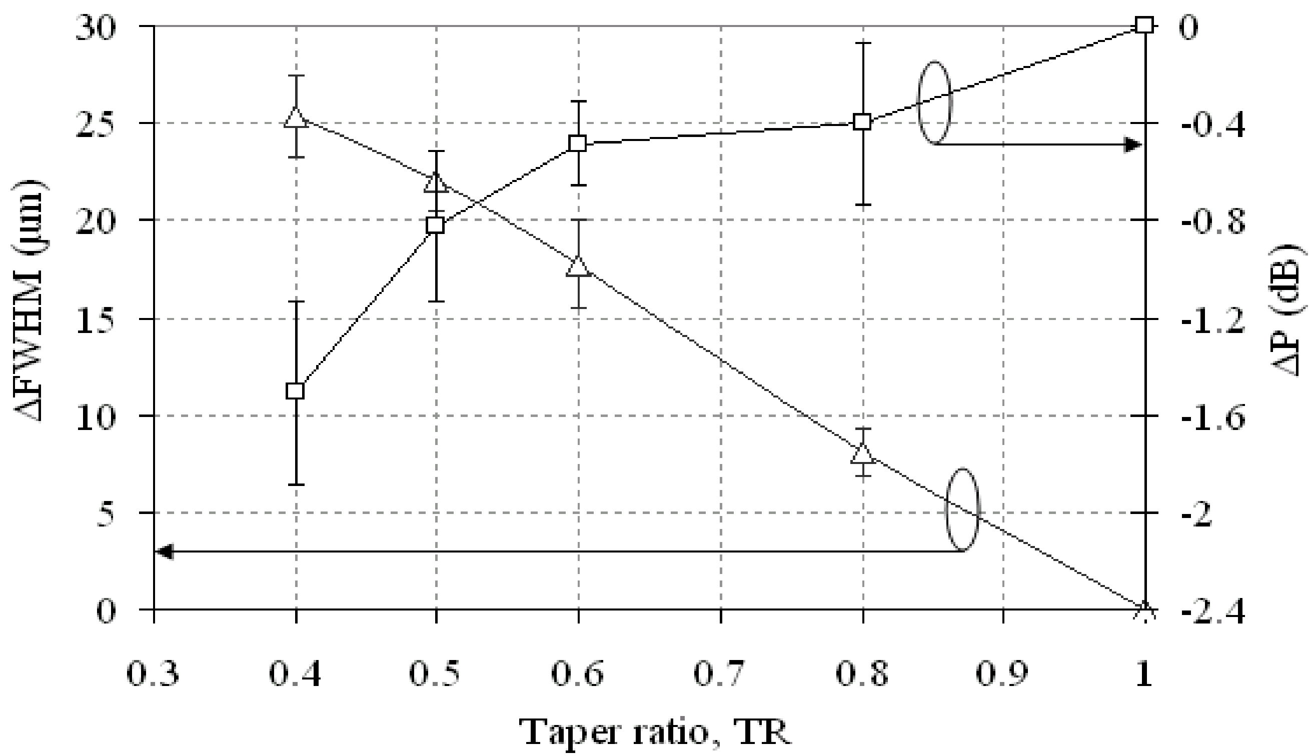


w = 50 μm, R = 13 mm

(left picture) in the first segment (first 10°).

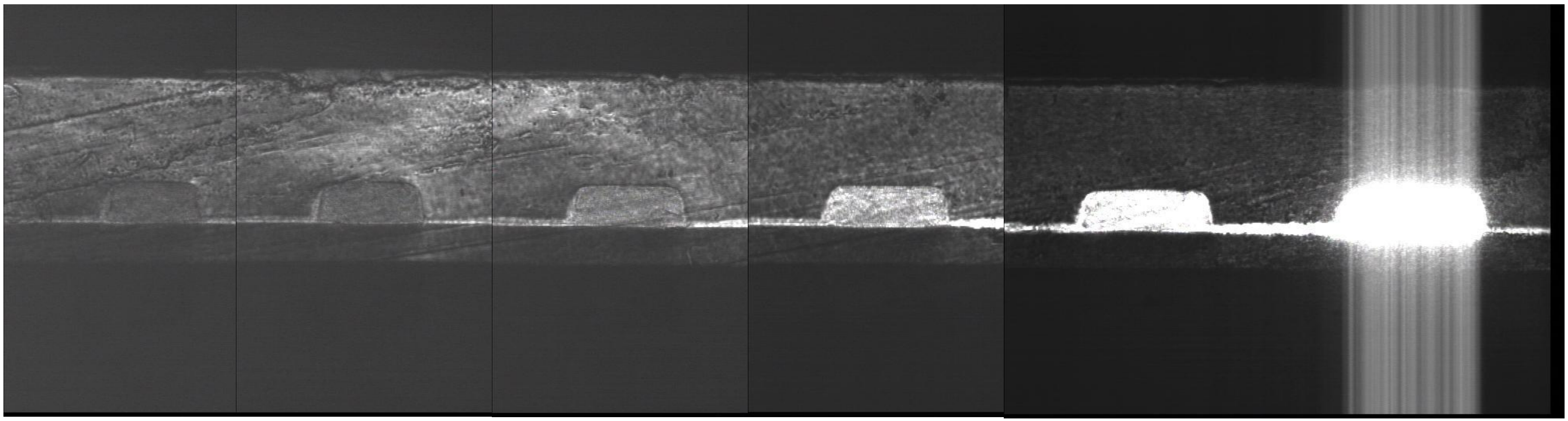
(right picture) in the 30° to 40° degree segment.

Differences in misalignment tolerance and loss as a function of taper ratio



- Graph plots the differences between a tapered bend and a bend
- There is a trade off between insertion loss and misalignment tolerance

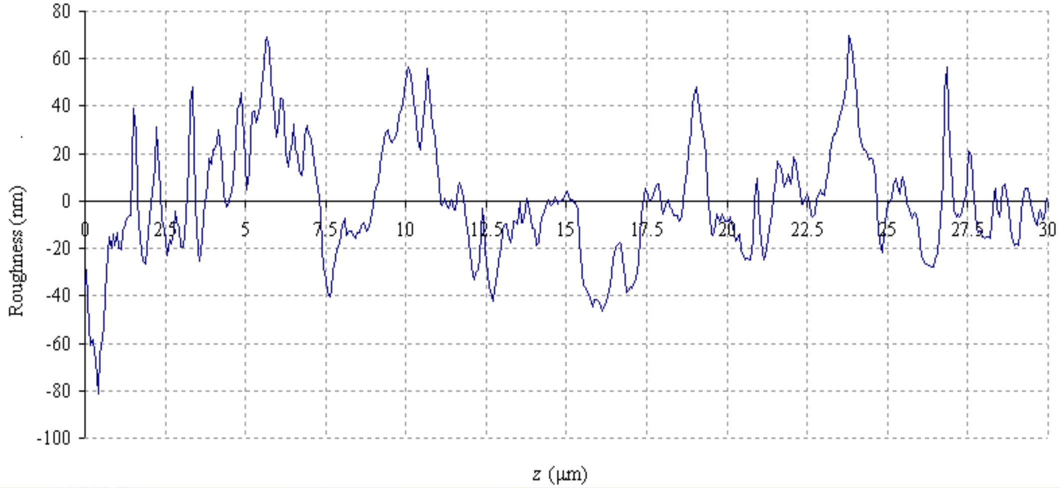
Crosstalk in Chirped Width Waveguide Array



100 µm 110 µm 120 µm 130 µm 140 µm 150 µm

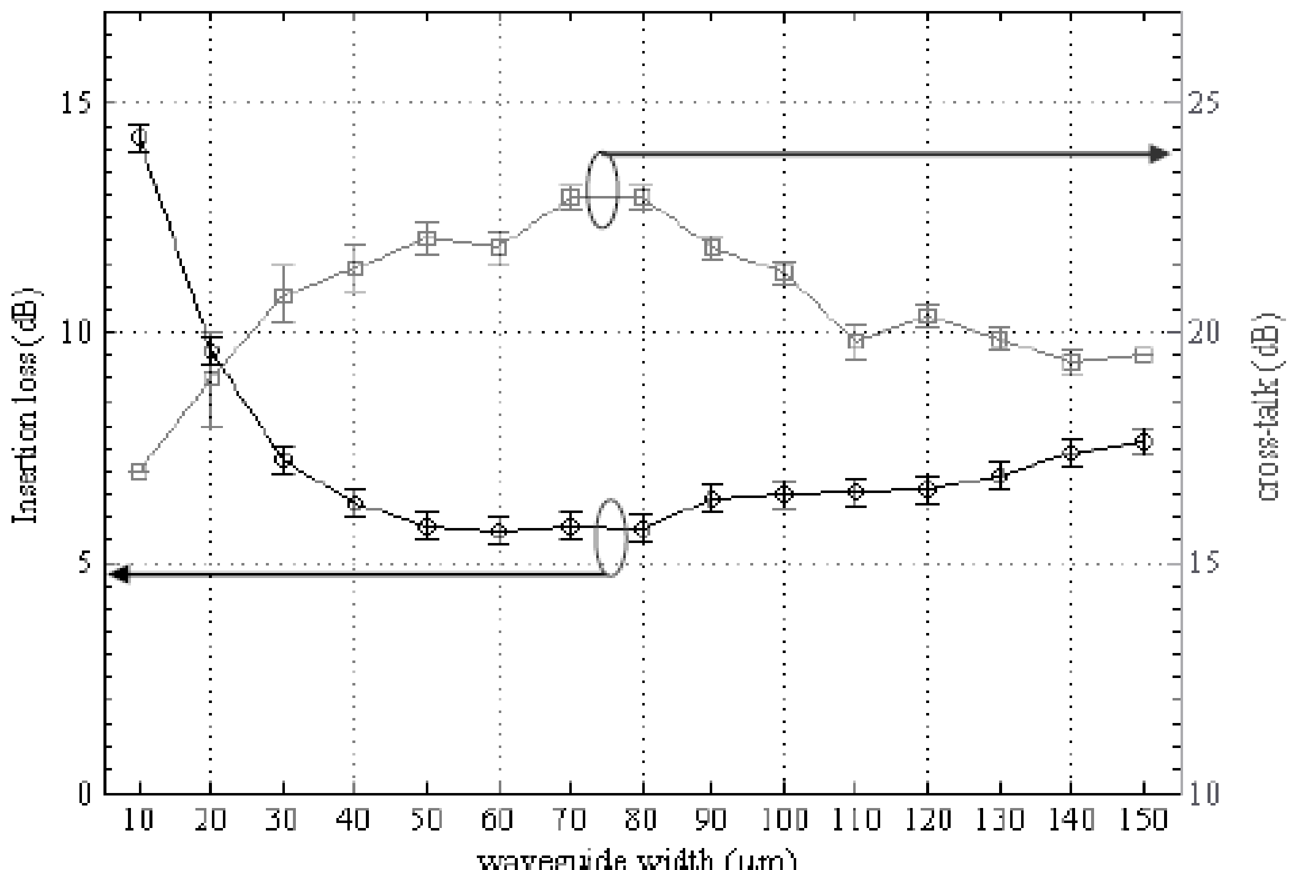
- Light launched from VCSEL imaged via a GRIN lens into 50 µm x 150 µm waveguide
- Photolithographically fabricated chirped with waveguide array
- Photomosaic with increased camera gain towards left

Surface roughness



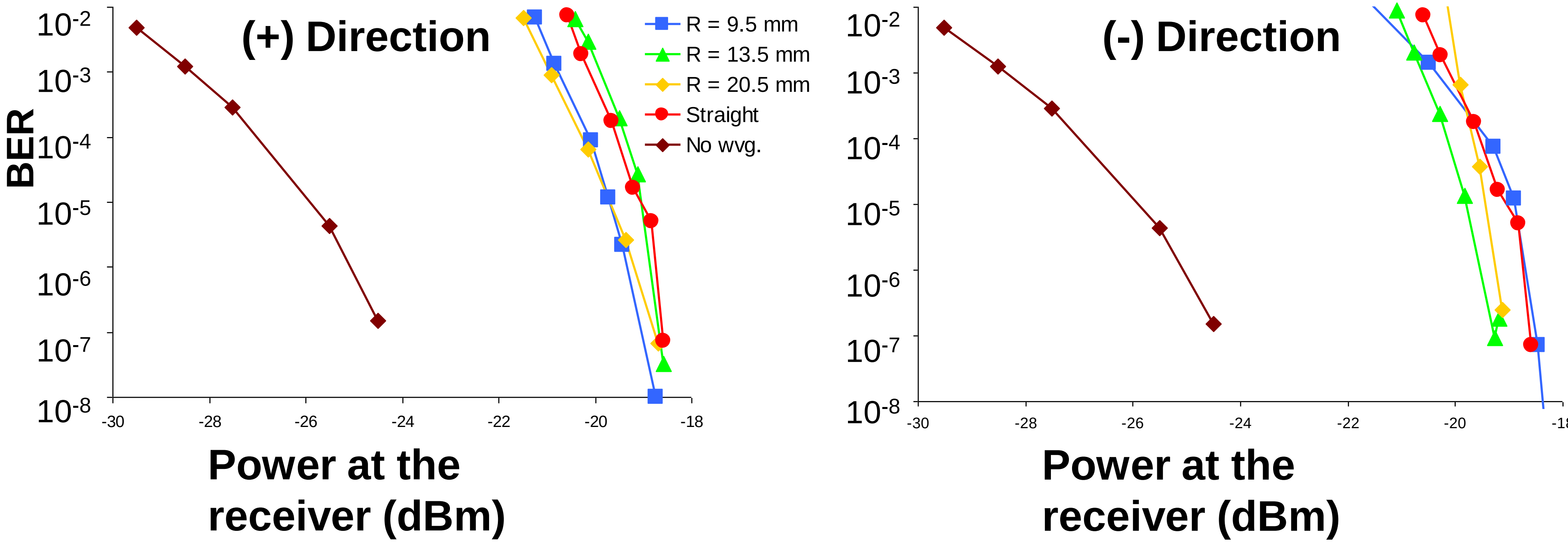
- RMS side wall roughness: 9 nm to 74 nm
- RMS polished end surface roughness: 26 nm to 192 nm.

