The Ie*e*MRC Opto-PCB Manufacturing Project

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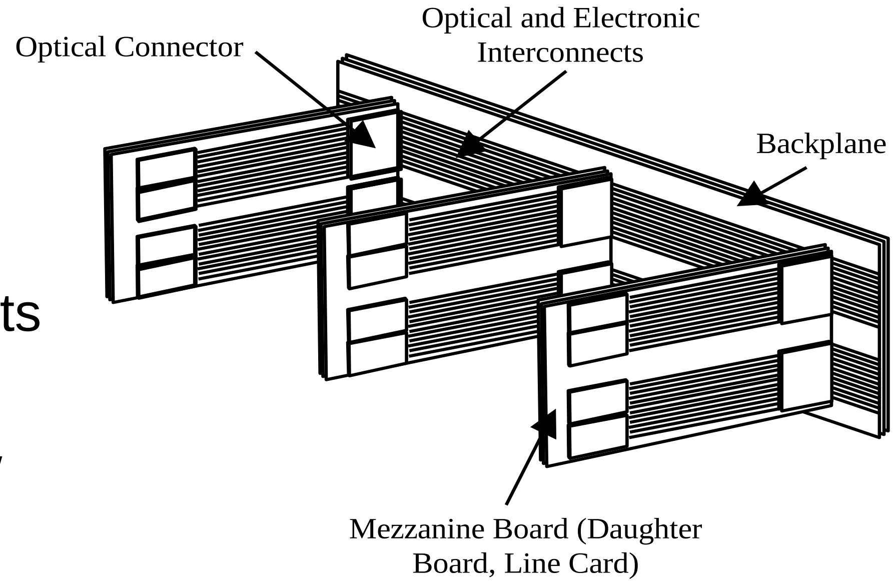
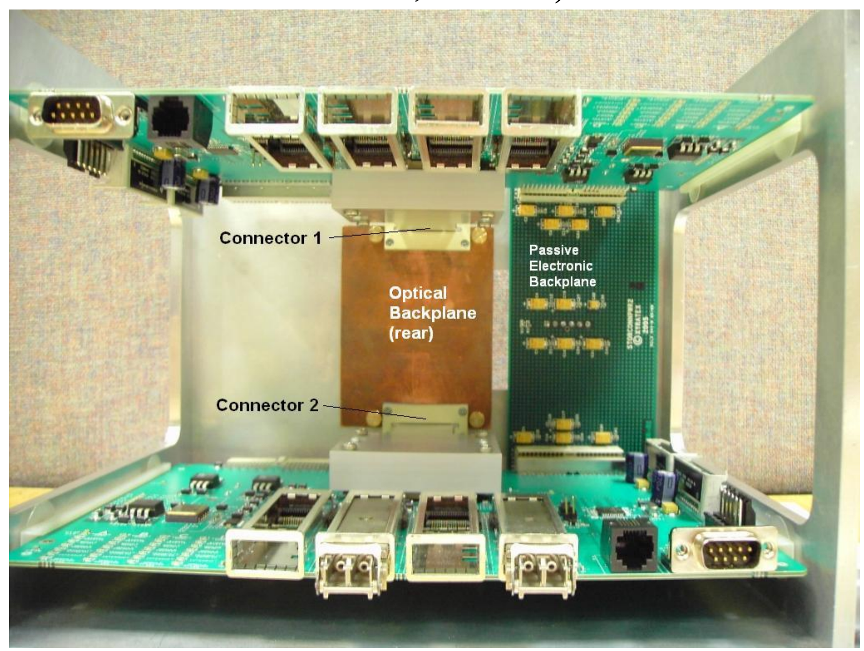
Outline



- 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

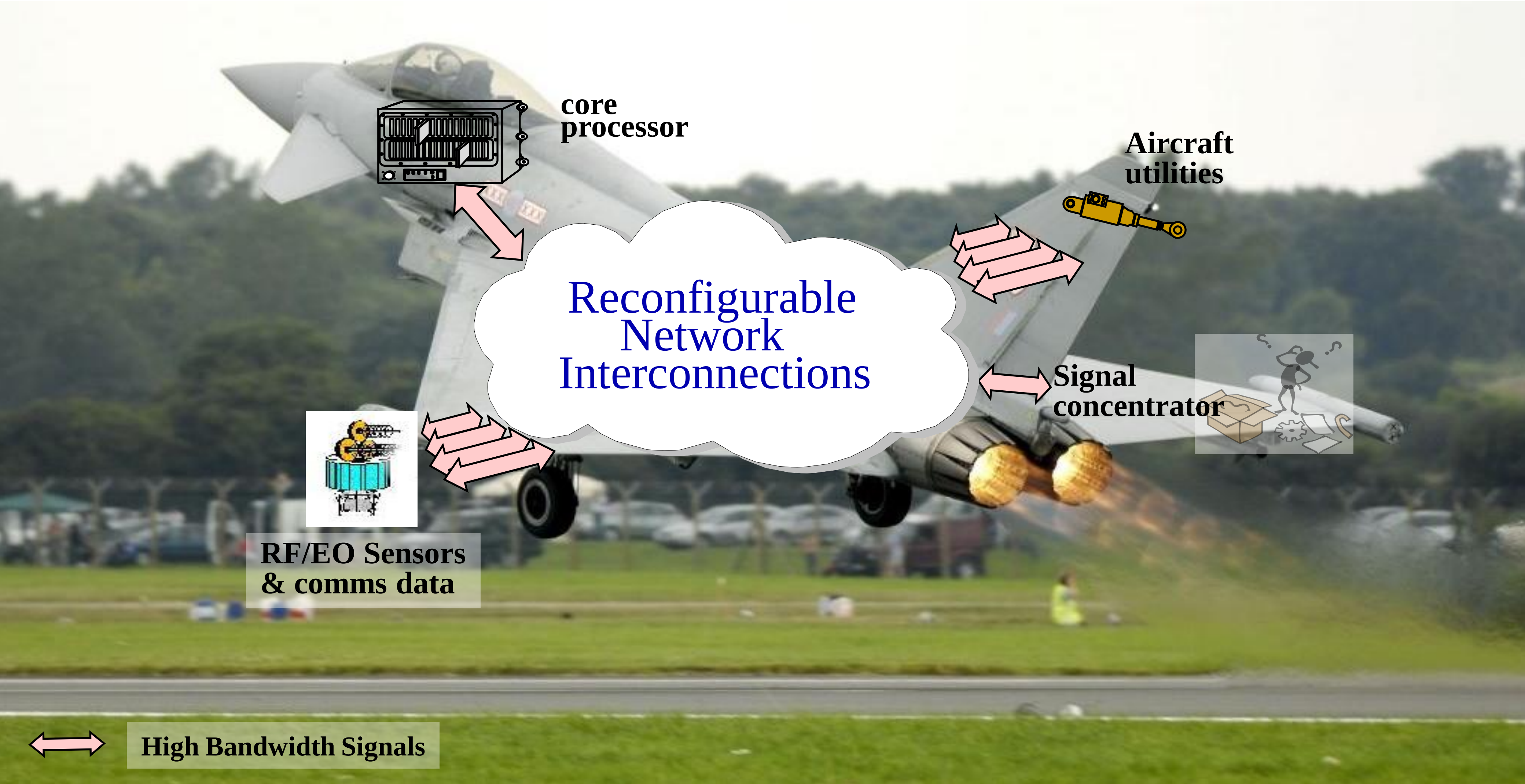
- Copper Track
  - EMI Crosstalk
  - Loss
  - Impedance control to minimize back reflections, additional equalisation, costly board material

- 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

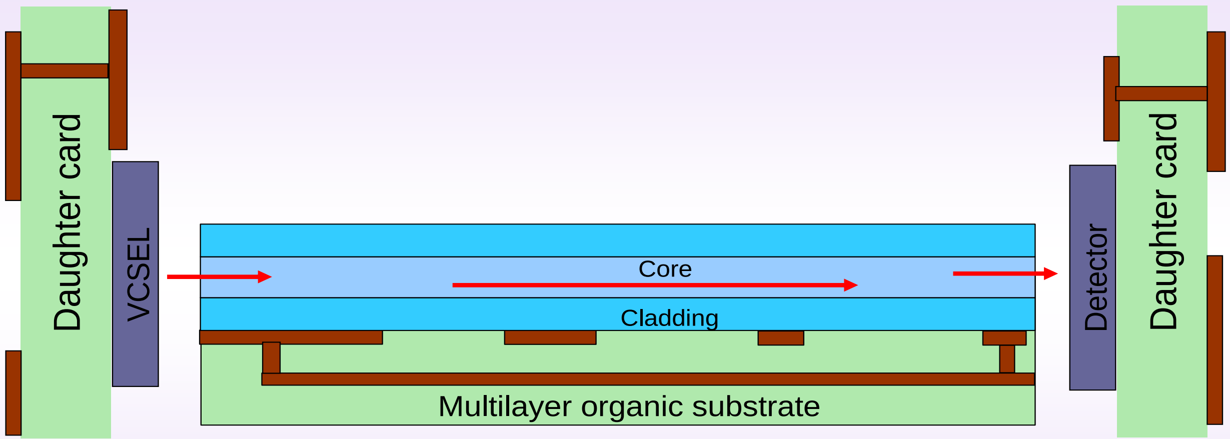
On-board Platform Applications



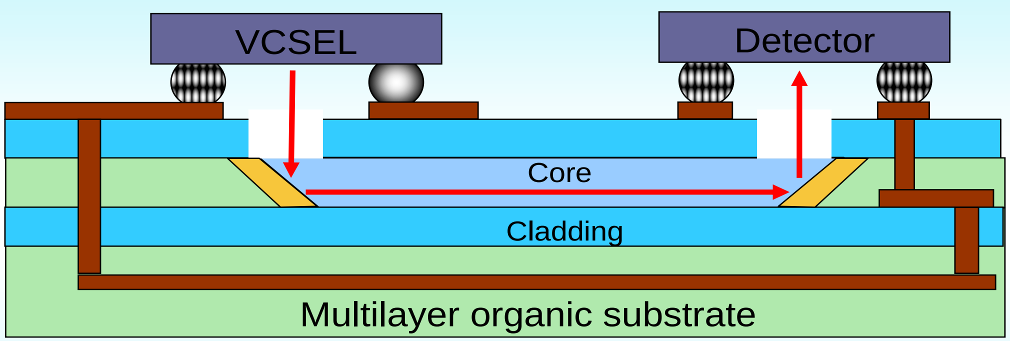
The Integrated Optical and Electronic Interconnect PCB Manufacturing (OPCB) project

- 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
- 2.9 years into the 3 year, £1.3 million project