Design rules for waveguide width depending on insertion loss and cross-talk

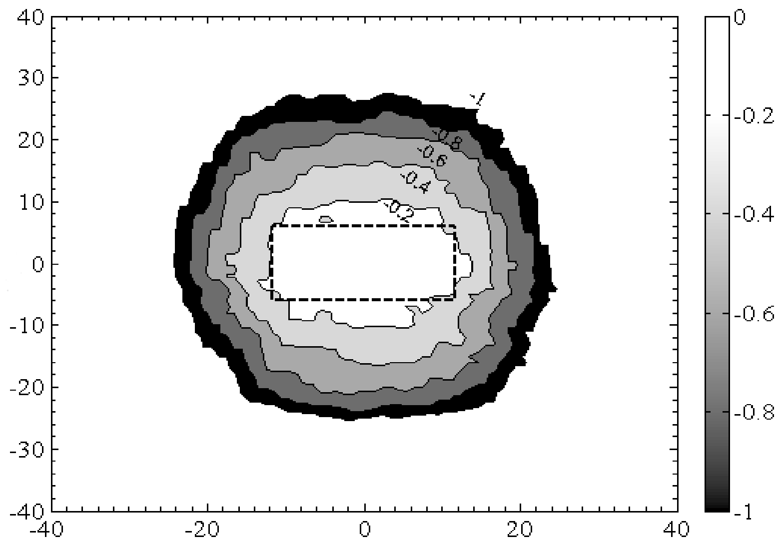


6~7dB for a 70 µm width waveguide

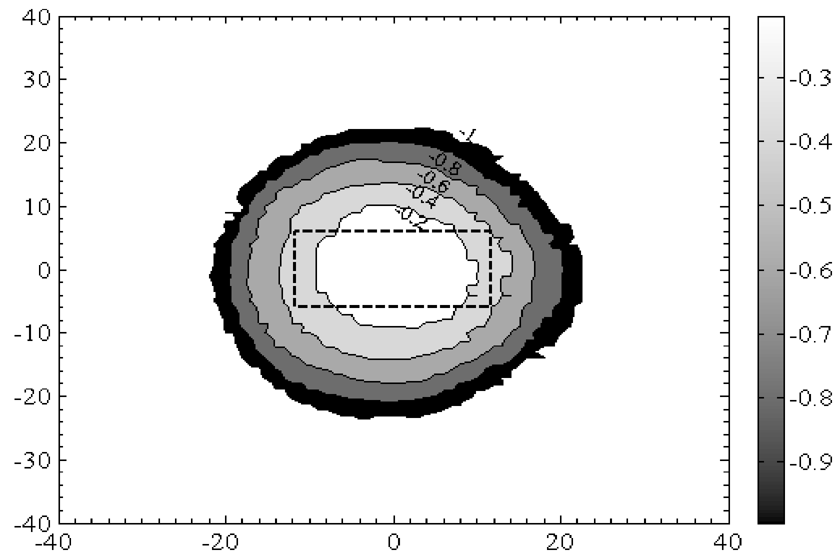
Bit error rate for laterally misaligned 1550 nm 2.5 Gb/s DFB laser



Contour map of VCSEL and PD misalignment



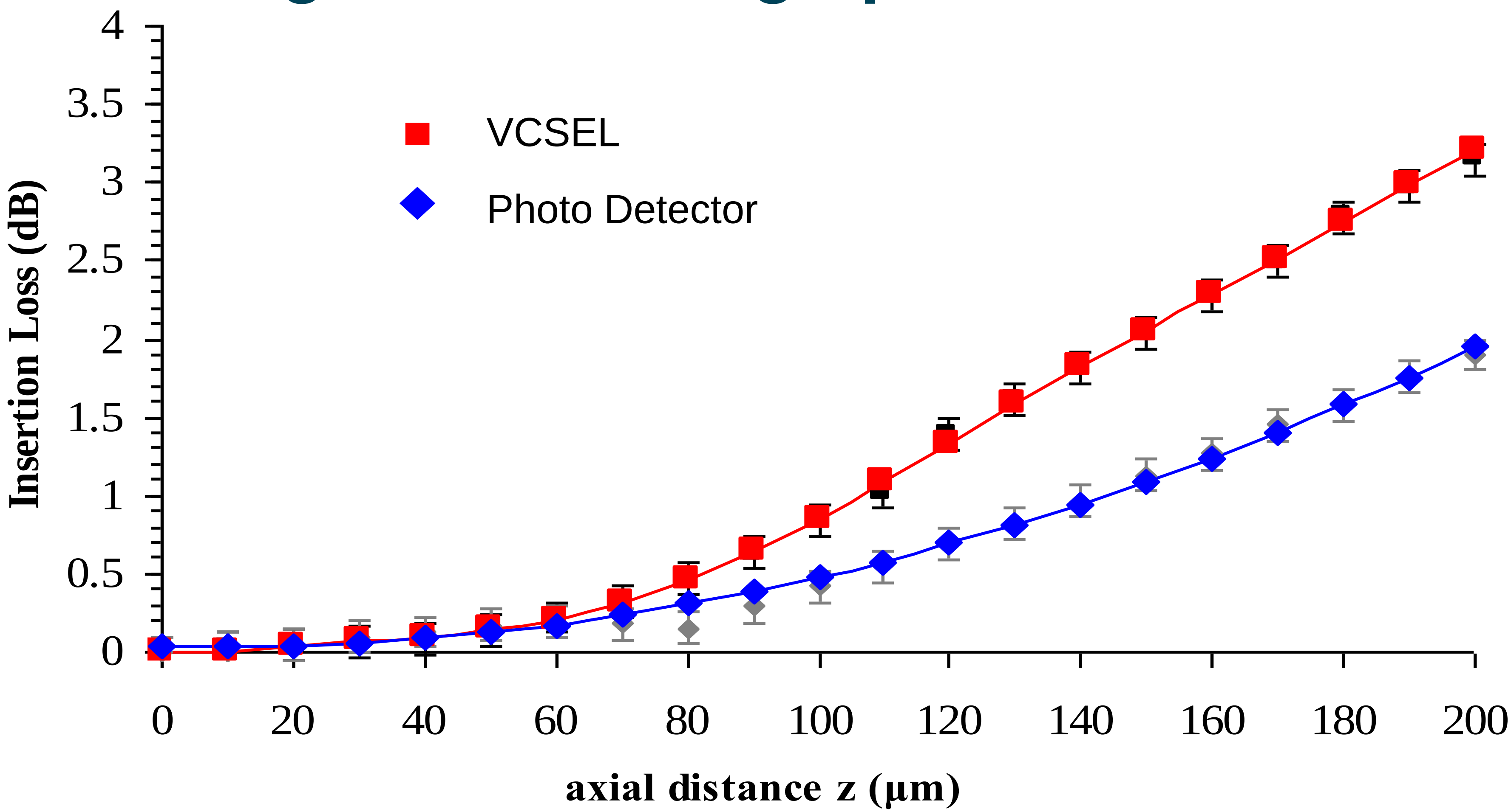
(a) Contour map of relative insertion loss compared to the maximum coupling position for VCSEL misalignment at z = 0.



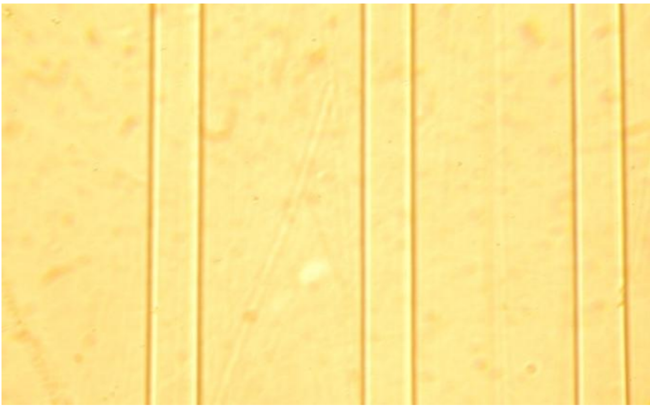
(b) Same for PD misalignment at *z* = 0. Resolution step was *Δx* = *Δy* = 1 µm.

- Dashed rectangle is the expected relative insertion loss according to the calculated misalignments along *x* and *y*.
- The minimum insertion loss was 4.4 dB, corresponded to x = 0, y = 0, z = 0

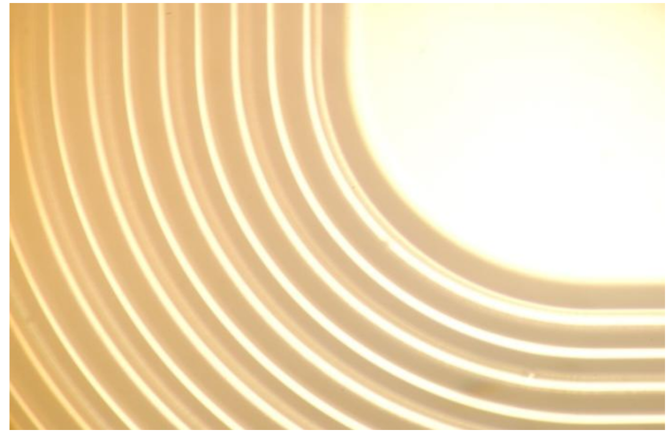
Coupling Loss for VCSEL and PD for misalignments along optic axis



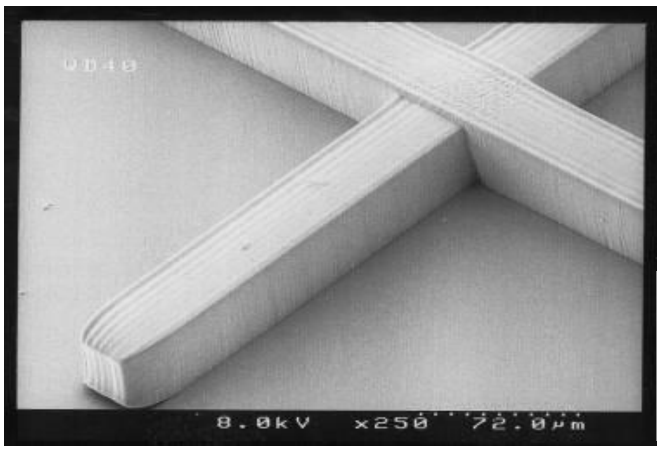
Fabrication Techniques and Waveguides Samples



Straight waveguides – Optical InterLinks



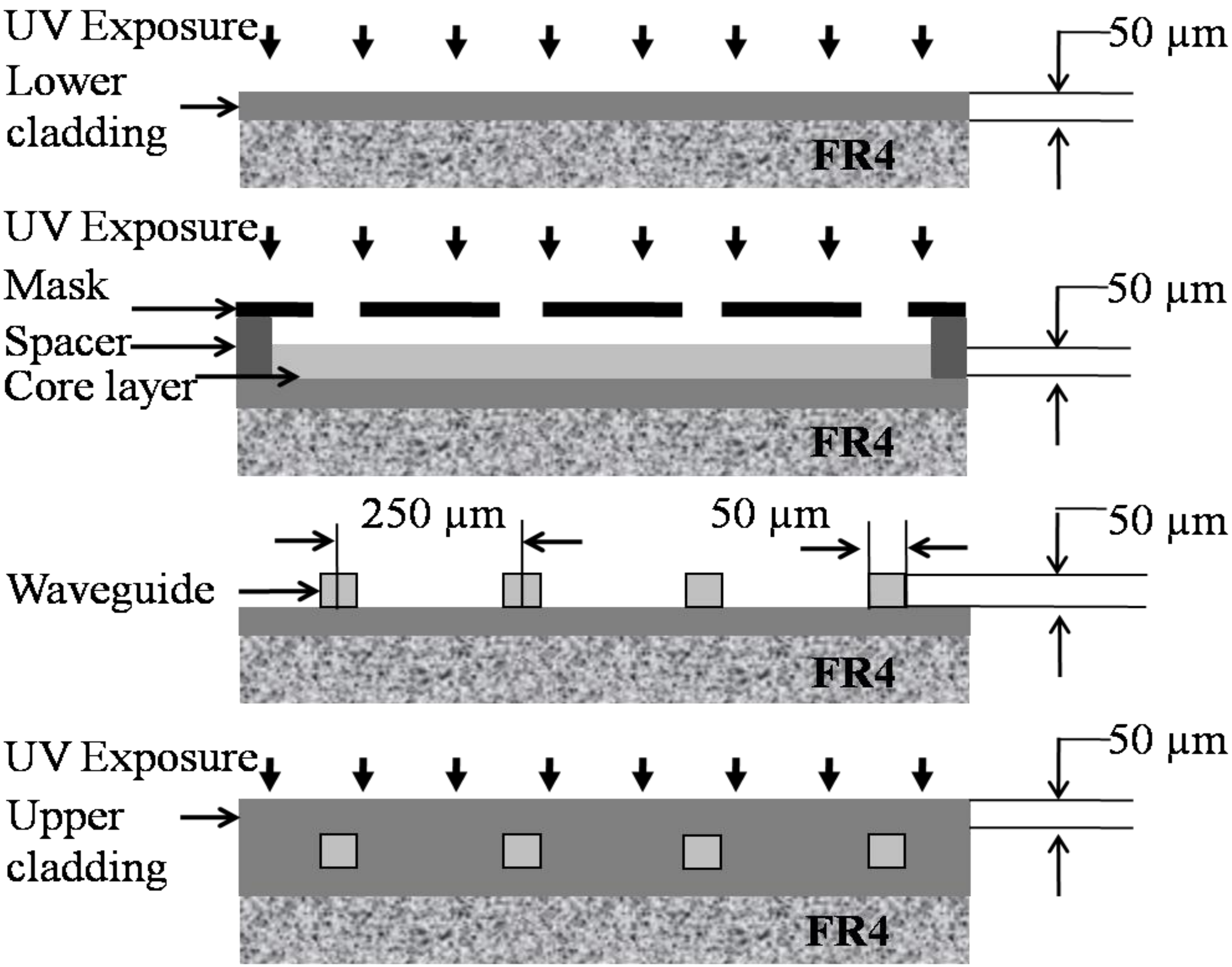
90° Crossings – Dow Corning



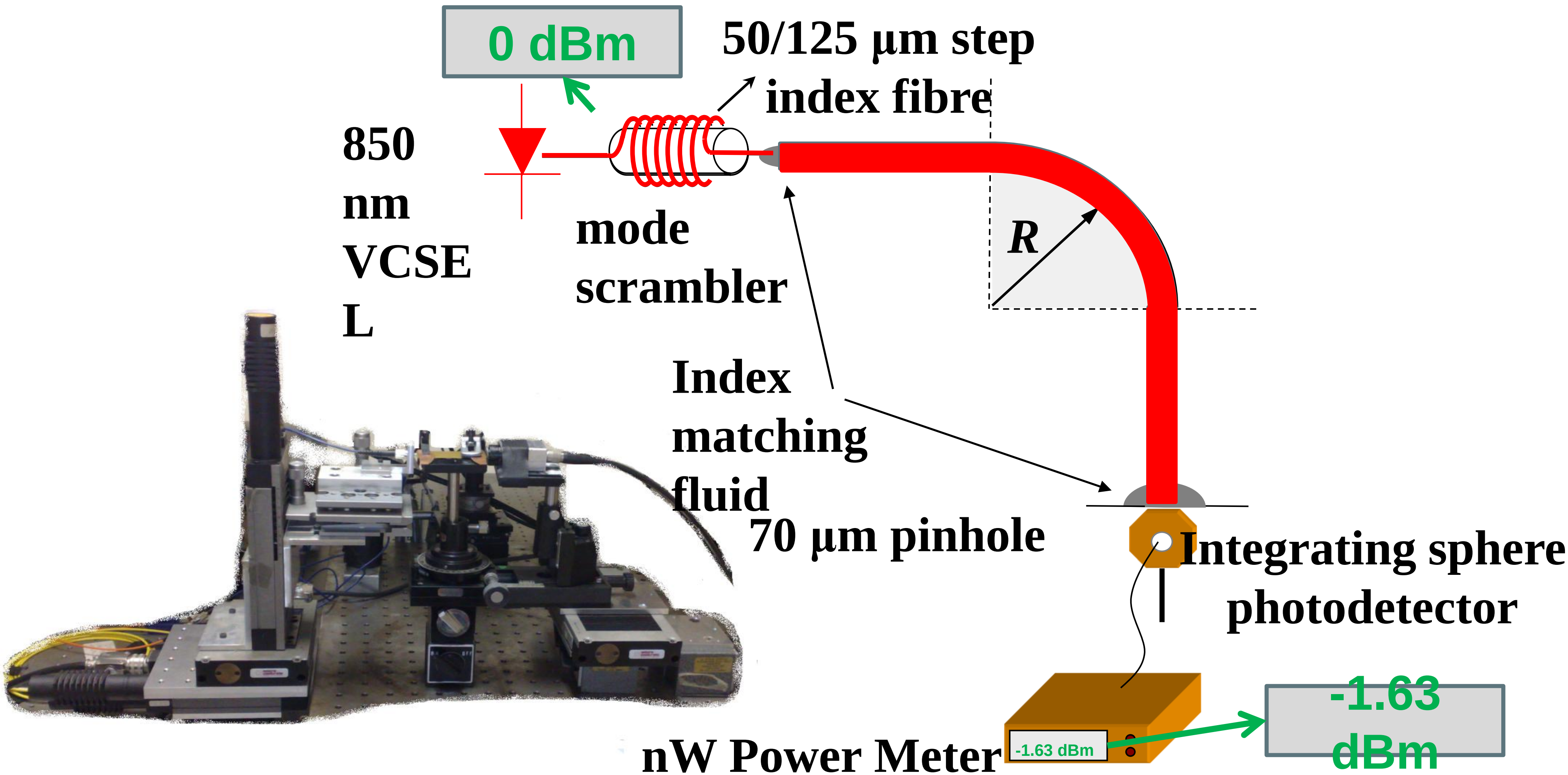
90° Crossings – Heriot Watt University

50° Crossings – Exxelis

Photolithographic Fabrication of Waveguides



Optical Loss Measurement



VCSEL Array for Crosstalk Measurement

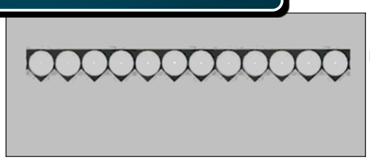
PIN Array

Source: Microsemi Corporation

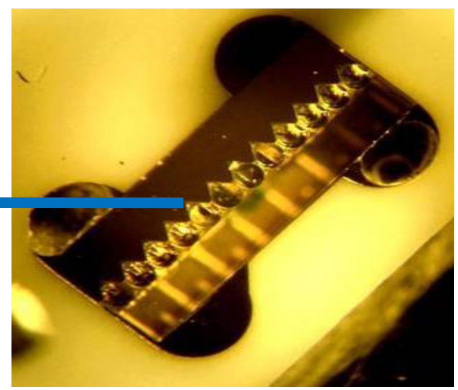
VCSEL Array

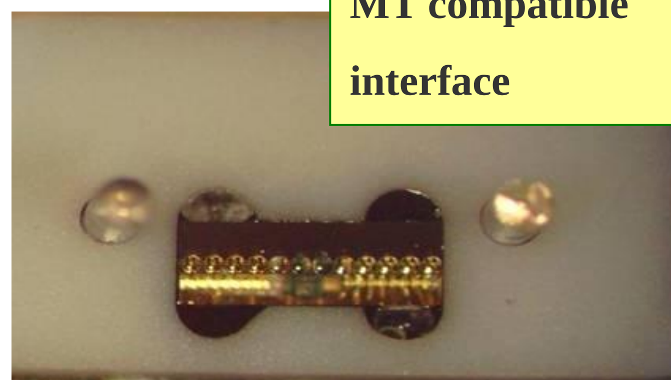
Source: ULM Photonics GmbH

GRIN Lens Array



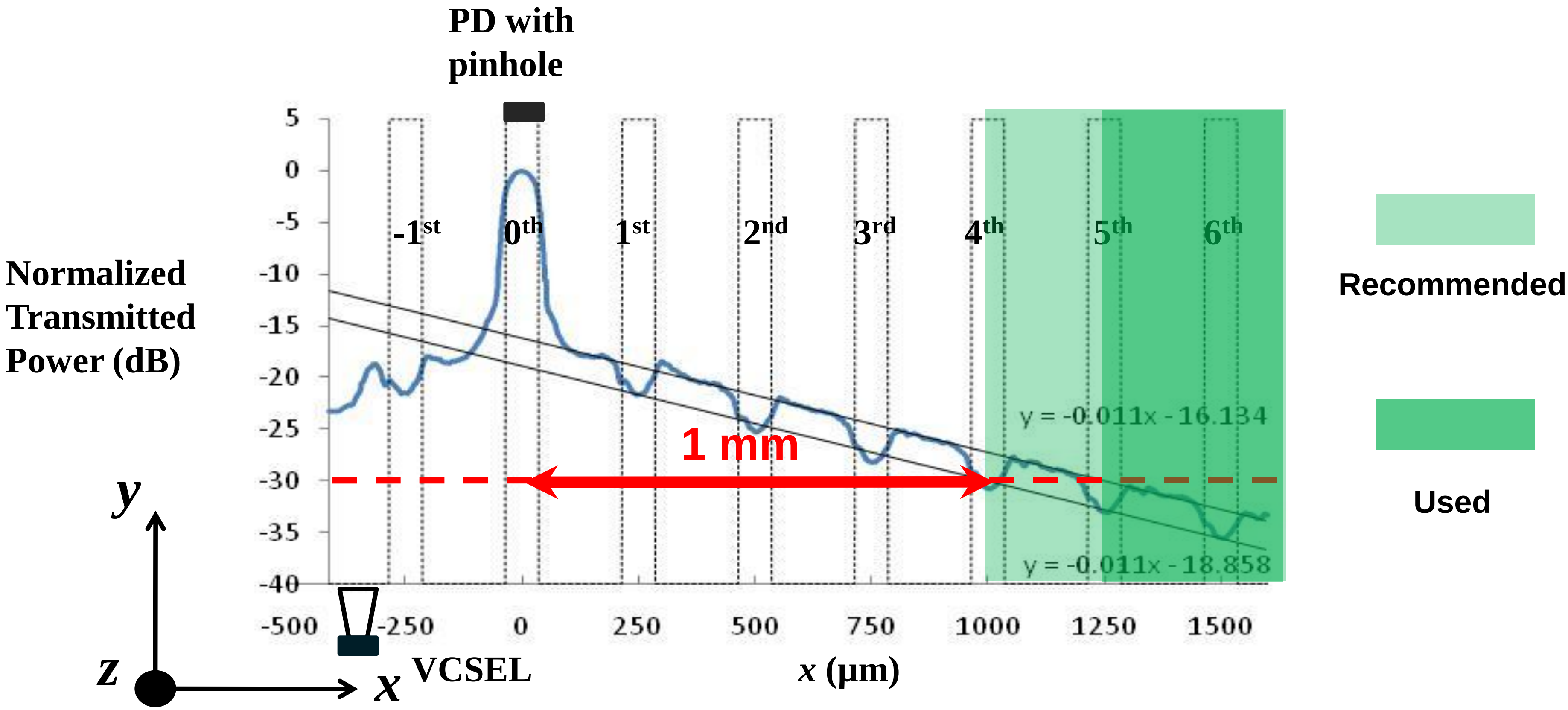
Source: GRINTech GmbH





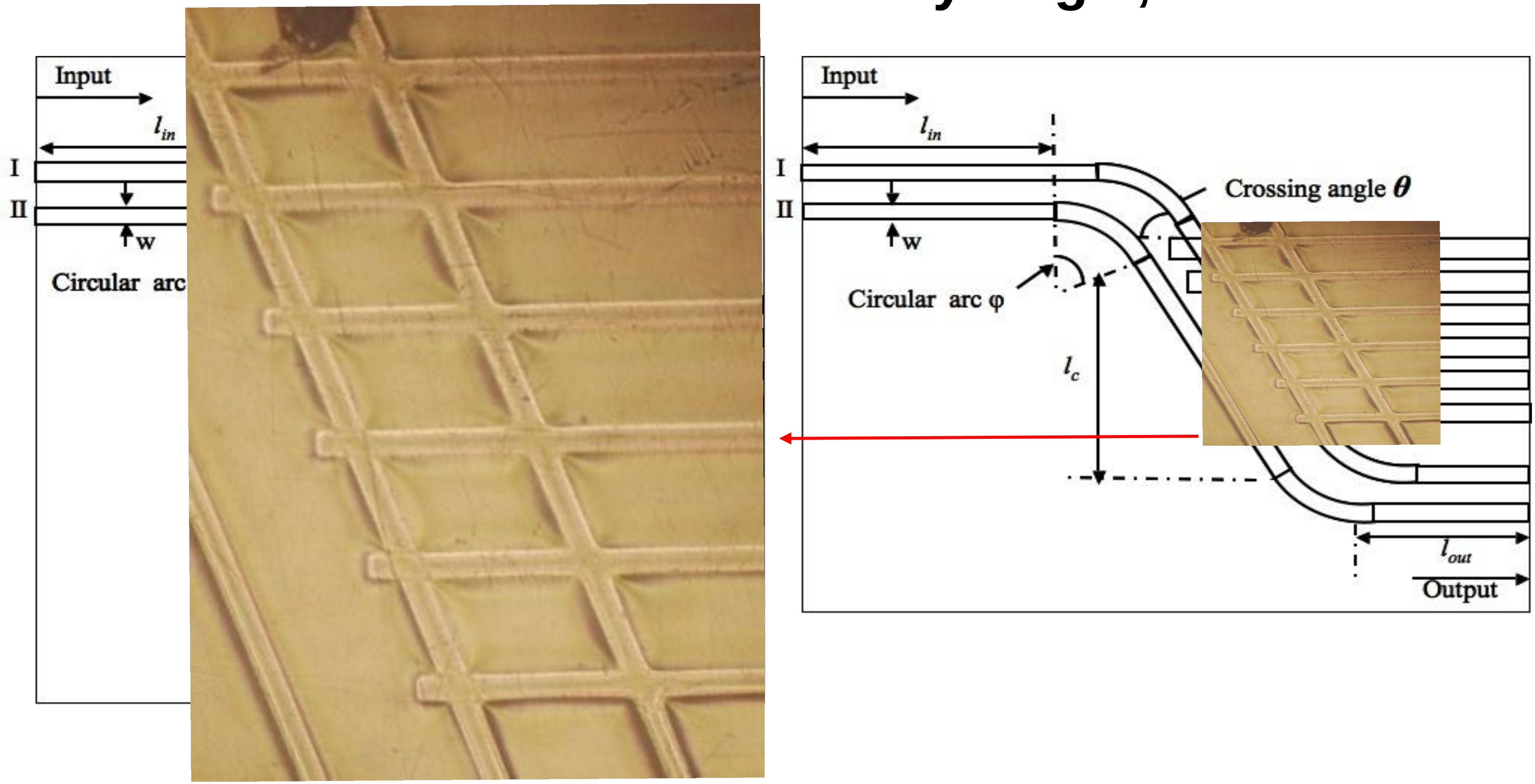
MT compatible interface

Design Rules for Inter-waveguide Cross Talk

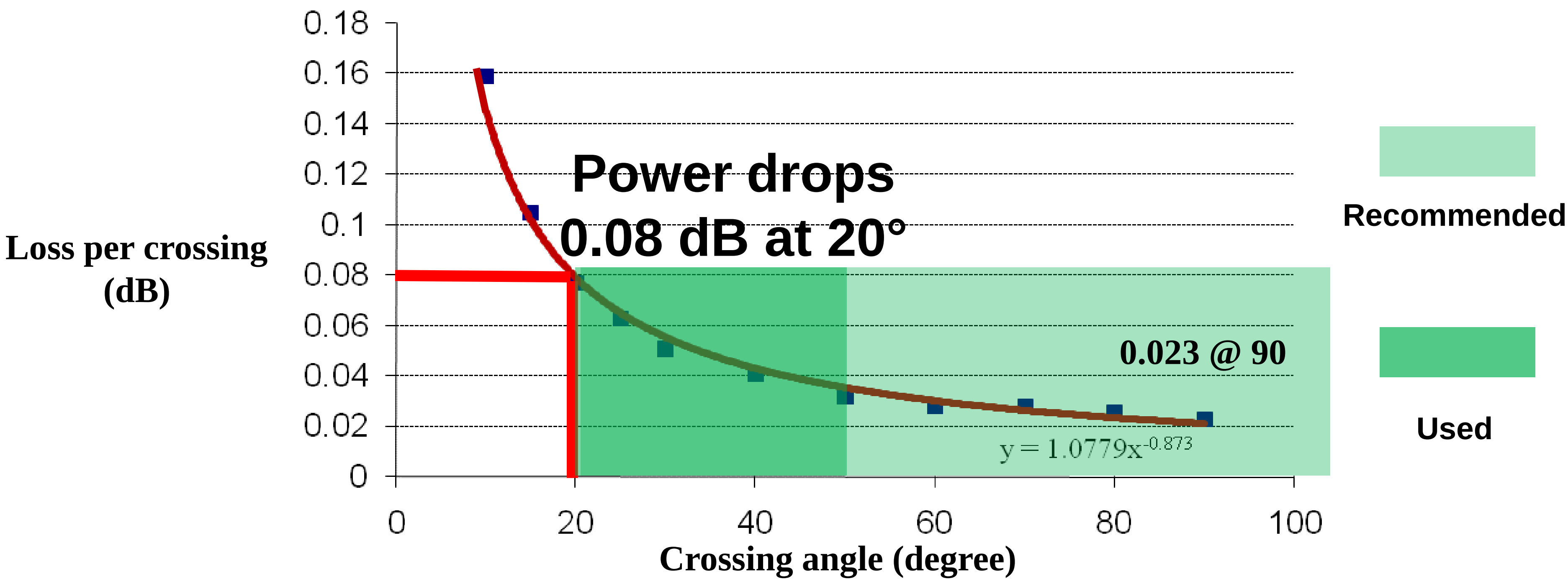


- 70 µm × 70 µm waveguide cross sections and 10 cm long
- In the cladding power drops linearly at a rate of 0.011 dB/µm
- Crosstalk reduced to -30 dB for waveguides 1 mm apart