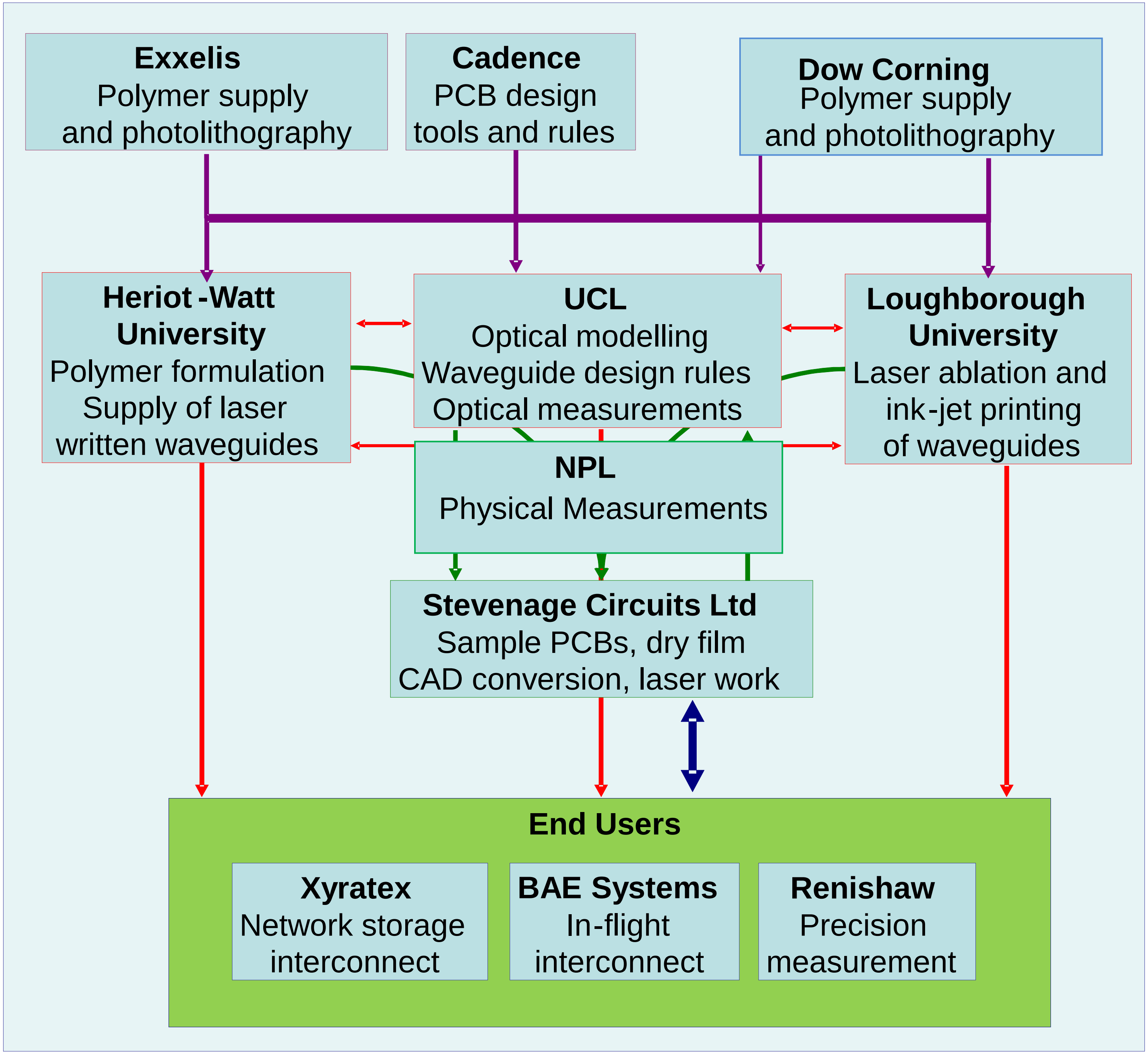
Integration of Optics and Electronics



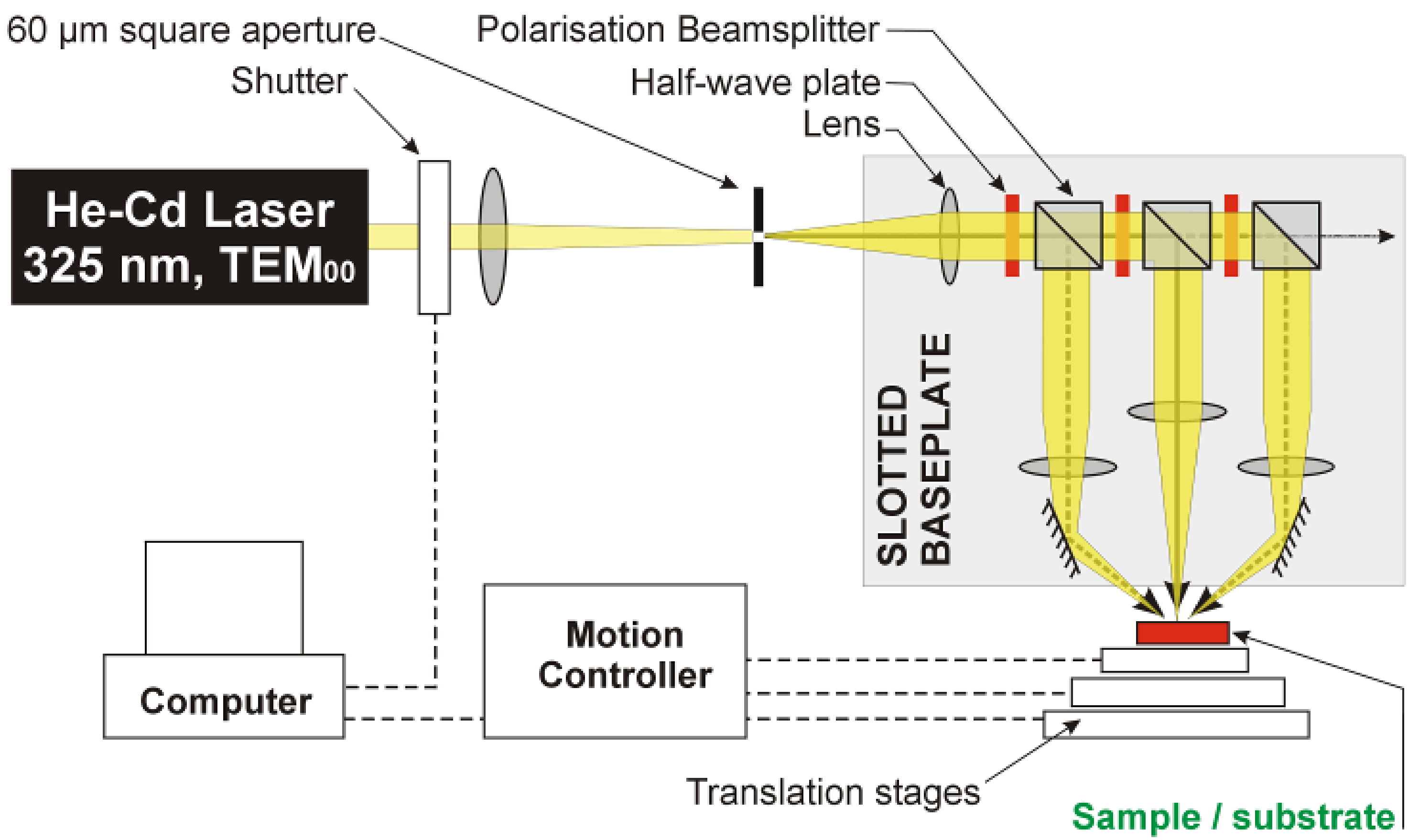
- Backplanes
  - Butt connection of “plug-in” daughter cards
  - In-plane interconnection
- Focus of OPCB project