Schematic Diagram Of Waveguide Crossings at 90° and at an Arbitrary Angle, θ

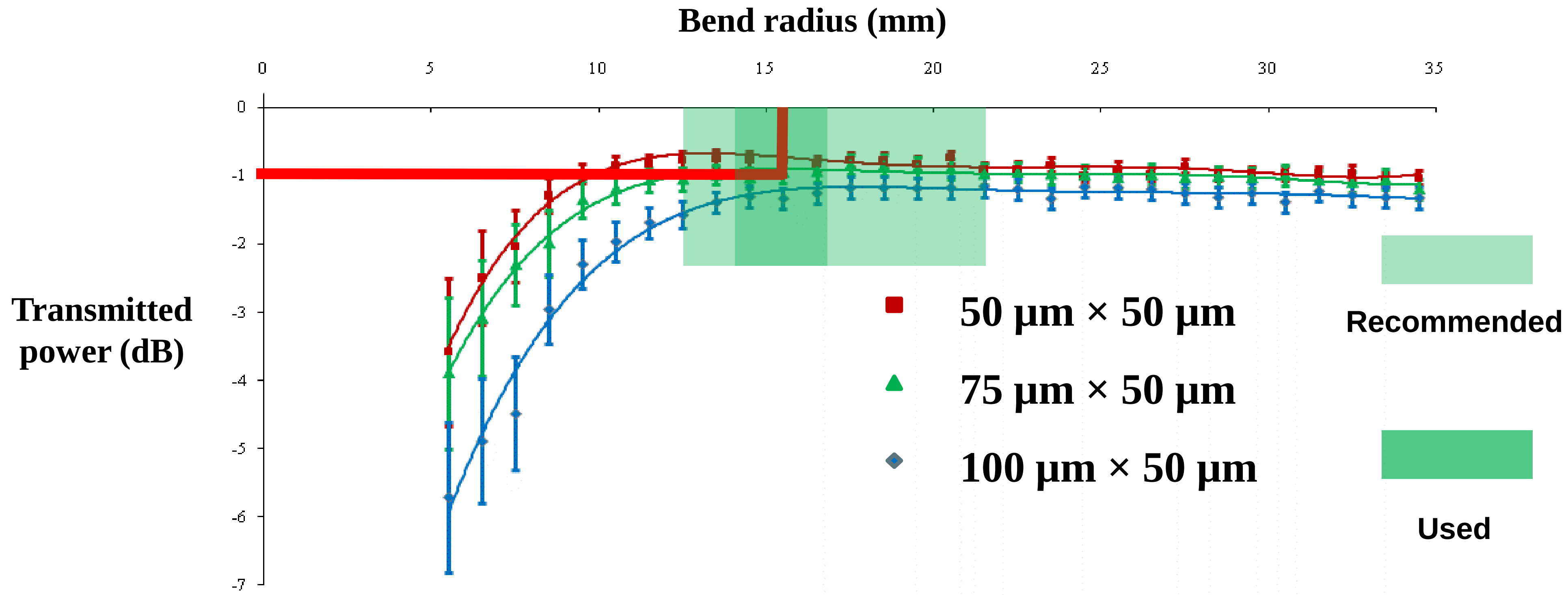


Design Rules for Arbitrary Angle Crossings



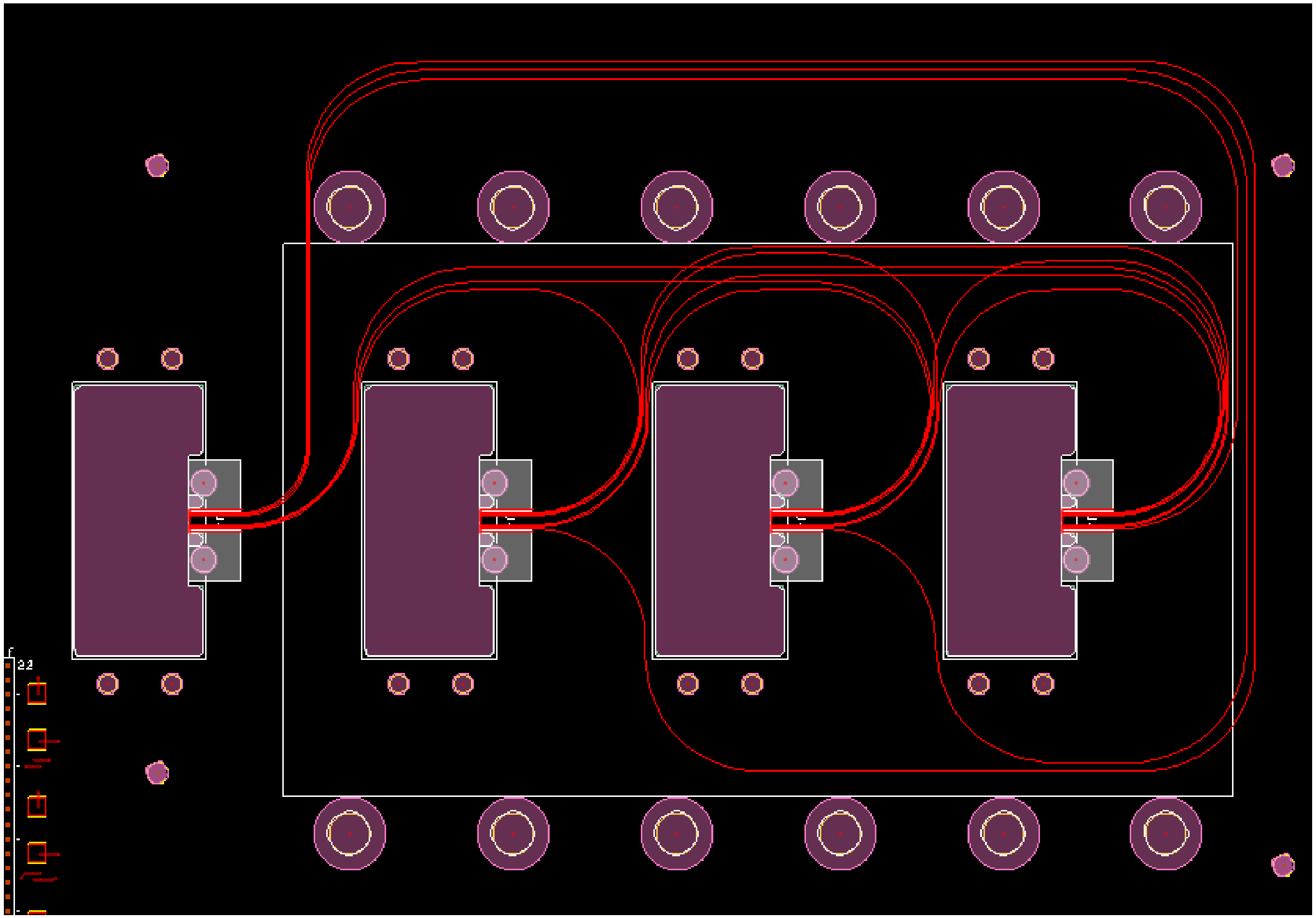
- Loss of 0.023 dB per 90° crossing consistent with other reports
- The output power dropped by 0.5% at each 90° crossing
- The loss per crossing (L_c) depends on crossing angle (θ), $L_c = 1.0779 \cdot \theta^{-0.8727}$

Loss of Waveguide Bends



Width (µm)	Optimum Radius (mm)	Maximum Power (dB)
50	13.5	-0.74
75	15.3	-0.91
100	17.7	-1.18

System Demonstrator

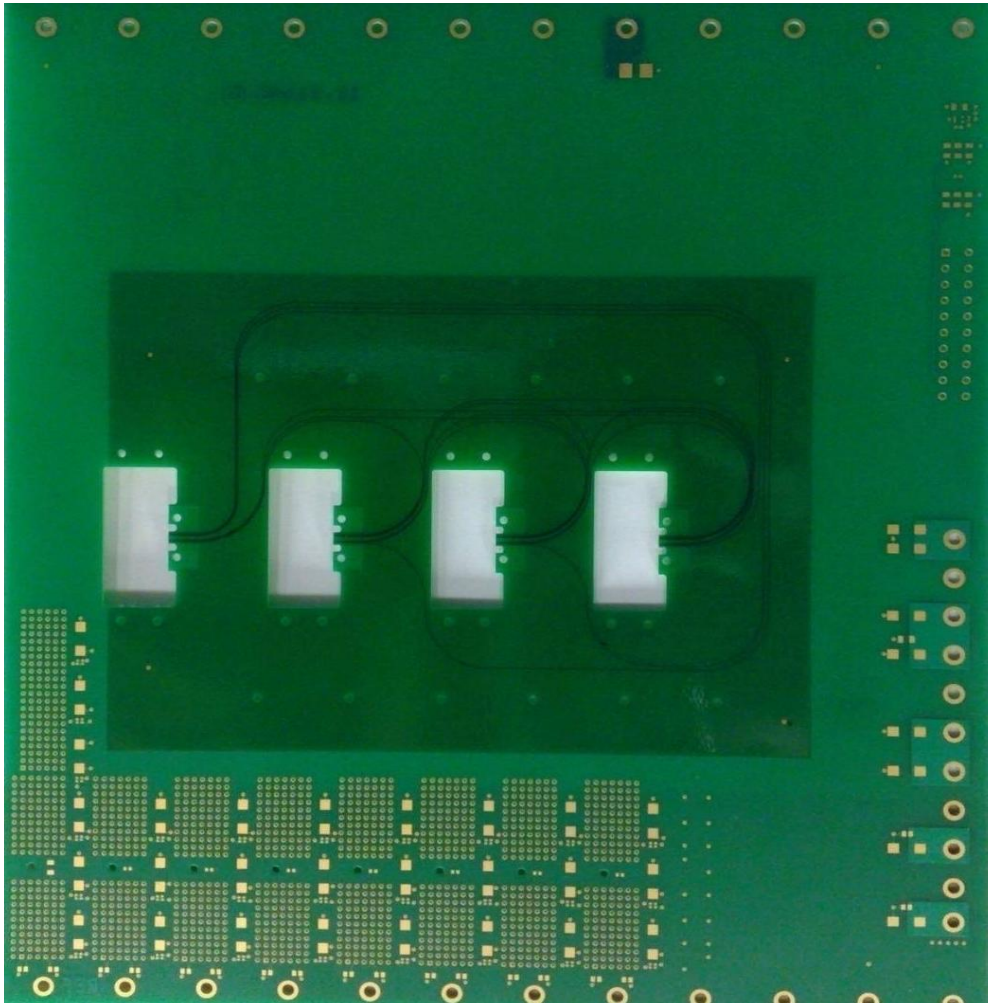


Fully connected waveguide layout using design rules

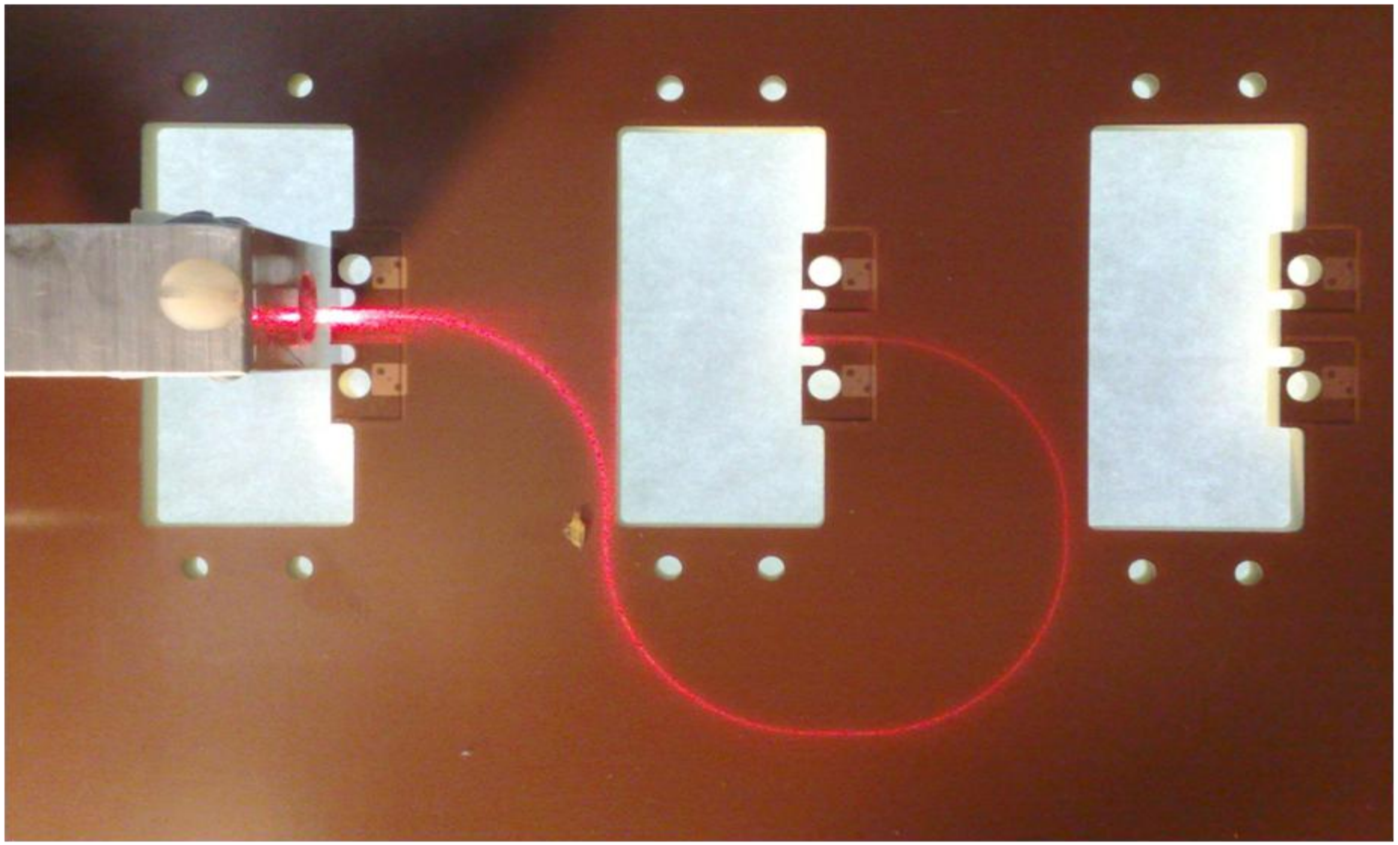
Power Budget

<table>
<tr><td>Input power (dBm/mW)</td><td colspan="30">-2.07 / 0.62</td></tr>
<tr><td></td><td colspan="30">Bend 90°</td></tr>
<tr><td>Radii (mm)</td><td colspan="5">15.000</td><td colspan="5">15.250</td><td colspan="5">15.500</td><td colspan="5">15.725</td><td colspan="5">16.000</td><td colspan="5">16.250</td></tr>
<tr><td>Loss per bend (dB)</td><td colspan="5">0.94</td><td colspan="5">0.91</td><td colspan="5">0.94</td><td colspan="5">0.94</td><td colspan="5">0.95</td><td colspan="5">0.95</td></tr>
<tr><td></td><td colspan="30">Crossings</td></tr>
<tr><td>Crossing angles (°)</td><td colspan="6">22.27</td><td colspan="6">29.45</td><td colspan="6">36.23</td><td colspan="6">42.10</td><td colspan="6">47.36</td></tr>
<tr><td>Loss per crossing (dB)</td><td colspan="6">0.078</td><td colspan="6">0.056</td><td colspan="6">0.047</td><td colspan="6">0.041</td><td colspan="6">0.037</td></tr>
<tr><td>Min. detectable power (dBm)</td><td colspan="30">-15 / 0.03</td></tr>
<tr><td>Min. power no bit error rate</td><td colspan="30">-12 / 0.06</td></tr>
</table>

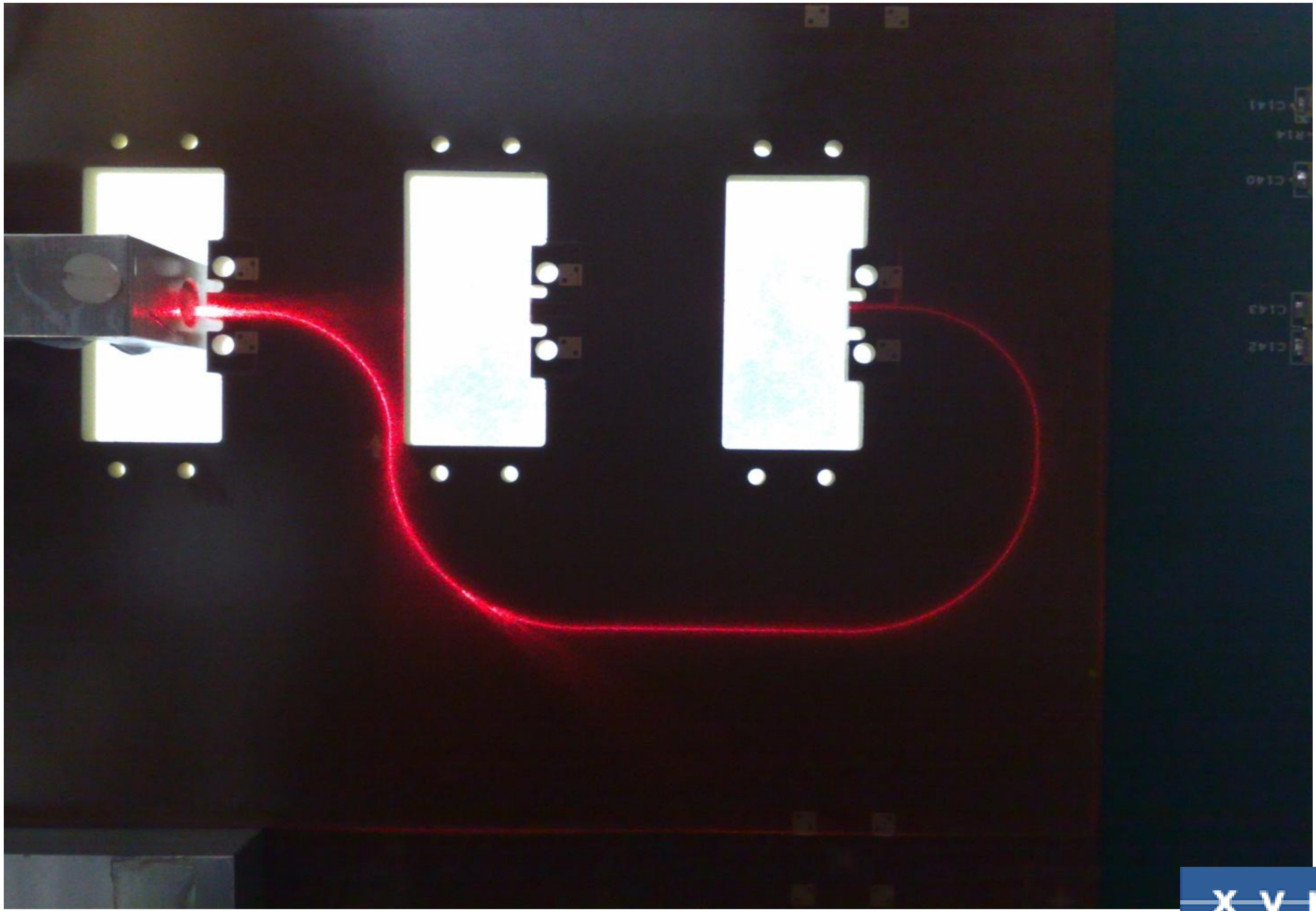
Demonstrator Dummy Board



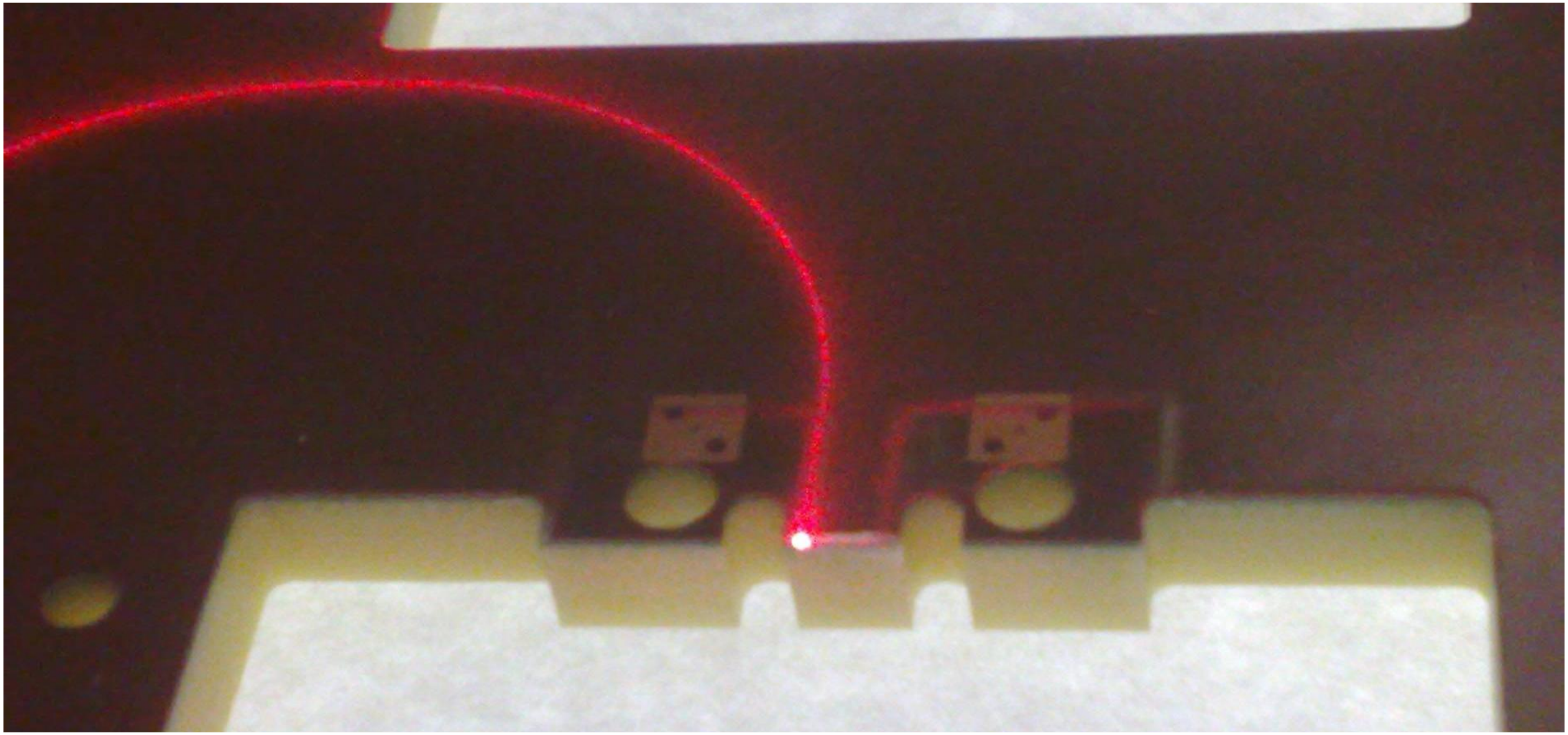
The Shortest Waveguide Illuminated by Red Laser