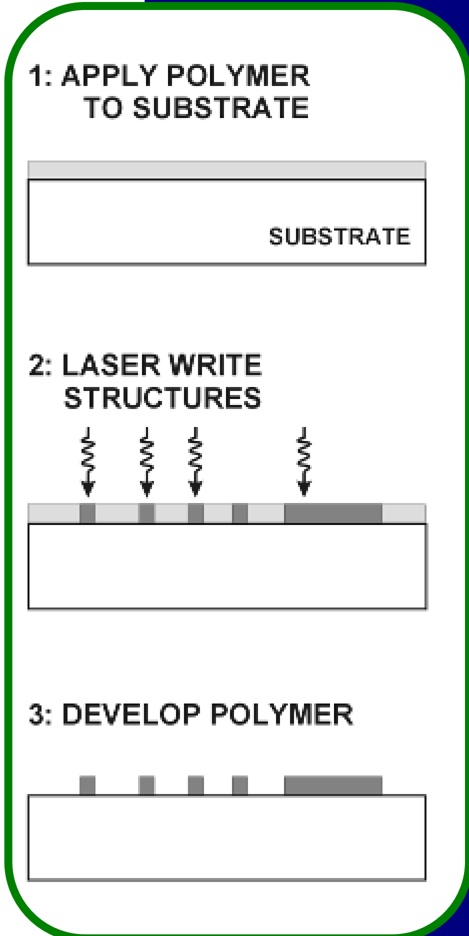


- Out-of-plane connection
  - 45 mirrors
  - Chip to chip connection possible


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

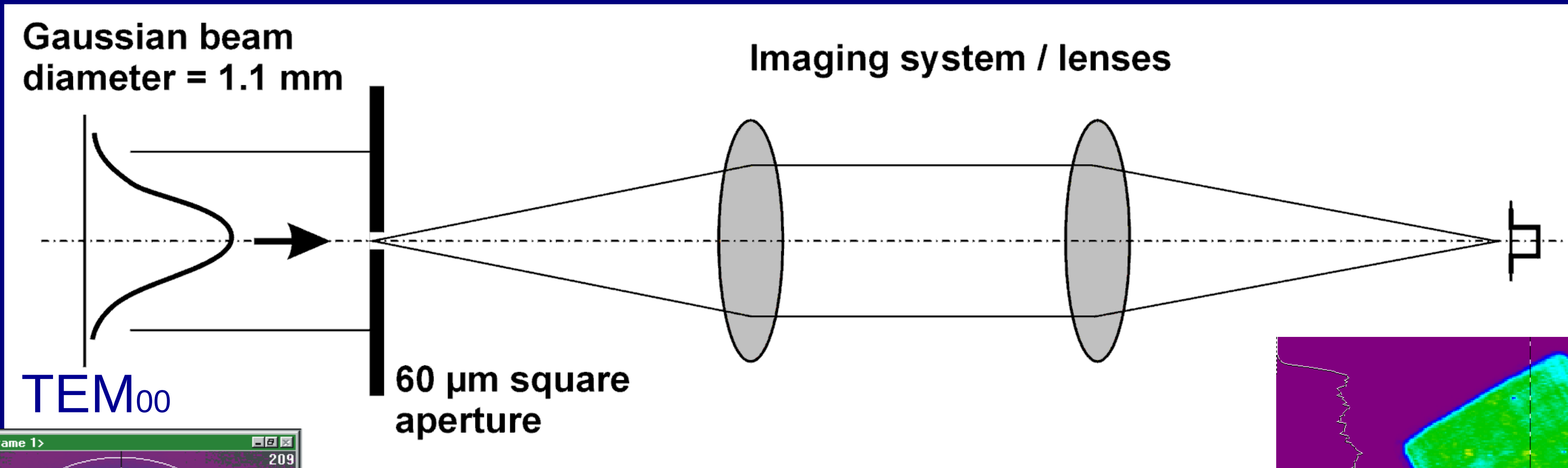
Direct Laser-writing Setup: Schematic

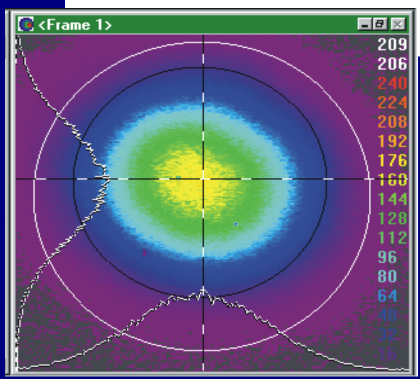


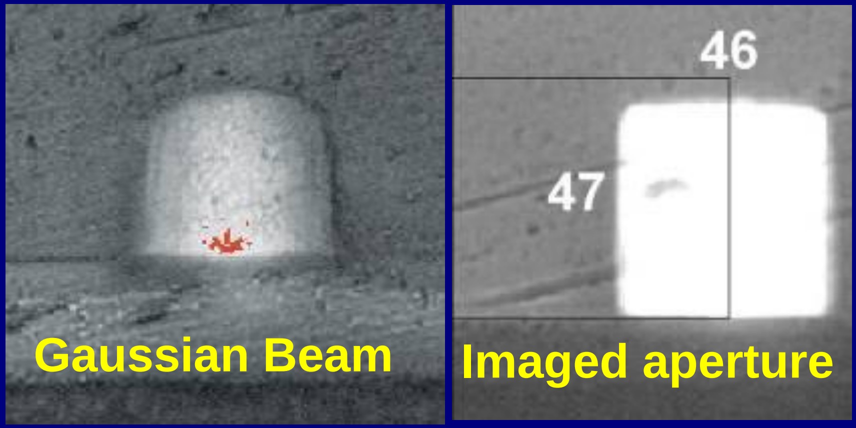


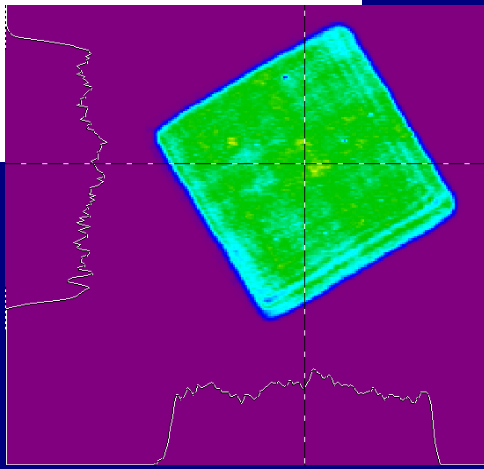
- **Slotted baseplate** mounted vertically over translation, rotation & vertical stages; components held in place with magnets
- By using two opposing 45º beams we minimise the amount of substrate rotation needed

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







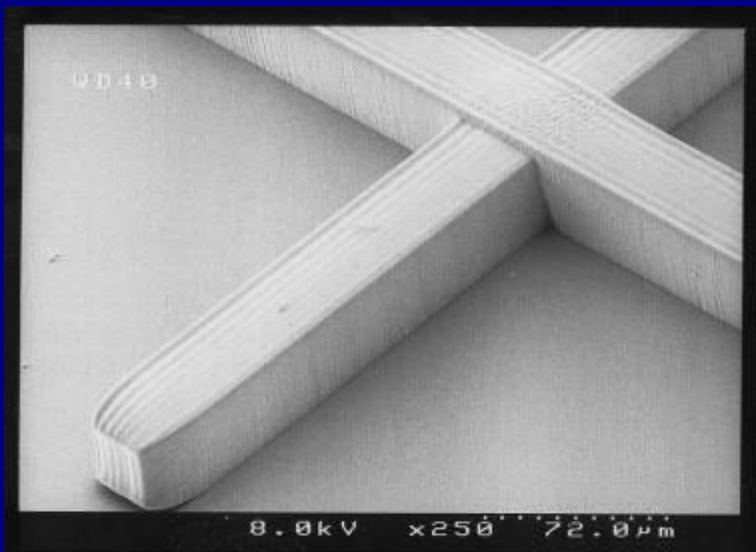


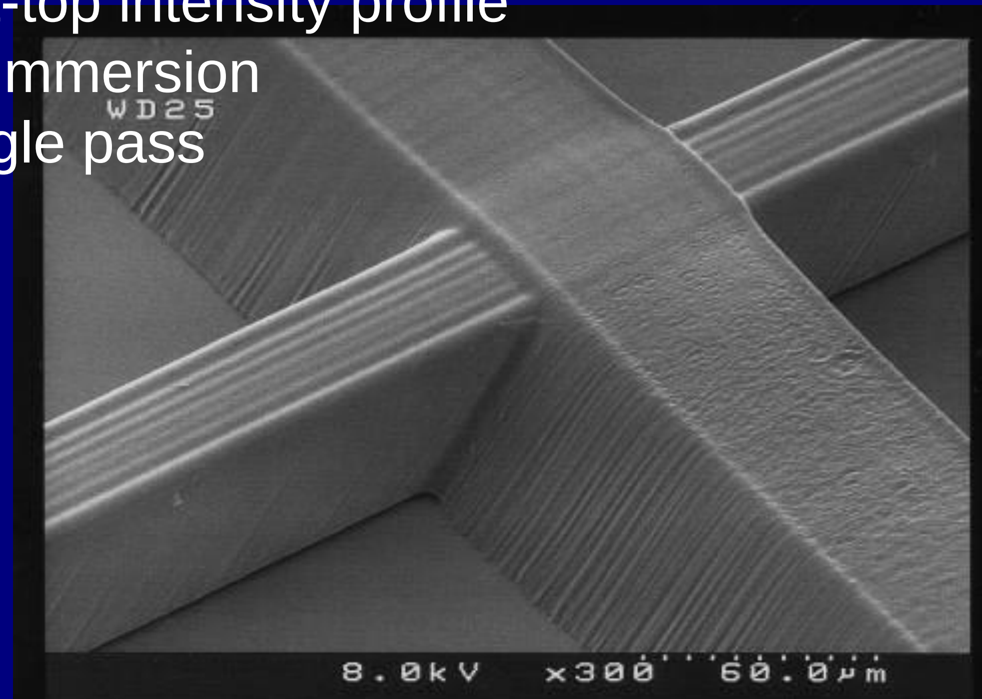
Images of the resulting waveguide core cross-sections

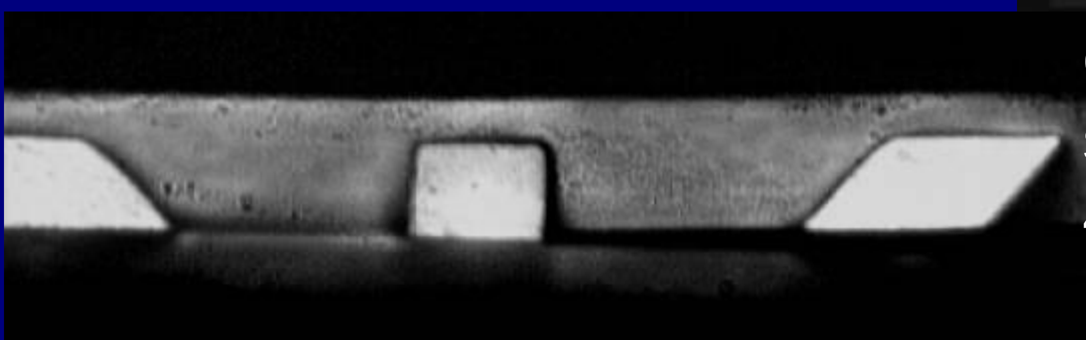
Laser written polymer structures

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





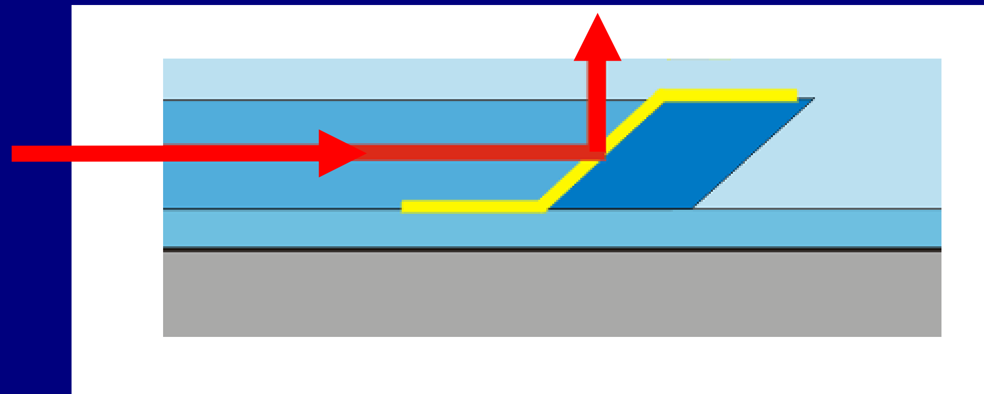


Optical microscope image showing end on view of the 45º surfaces

Waveguide terminated with 45-deg mirror

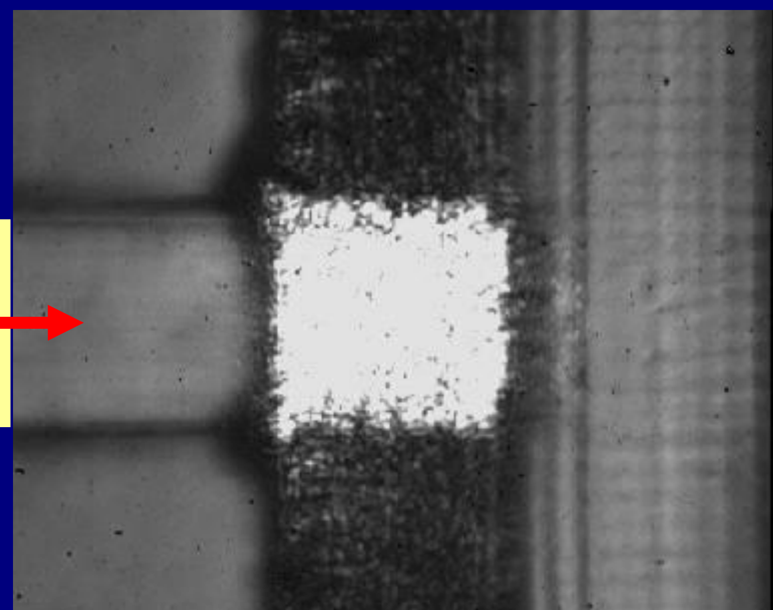
Out-of-plane coupling,

using 45-deg mirror (silver)



Microscope image looking
down on mirror
coupling light towards camera

OPTICAL INPUT



Current Results

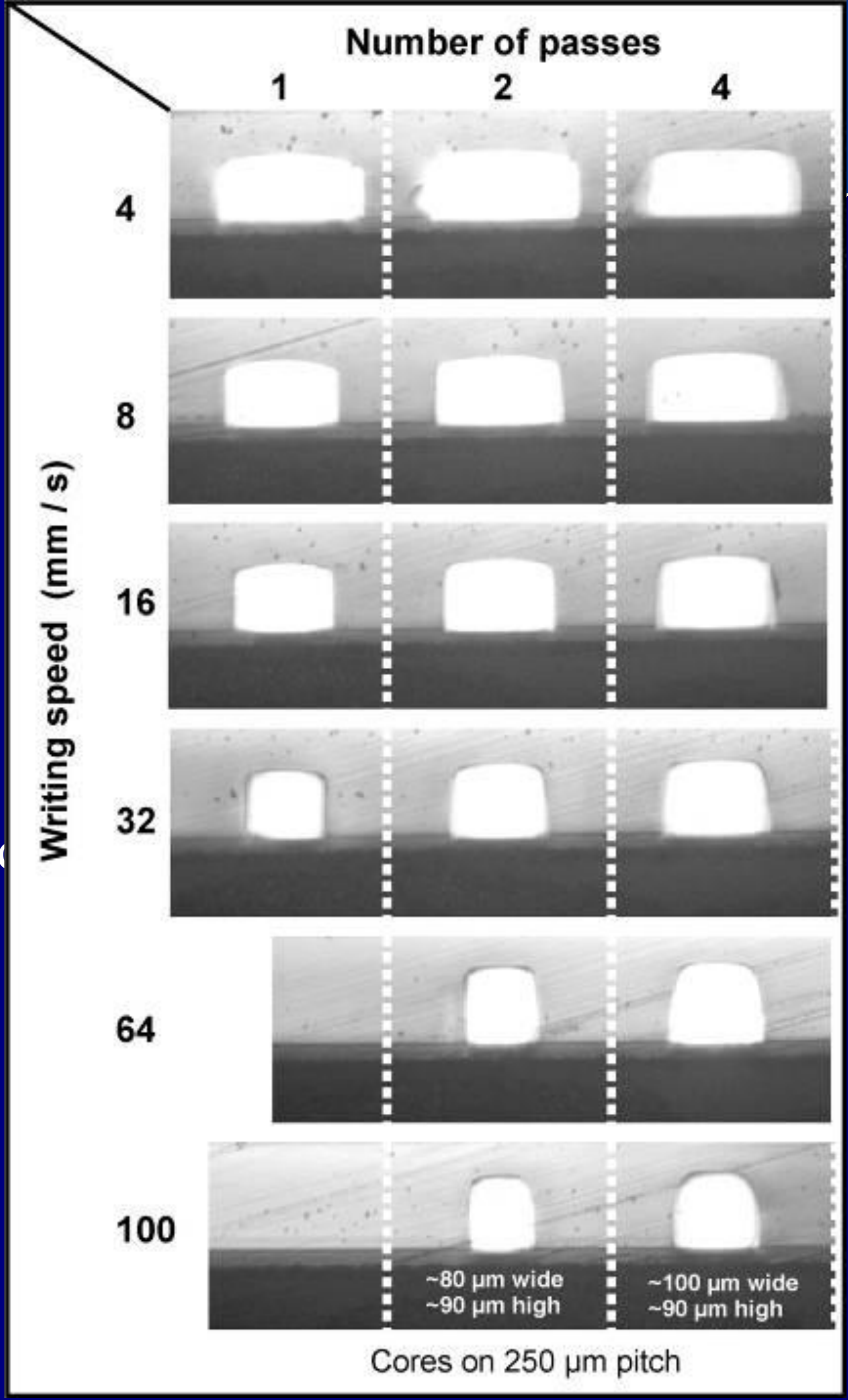
Laser-writing Parameters:

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

Polymer:

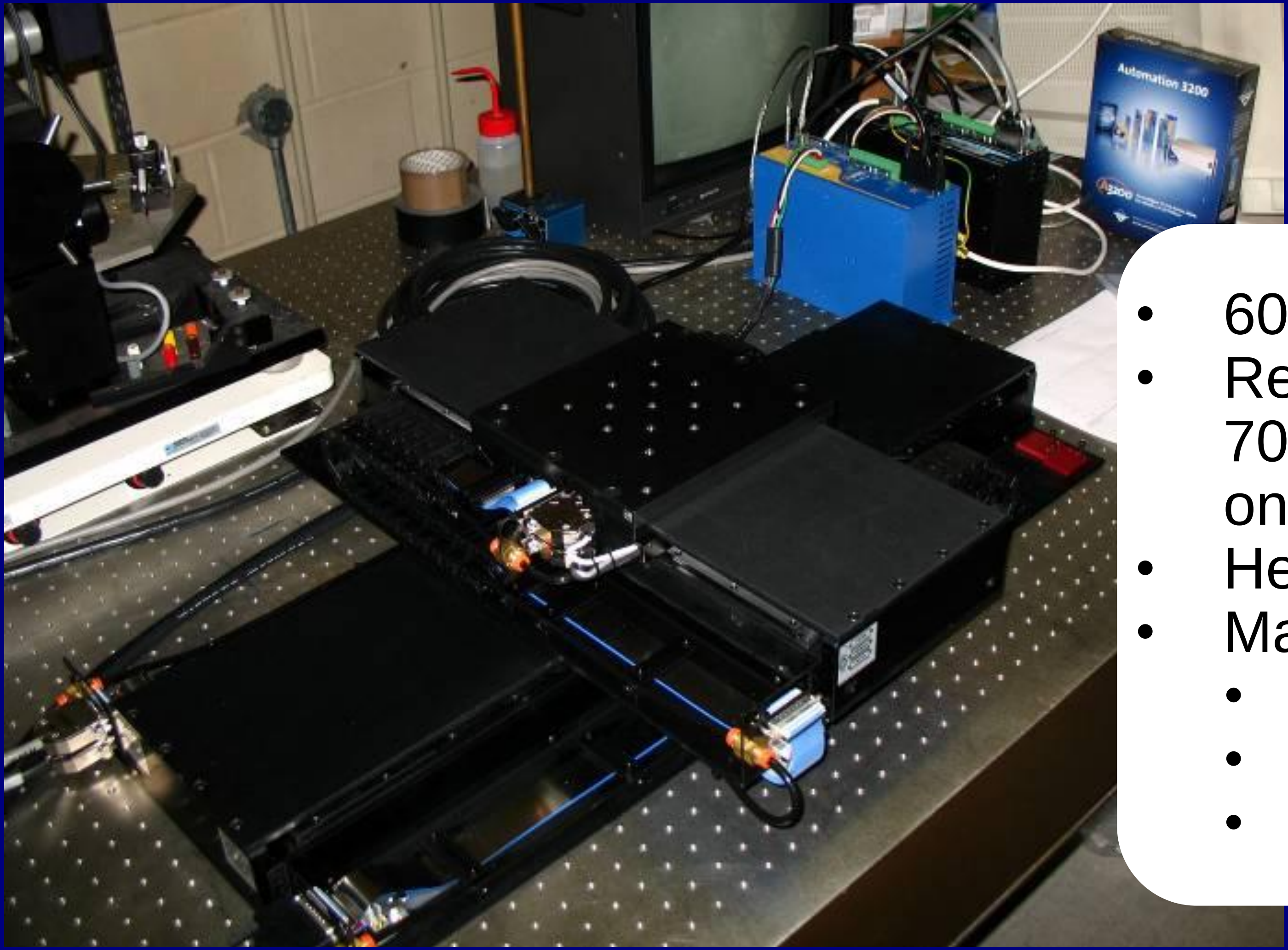
- Custom multifunctional acrylate photo-polymer
- Fastest “effective” writing speed to date: 50 mm/s

(Substrate: FR4 with polymer undercladding)



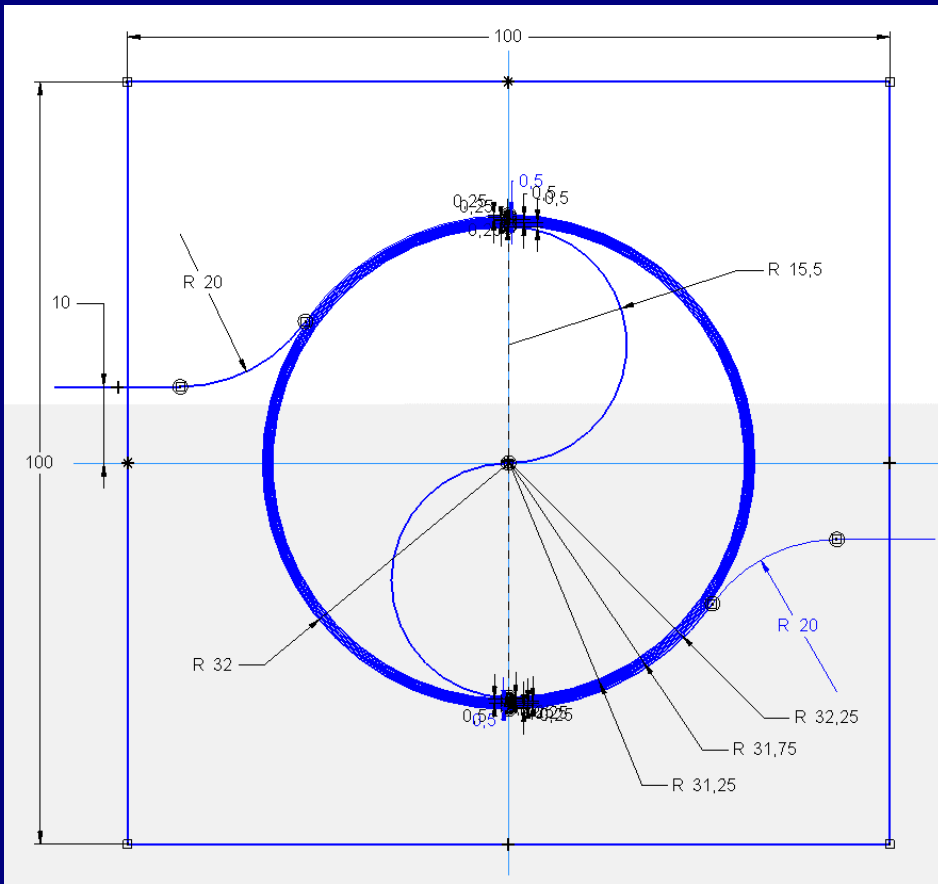
Large Board Processing: Writing

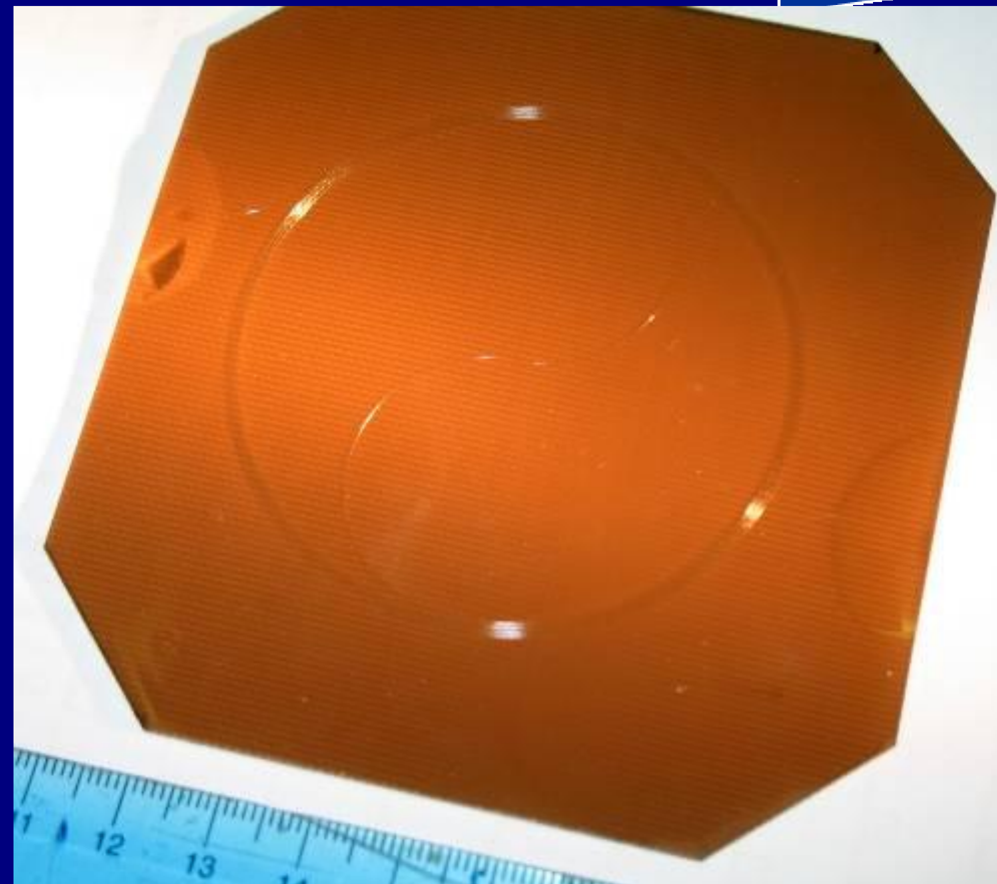
- Stationary “writing head” with board moved using Aerotech sub-µm precision stages
- Waveguide trajectories produced using CAD program