Waveguide with 2 Crossings Connected 1st to 3rd Linecard Interconnect



Output Facet of the Waveguide Interconnection



Data storage protocol and form factor trends

Disk drive form factors decreasing

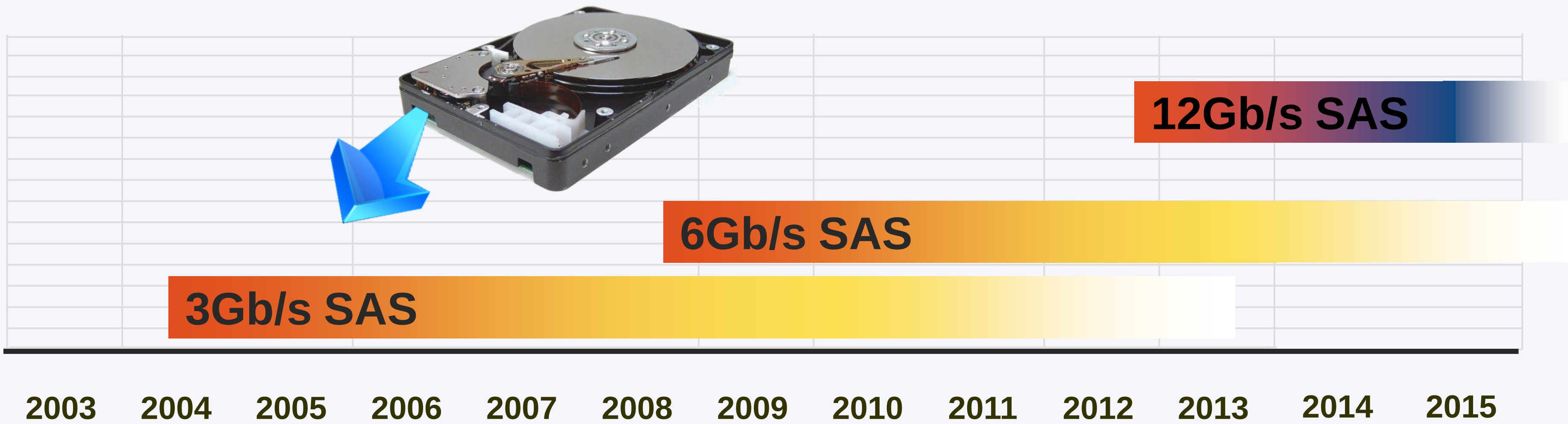
3.5” HDD

2.5” HDD

2.5” SSD

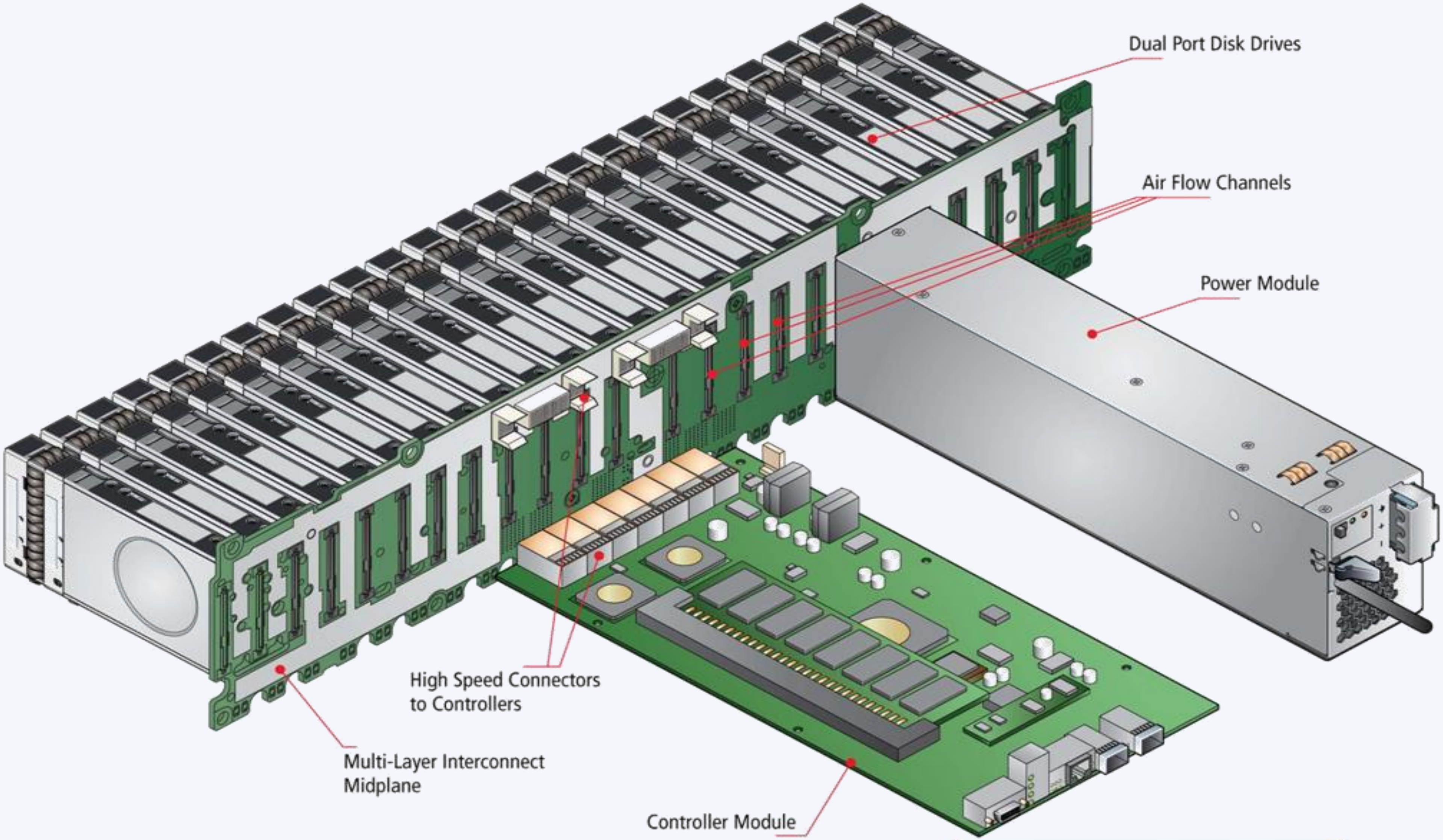
1.8” SSD

Data storage interconnect speeds increasing



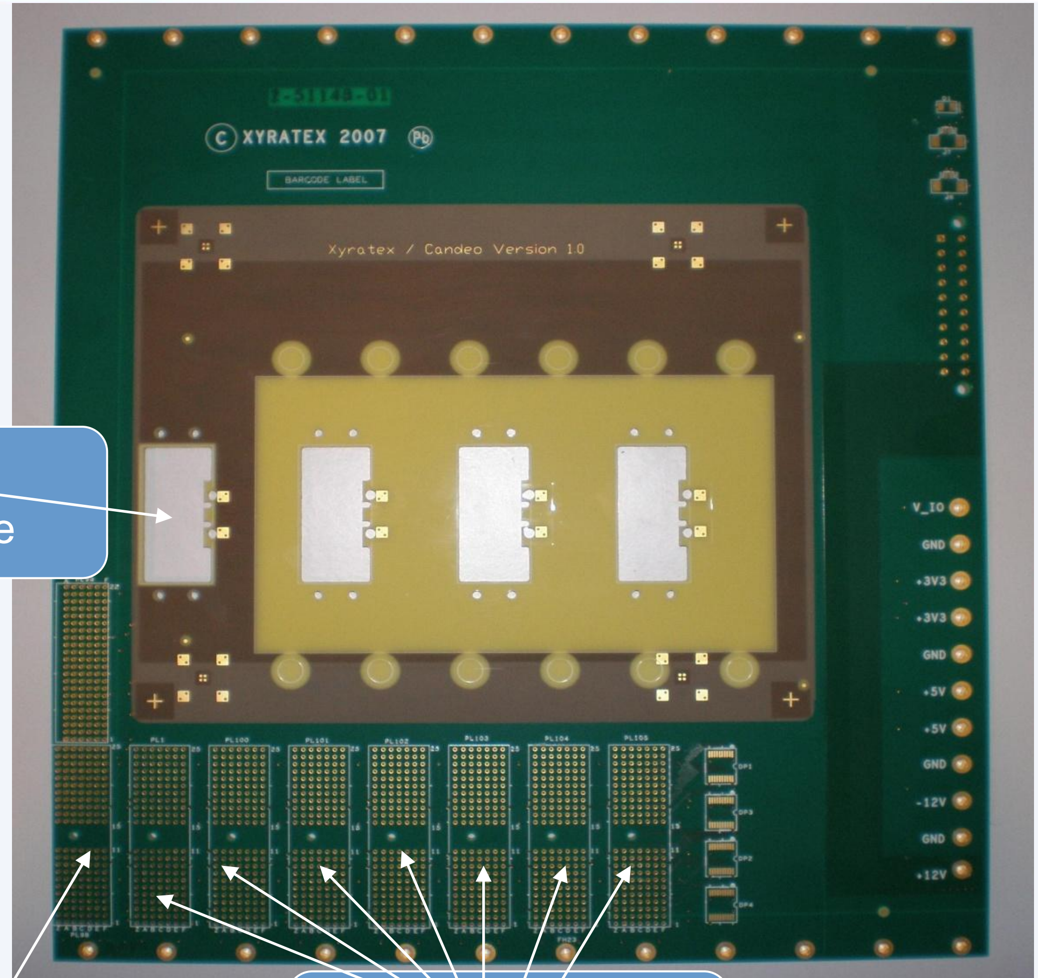
Source: SCSI Trade Association Sep 08 www.scsita.org

Design and performance constraints



Hybrid Electro-Optical Printed Circuit Board

- ❑ Standard Compact PCI backplane architecture
- ❑ 12 electrical layers for power and C-PCI signal bus and peripheral connections
- ❑ Electrical C-PCI connector slots for SBC and line cards
- ❑ 1 polymeric optical layer for high speed 10 GbE traffic
- ❑ 4 optical connector sites
- ❑ Dedicated point-to-point optical waveguide architecture



ELECTRO-OPTICAL BACKPLANE

Hybrid Electro-Optical Printed Circuit Board

- ❑ Standard Compact PCI backplane architecture
- ❑ 12 electrical layers for power and C-PCI signal bus and peripheral connections
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- ❑ 1 polymeric optical layer for high speed 10 GbE traffic
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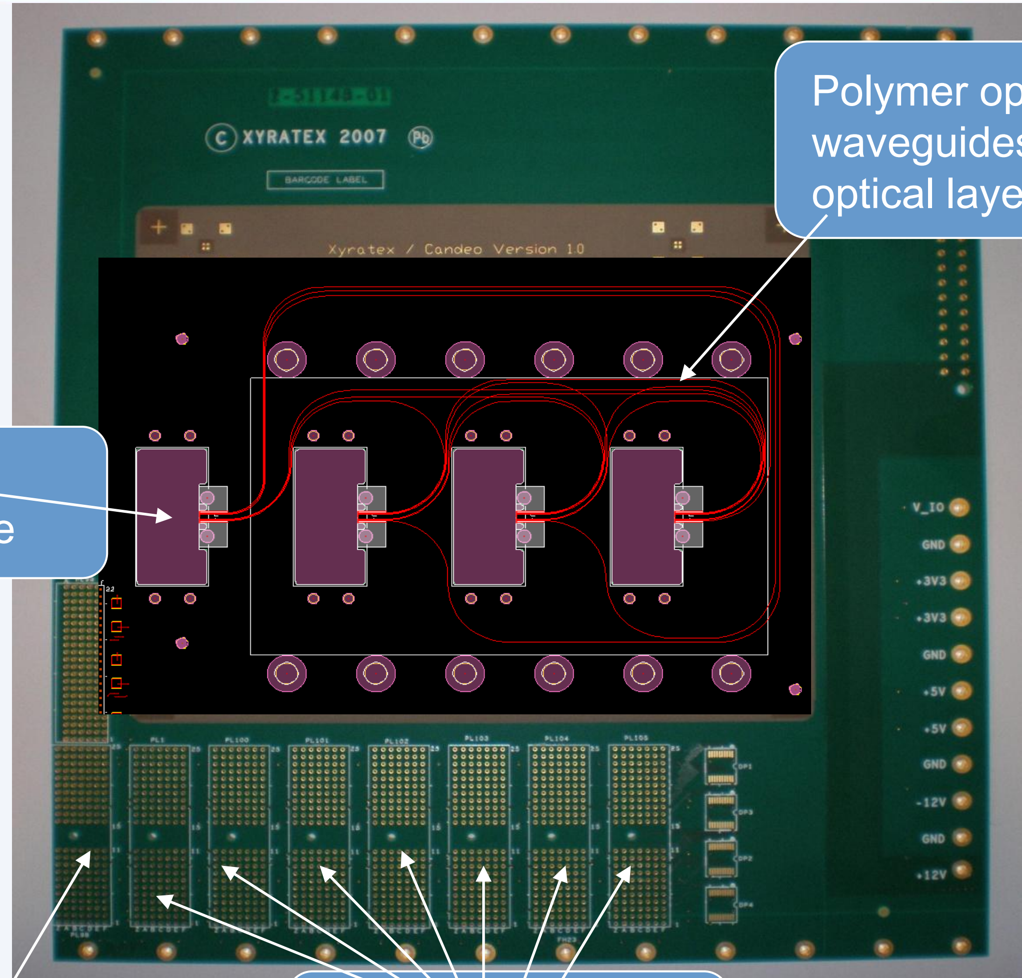
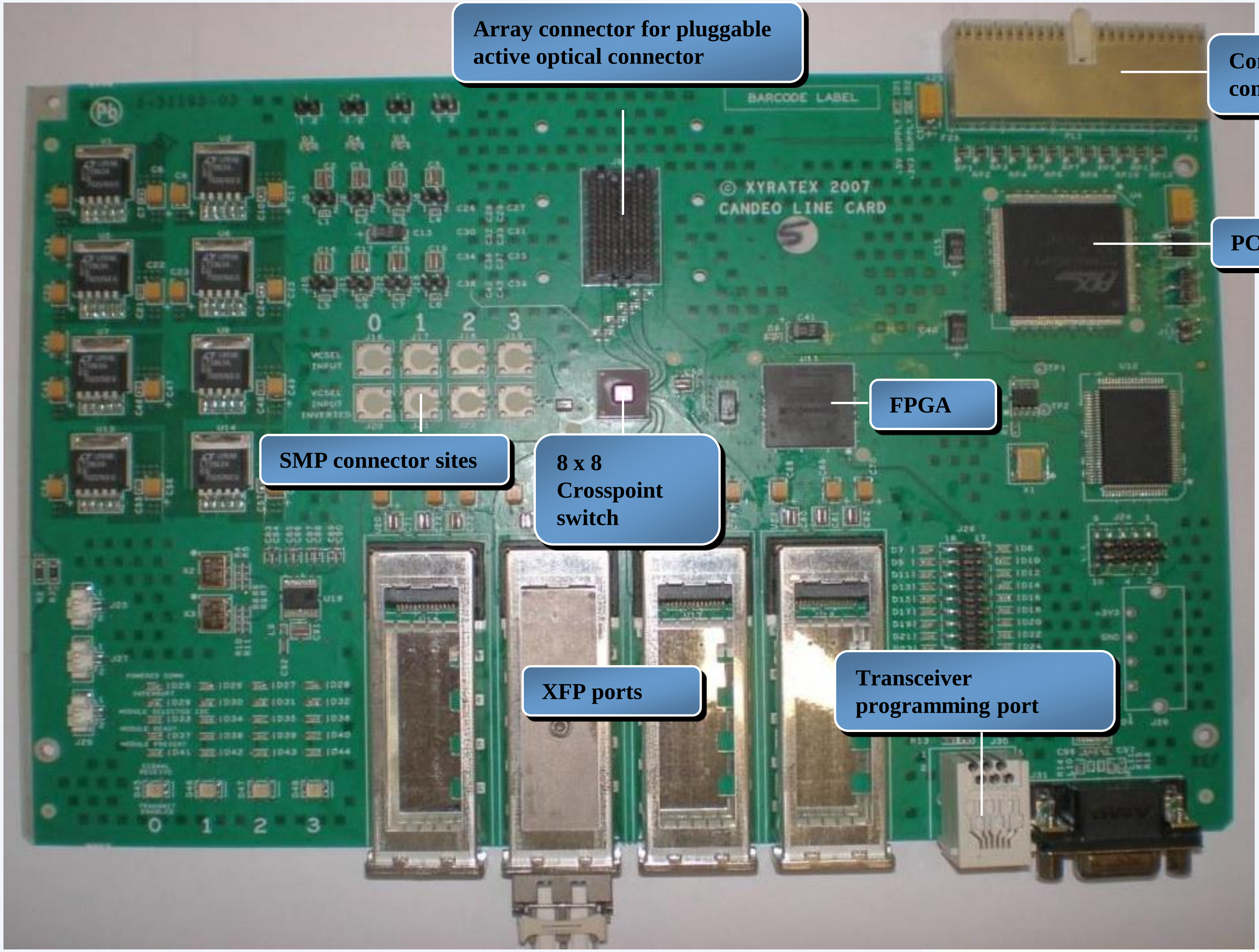
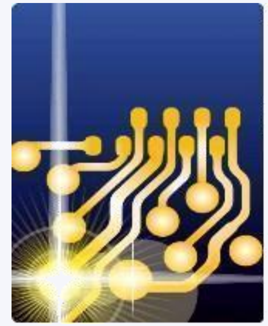
- ❑ Dedicated point-to-point optical waveguide architecture