- 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



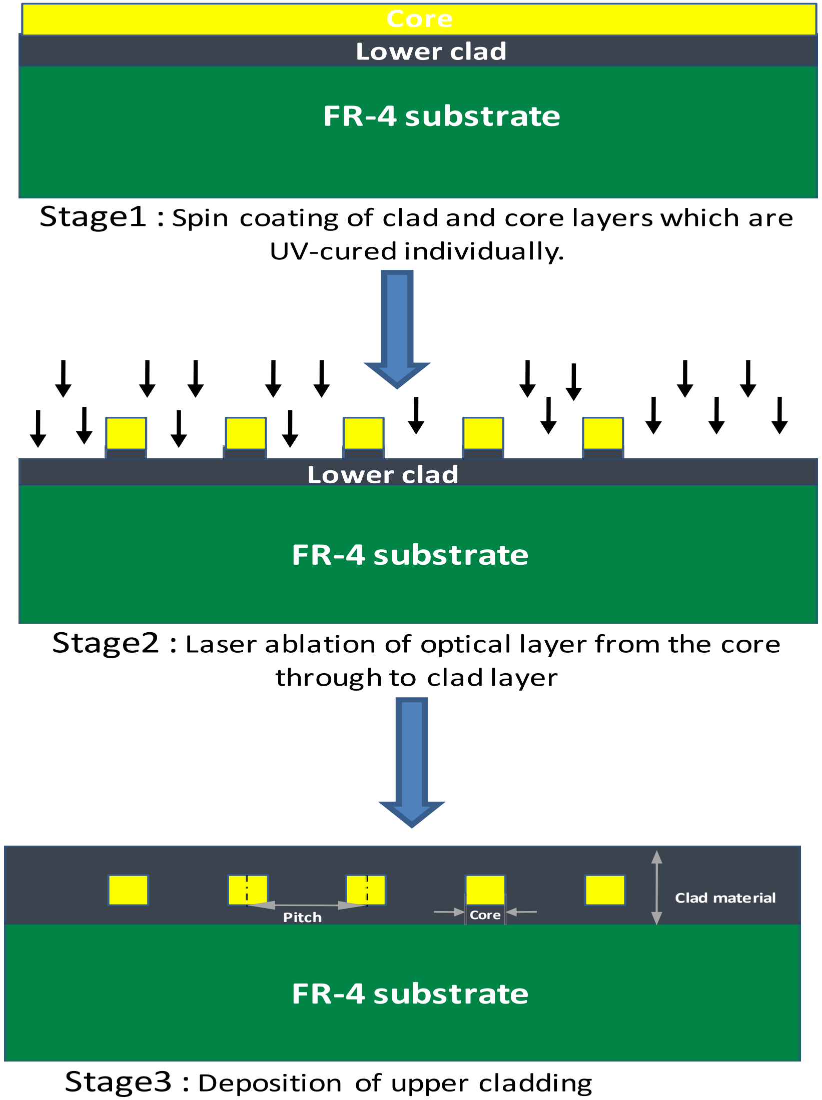


The spiral was fabricated using a Gaussian intensity profile at a writing speed of 2.5 mm/s on a 10 x 10 cm lower clad FR4 substrate. Total length of spiral waveguide is **~1.4 m**. The spiral was upper cladded at both ends for cutting.

Laser Ablation of Optical Waveguides

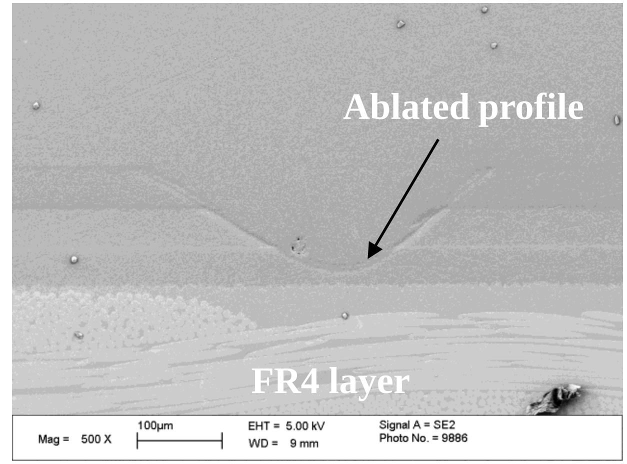
- Research
  - Straight waveguides
  - 2D & 3D integrated mirrors
- Approach
  - Excimer laser – Loughborough
  - CO_2 laser - Loughborough
  - UV Nd:YAG – Stevenage Circuits Ltd
- Optical polymer
  - Truemode® – Exxelis
  - Polysiloxane – Dow Corning

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

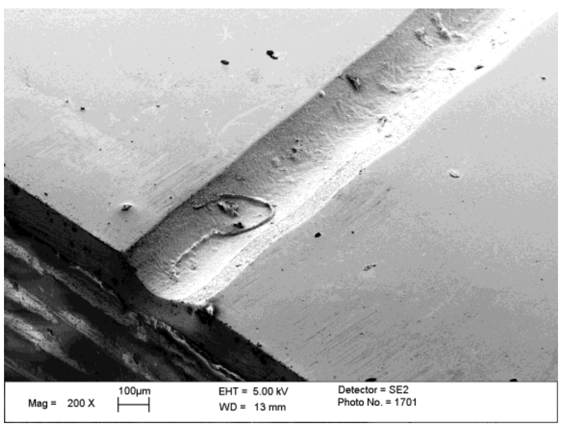


Machining of Optical Polymer with CO_2 Laser

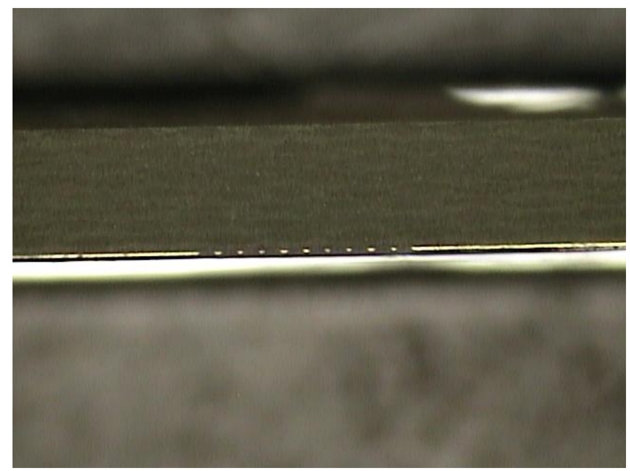
- System
  - 10 Watt(max.) power CW beam
  - Wavelength = 10.6 µm (infrared)
- Process
  - Thermally-dominated ablation process
- Machining quality
  - Curved profile
  - Waveguide fabrication underway



Side view of machined trench

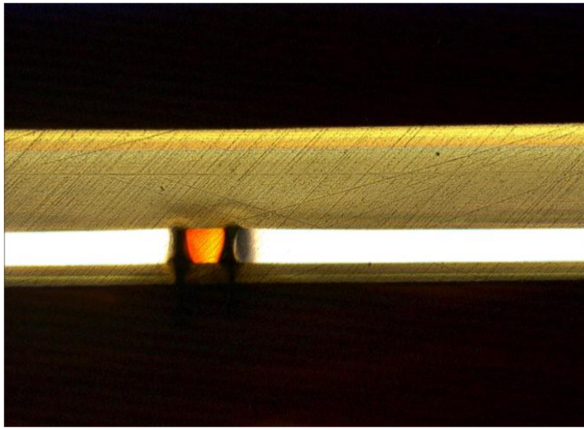


Machined trench

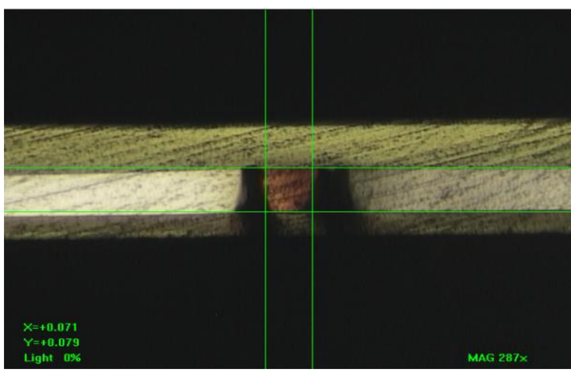


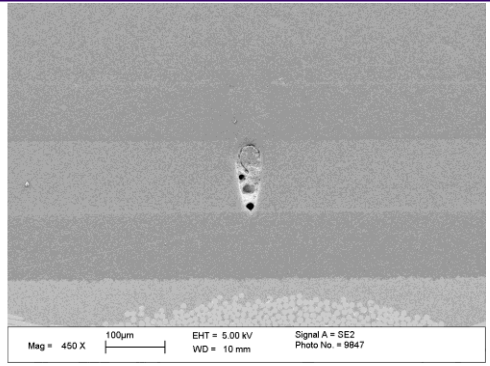
Waveguides (side view)

UV Nd:YAG machining in collaboration with Stevenage Circuits Ltd

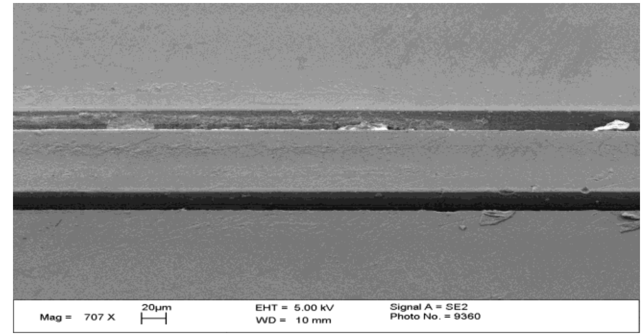


- **Waveguide of 71 µm x 79 µm fabricated using UV Nd:YAG**
- **Waveguide detected using back lighting**





Side view

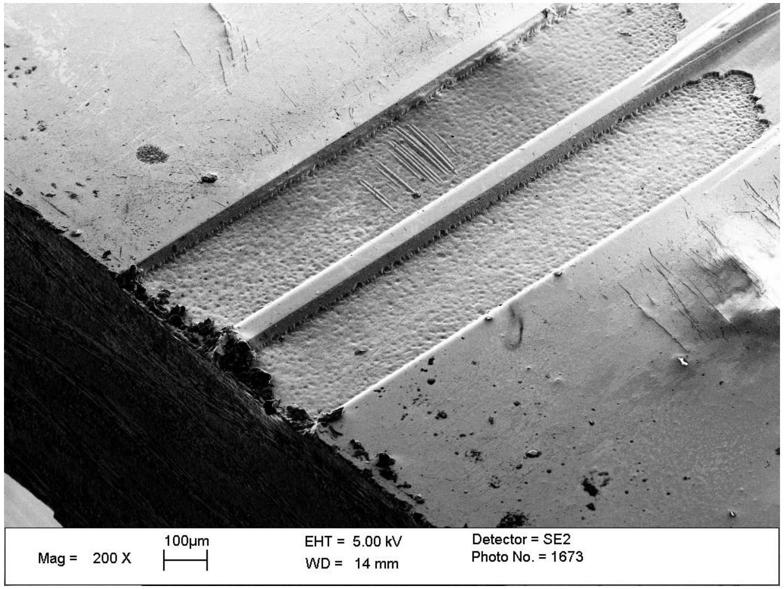


Plan view

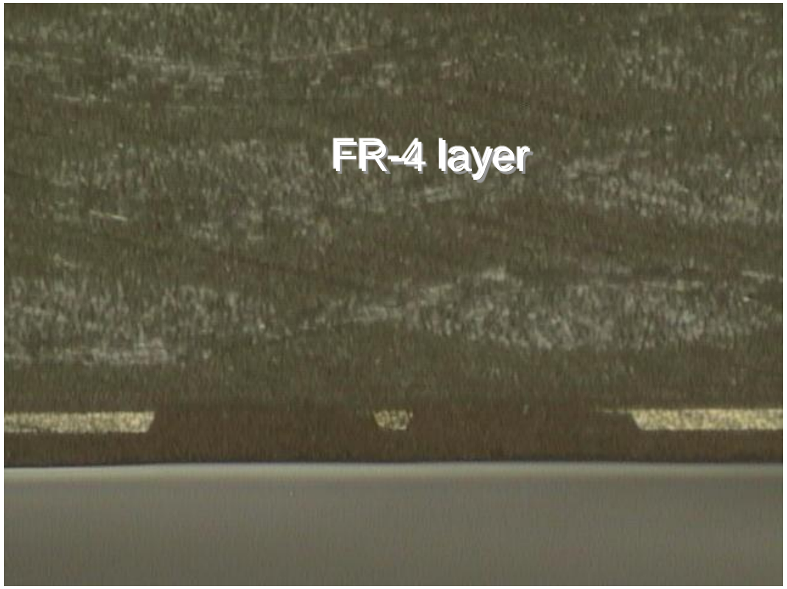
- System
  - 355 nm (UV) Pulsed laser with 60 ns pulse width and Gaussian beam (TEM_{00}) or "Tophat" profile at Stevenage Circuits Ltd.
- Process
  - Photochemically-dominated ablation process.
- Waveguide quality
  - Minimum Heat Affected Zone
  - Propagation loss measurement underway

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.

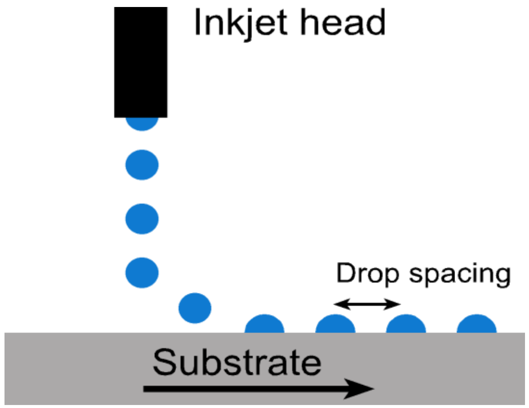


Machined trenches

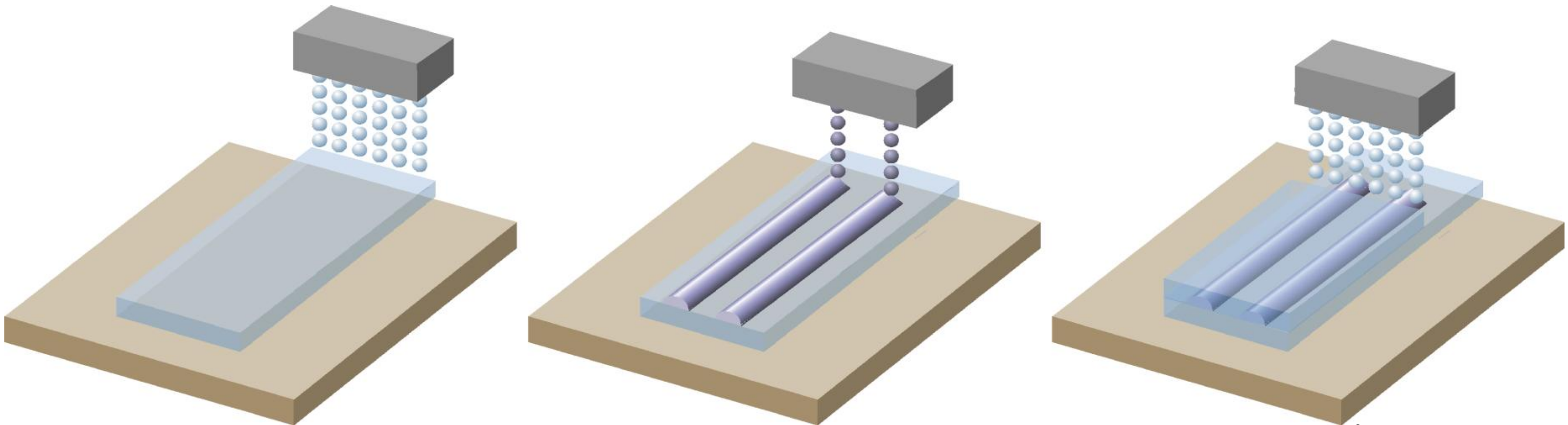


Waveguide structure

Inkjetting as a Route to Waveguide Deposition



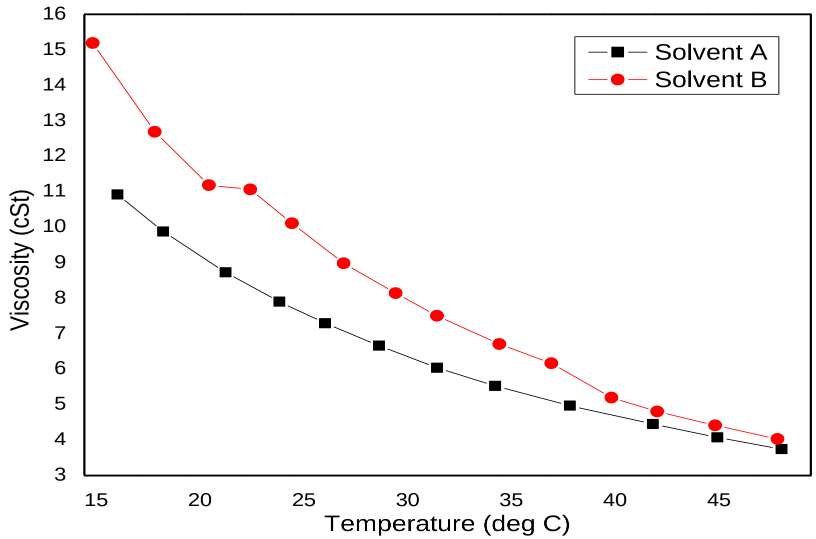
- Print polymer then UV cure
- Advantages:
  - controlled, selective deposition of core and clad
  - less wastage: picolitre volumes
  - large area printing
  - low cost

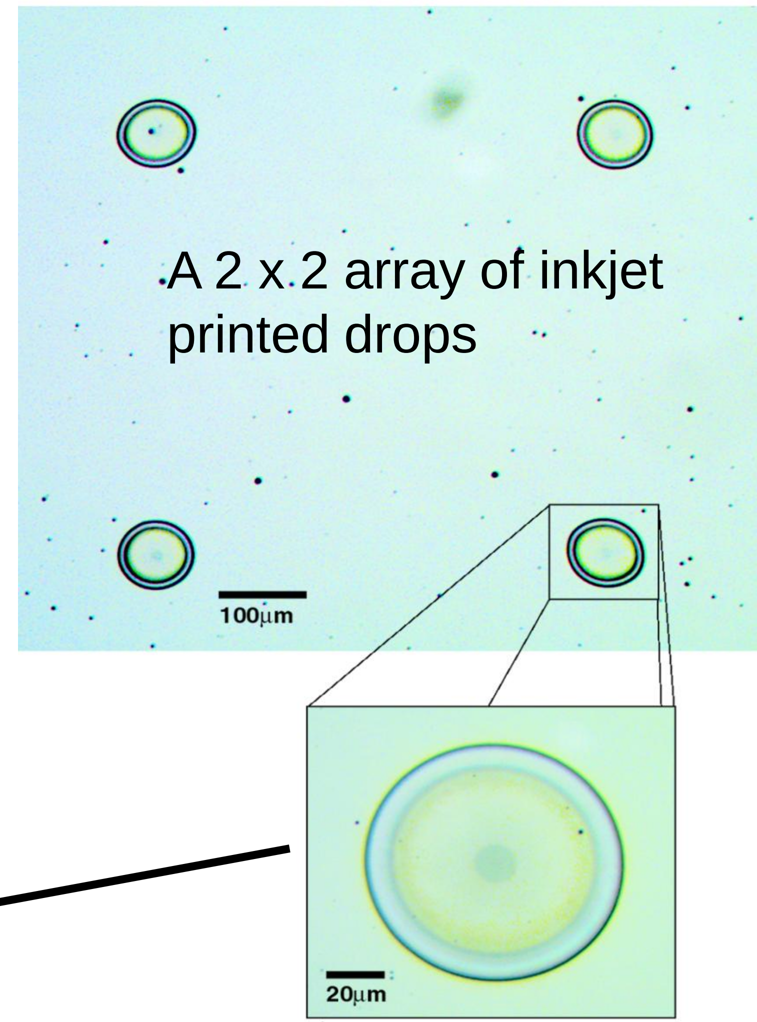


Deposit Lower Cladding | **Deposit Core** | **Deposit Upper Cladding**

Challenges of Inkjet Deposition

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

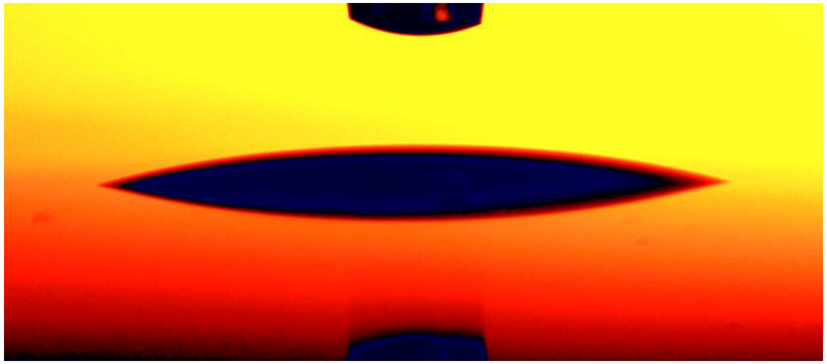




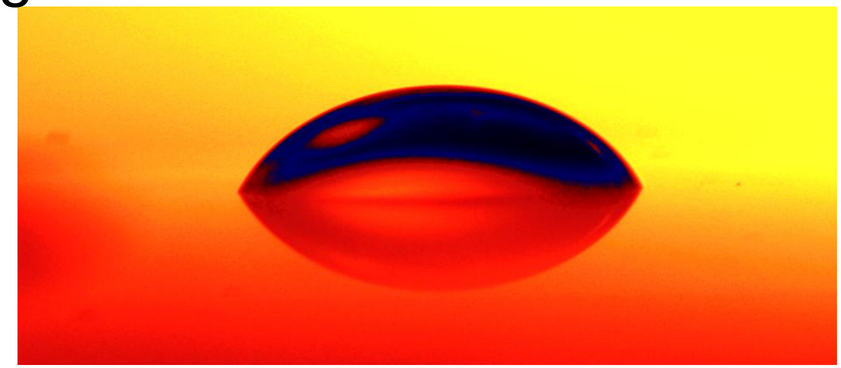
Cross-section of dried droplet "coffee-stain" effect