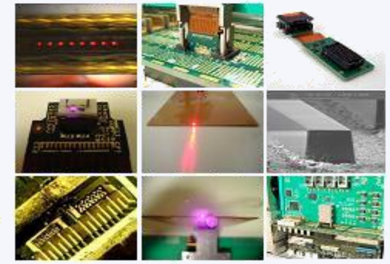


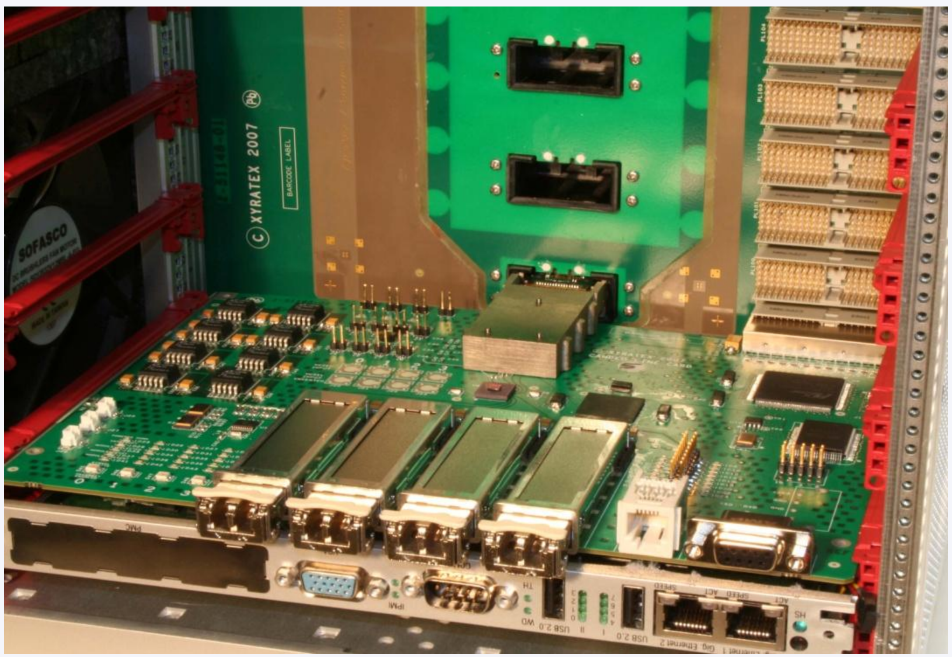
High Speed Switching Line Card

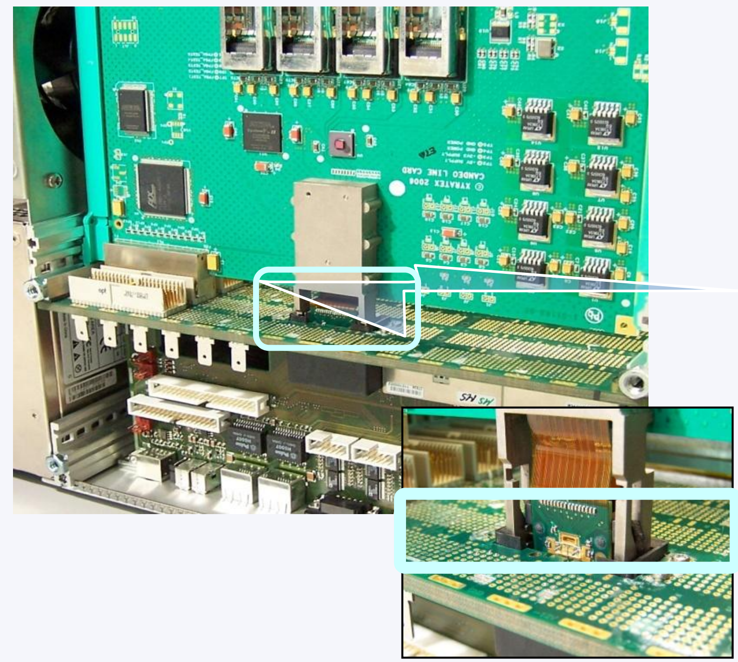


Active optical backplane connector

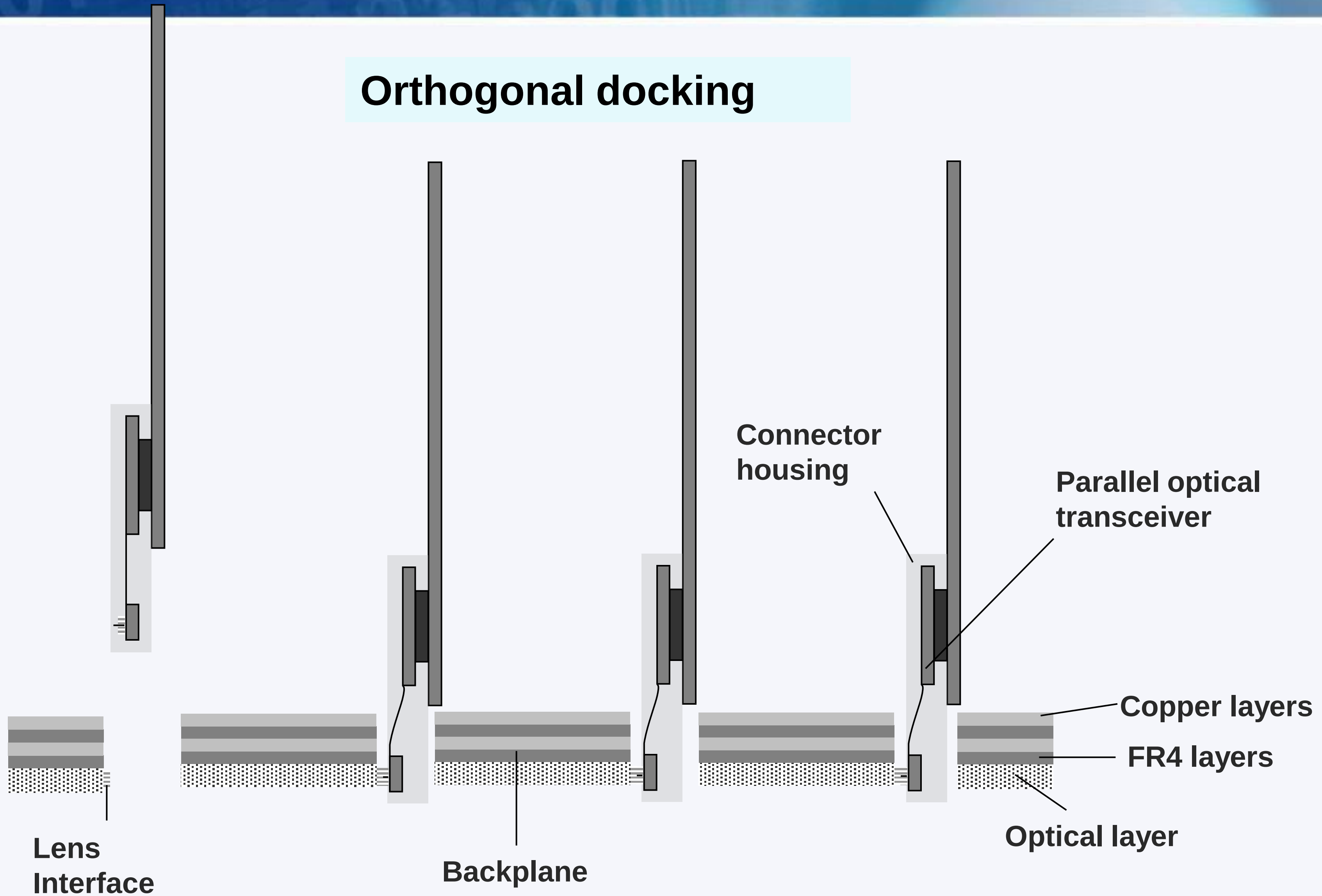






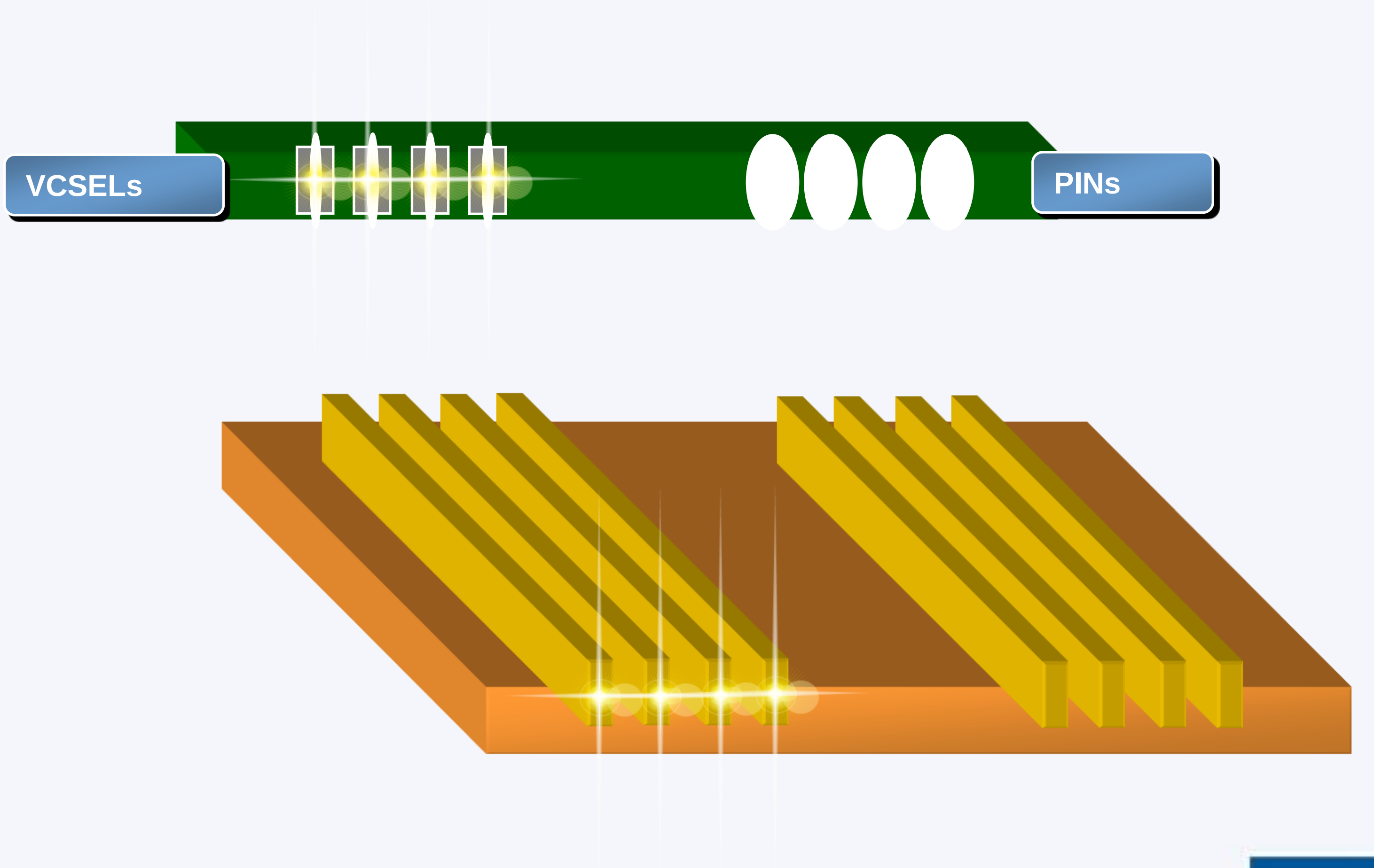


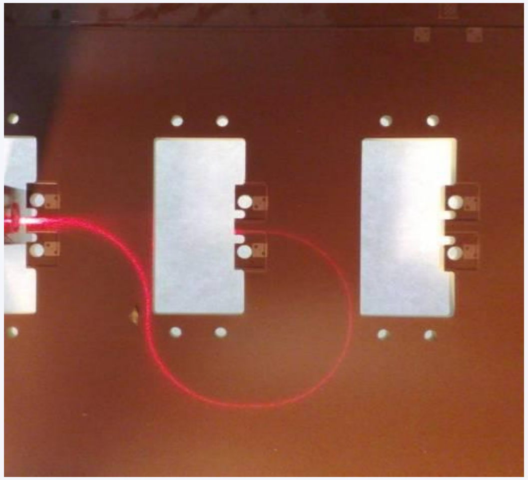
Optical backplane connection architecture



Optical backplane connection architecture

Butt-coupled in-plane connection

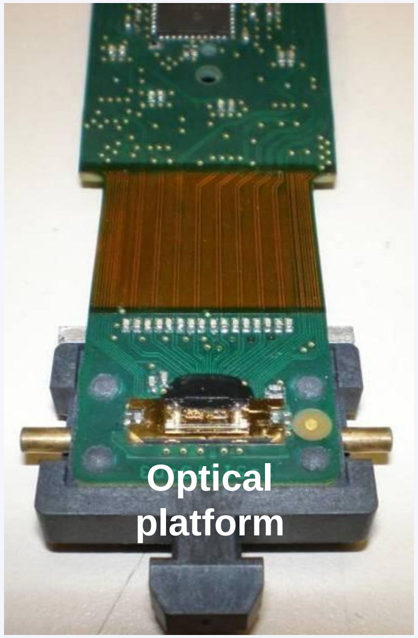


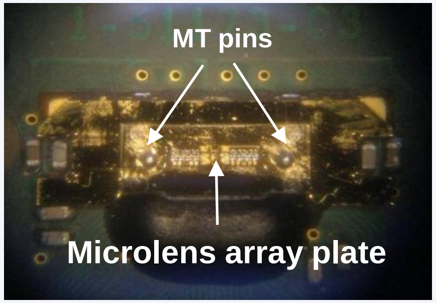


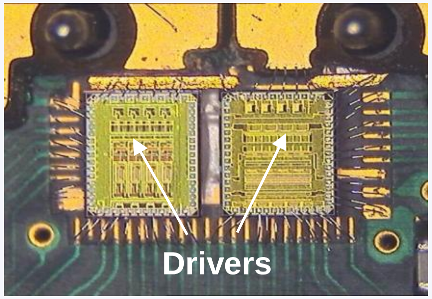
Single waveguide illuminated

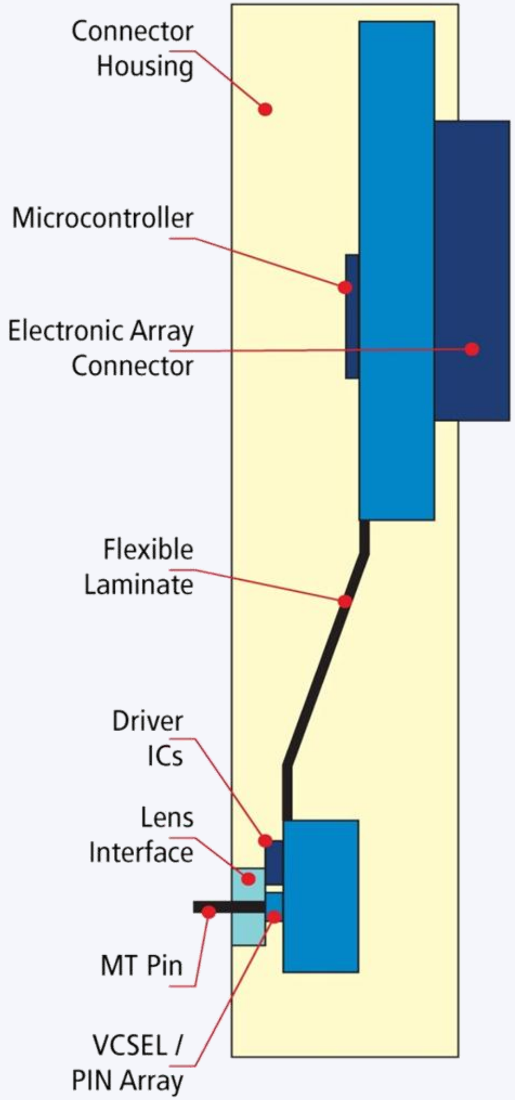
Parallel optical transceiver

- Mechanically flexible optical platform
- MT compatible optical interface
- Geometric microlens array
- Quad VCSEL driver and TIA/LA
- VCSEL / PIN arrays on pre-aligned frame