Changing Surface Wettability

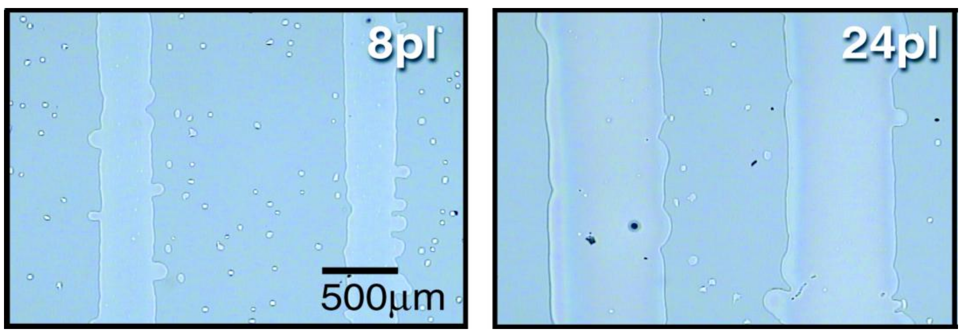
Contact Angles



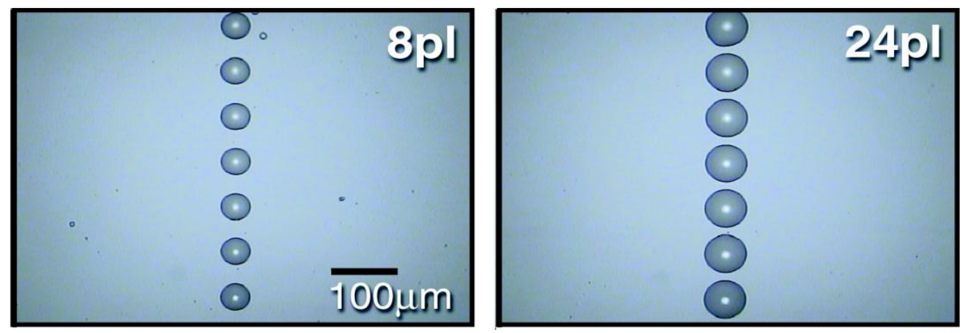
Core material on cladding



Core material on modified glass surface (hydrophobic)



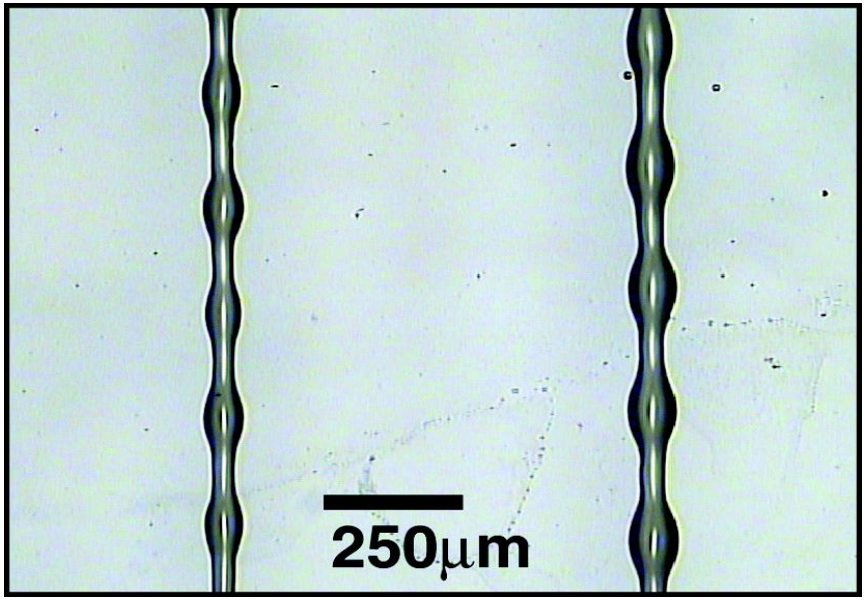
Large wetting - broad inkjetted lines



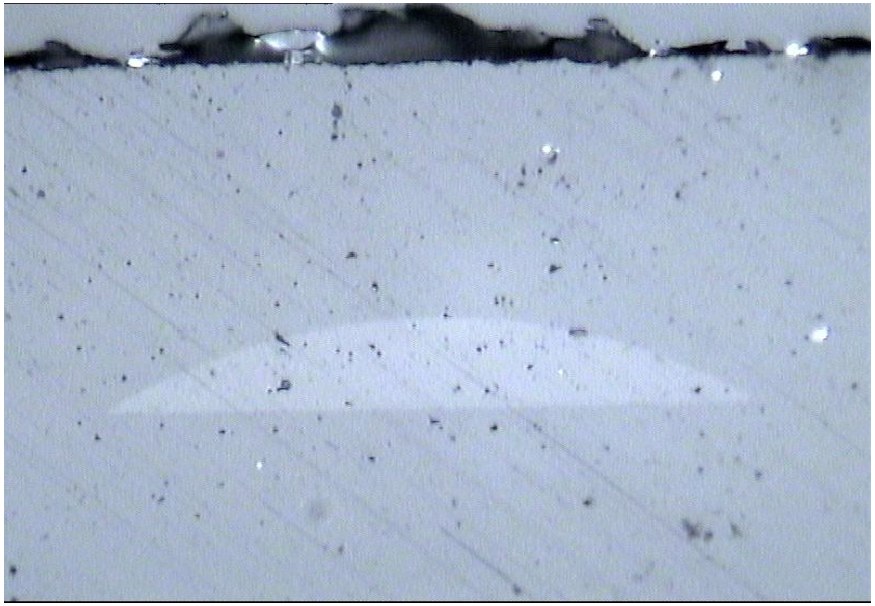
Reduced wetting – discrete droplets

Identical inkjetting conditions - spreading inhibited on modified surface

Towards Stable Structures



Stable line structures with periodic features



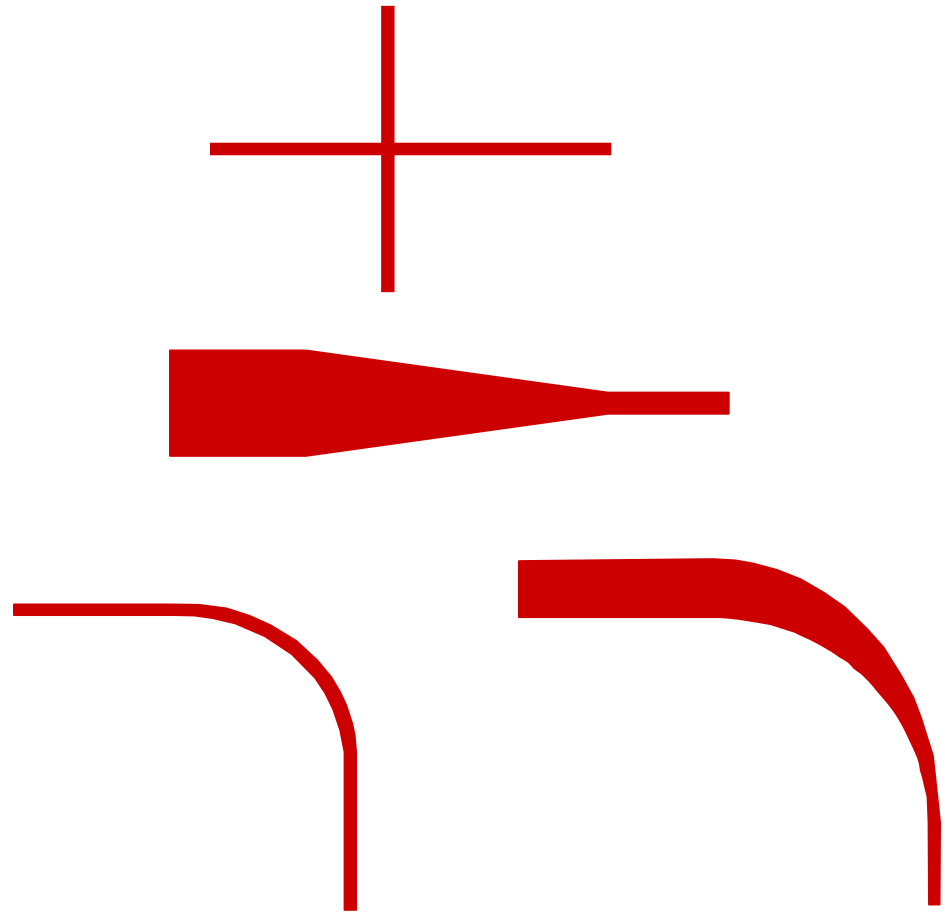
Cross section of inkjetted core material surrounded by cladding (width 80 microns)