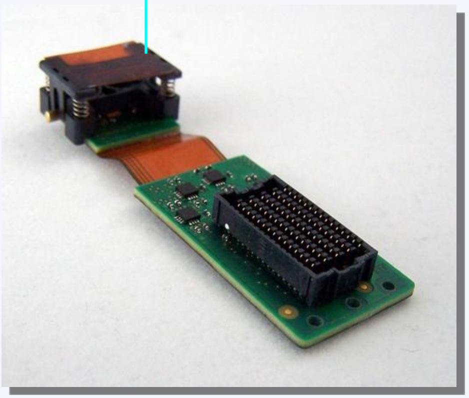


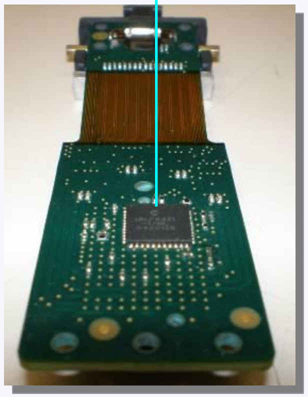


Active pluggable connector

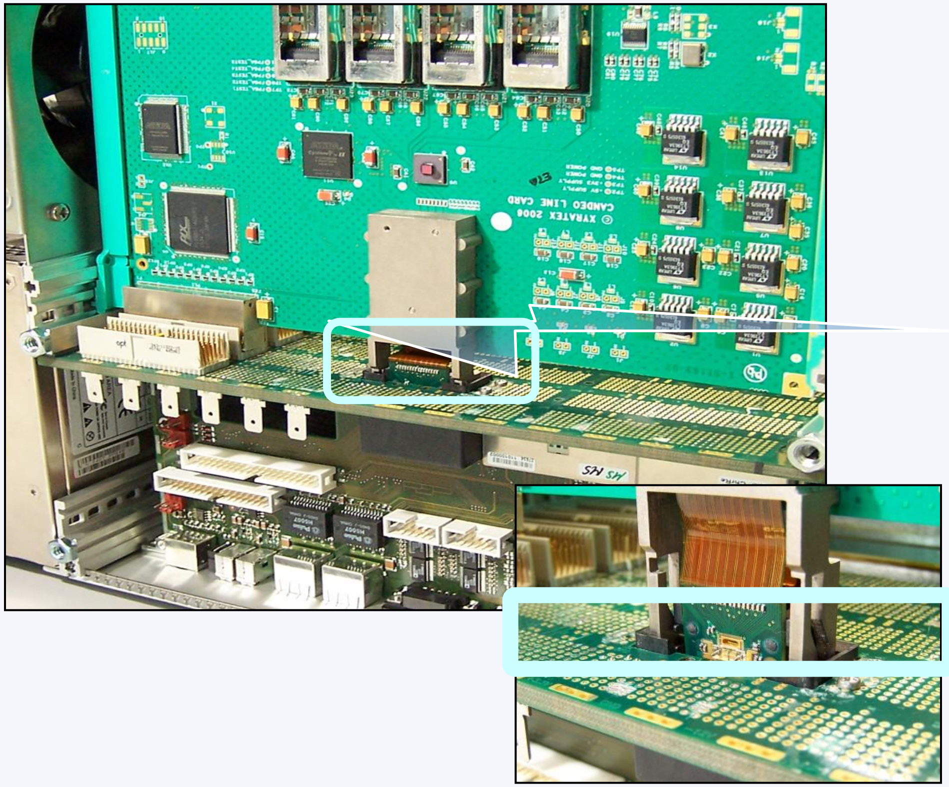
Parallel optical transceiver

Spring loaded platform **Microcontroller**



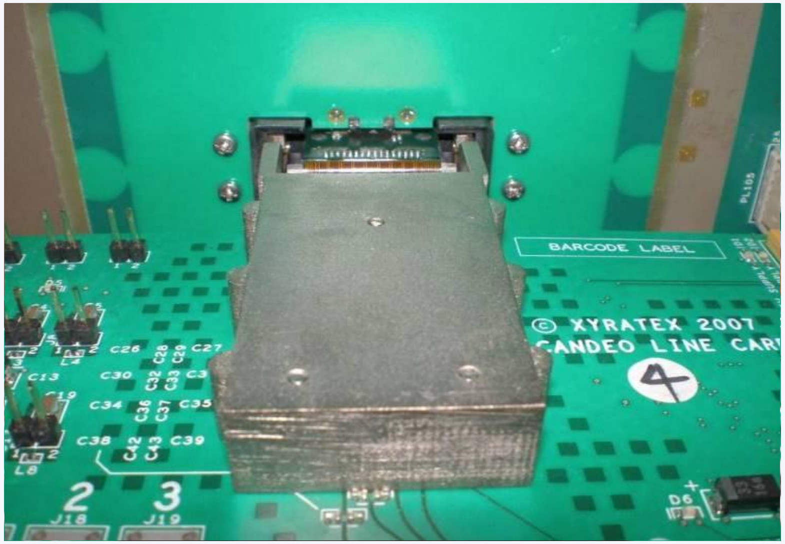


Connector module

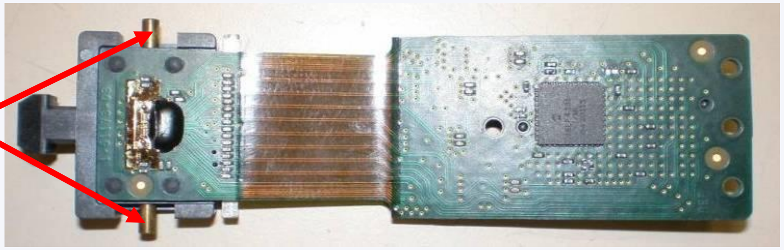


Connector engagement mechanism

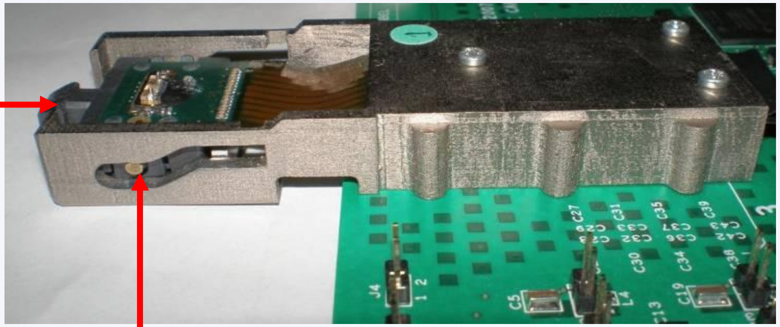
Docked



Cam followers



Ramped plug



Cam track

Peripheral test cards

Optical connector site

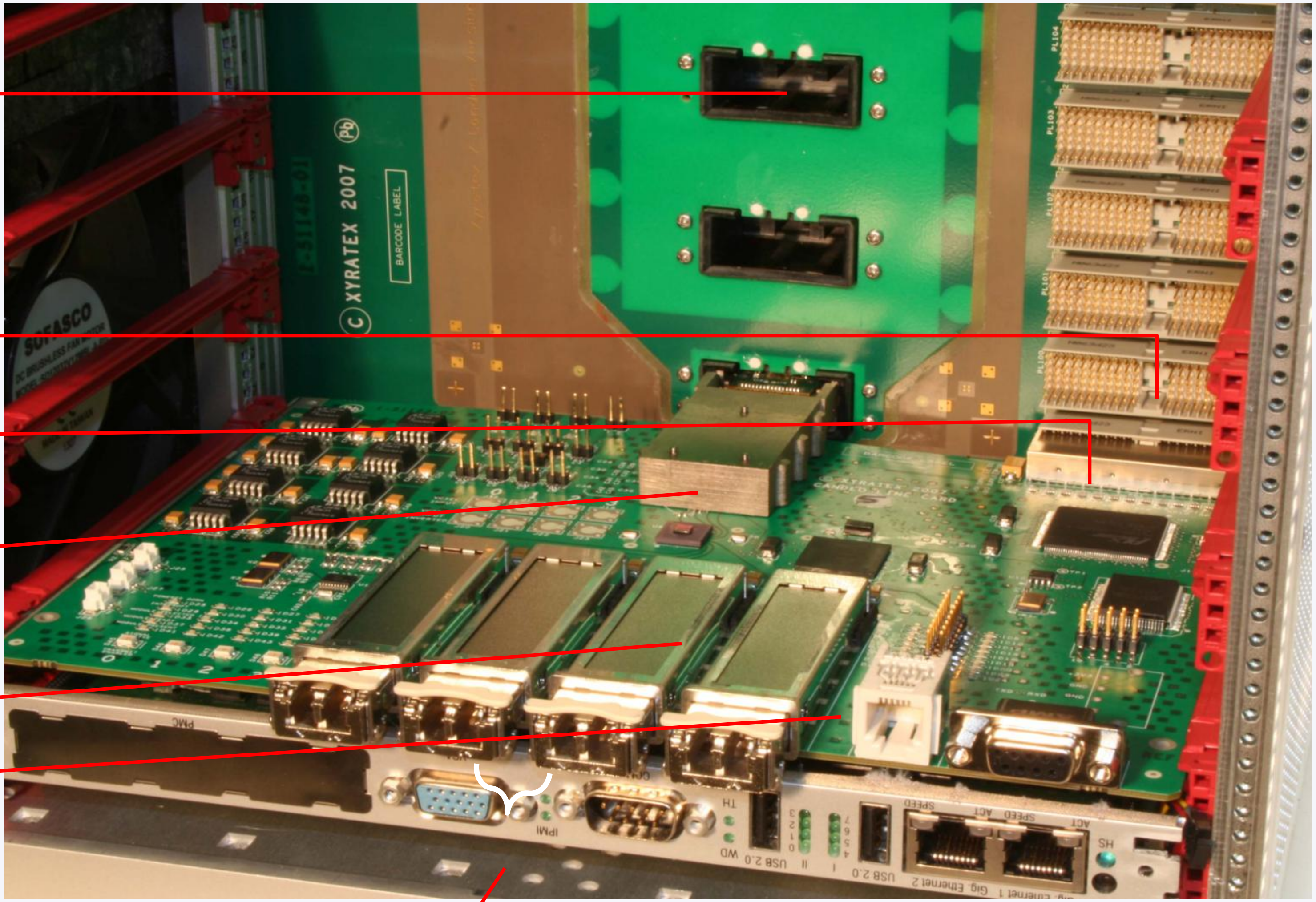
C-PCI connector

PCI bridge

Array connector

8 x 8 crosspoint switch

FPGA



XFP front end

Demonstration platform

Compact PCI chassis

Electro-optical midplane

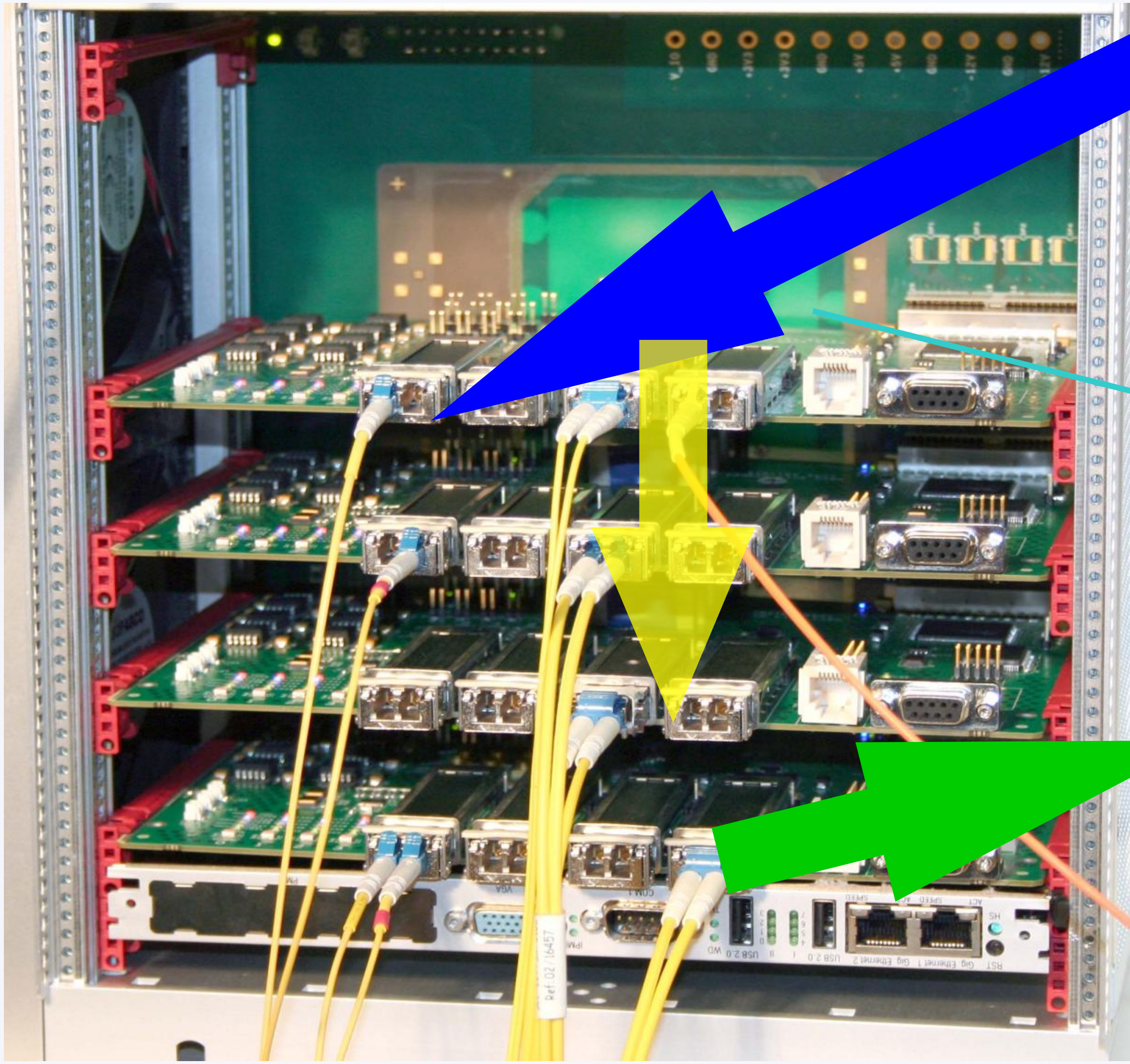
Pluggable optical connector

Peripheral test card

Single board computer

xyratex

High speed data transmission measurements



1st test card
- ❑ 10 GbE LAN test data
- ❑ Injected into front end

Electro-optical midplane
- ❑ Pluggable connectors
- ❑ Polymer waveguides

Target test card
- ❑ Retrieved through front end
- ❑ Signal integrity measured

Acknowledgments

- **University College London, UK**
  - Kai Wang, Hadi Baghsiahi, F. Aníbal Fernández, Ioannis Papakonstantinou
- **Loughborough University, UK**
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  - Dougal Stewart, Jonathan Calver, Jeremy Rygate, Steve Payne, Witold Kandulski
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  - Dave Milward, Richard Pitwon, Ken Hopkins, Malcolm Muggeridge
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