A balance between wettability, line stability and adhesion

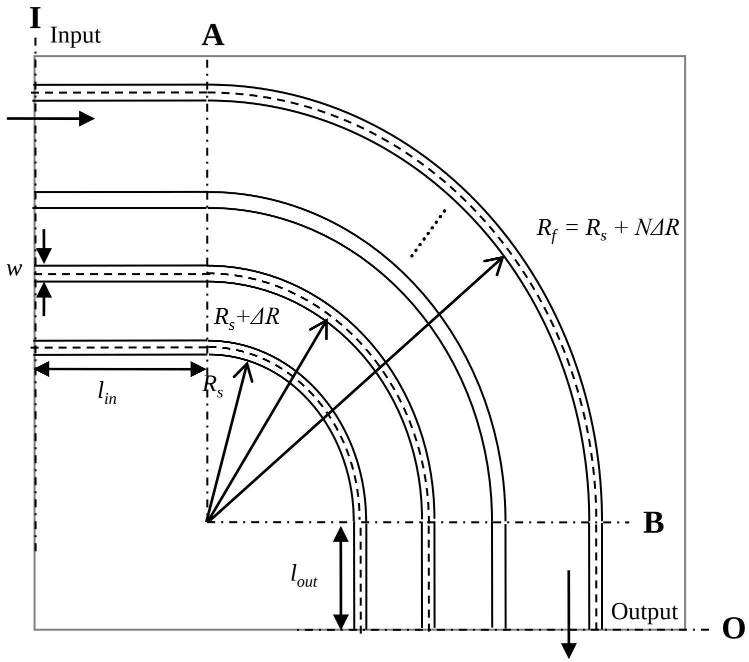
Waveguide components and measurements

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

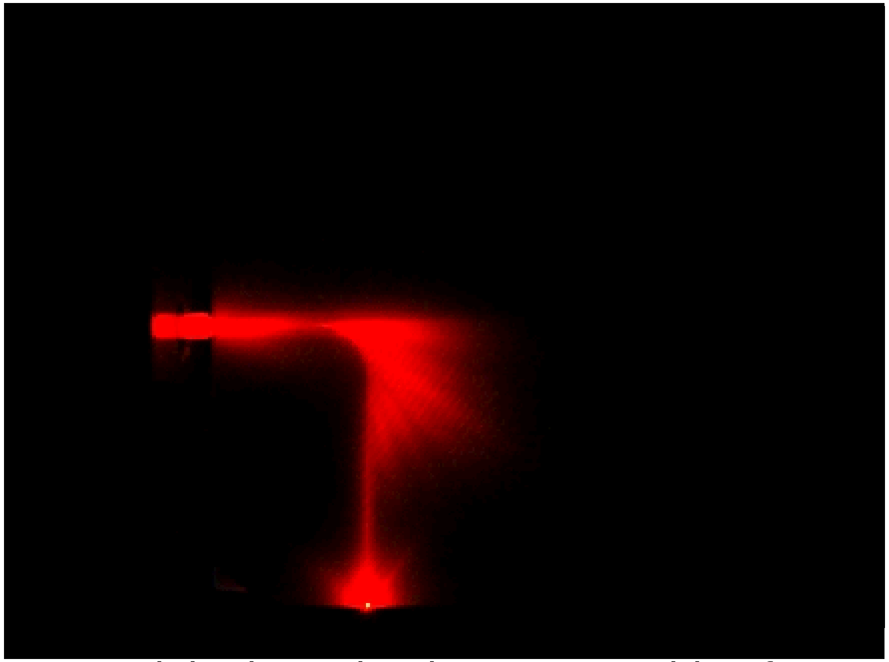
- Loss
- Crosstalk
- Misalignment tolerance
- Surface Roughness
- Bit Error Rate, Eye Diagram



Optical Power Loss in 90 Waveguide Bends



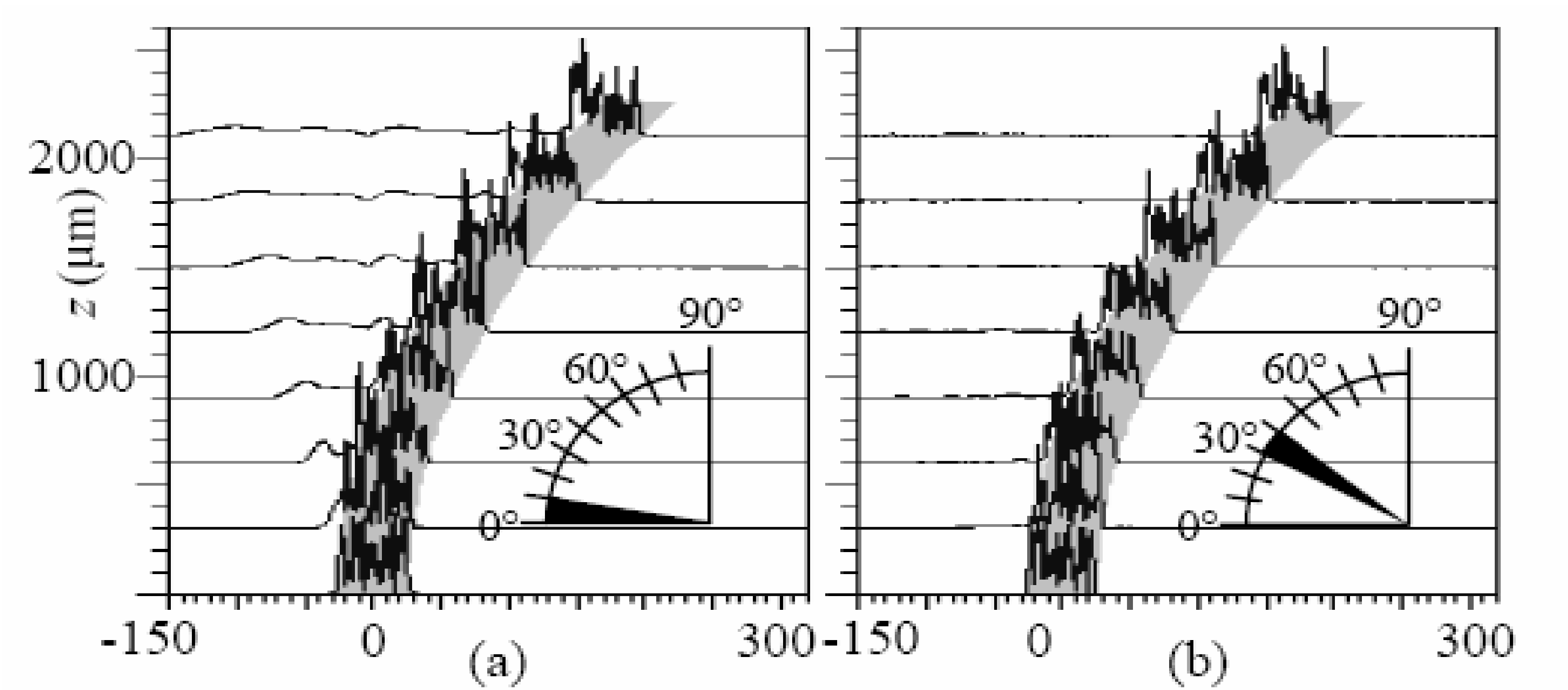
Schematic diagram of one set of curved waveguides.



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

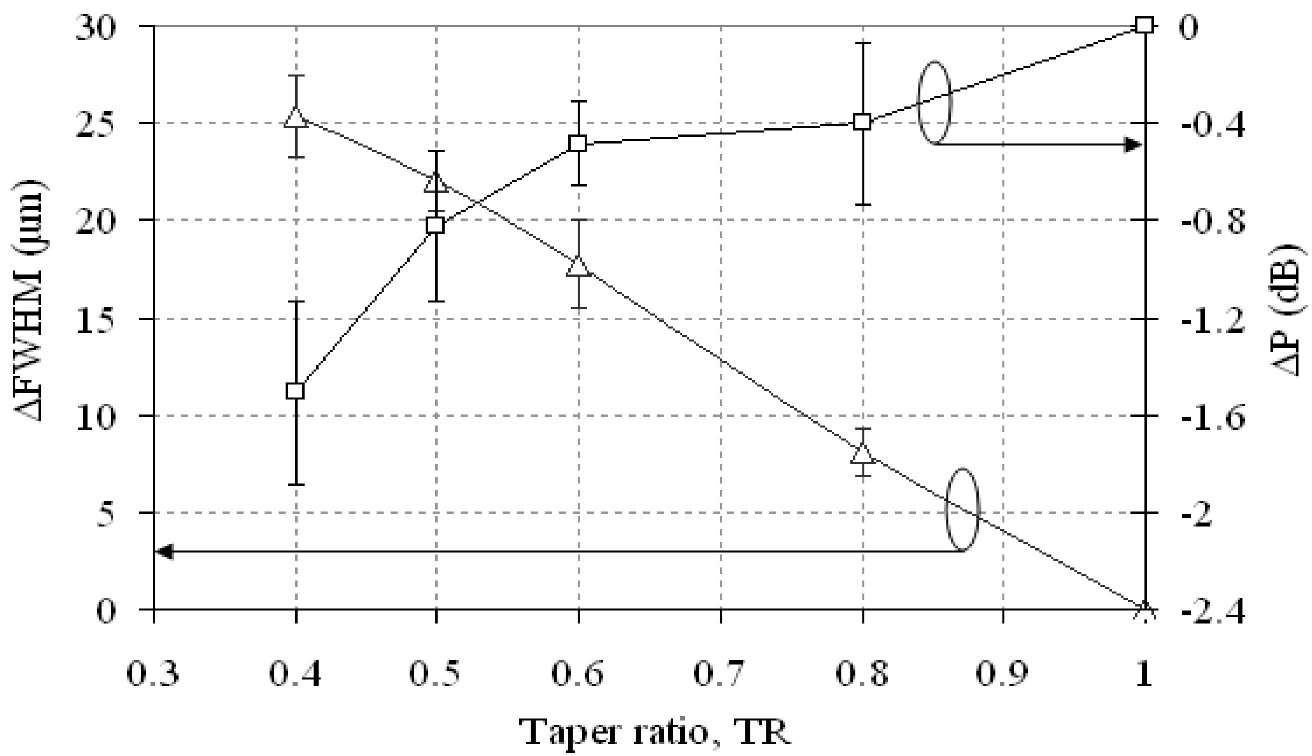


w = 50 μm, R = 13 mm

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

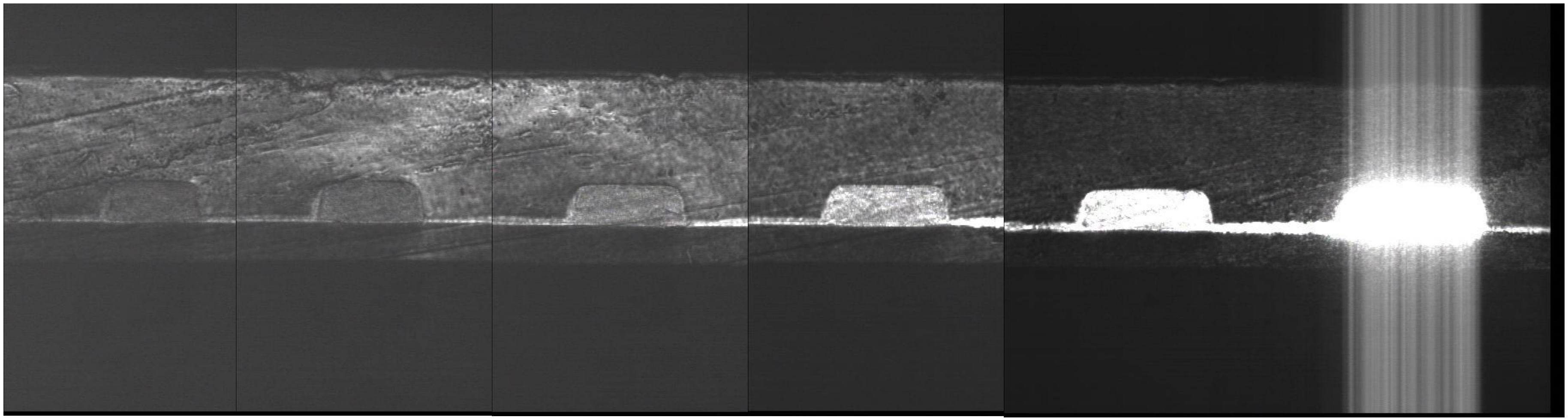
(right picture) in the 30° to 40° degree segment.

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

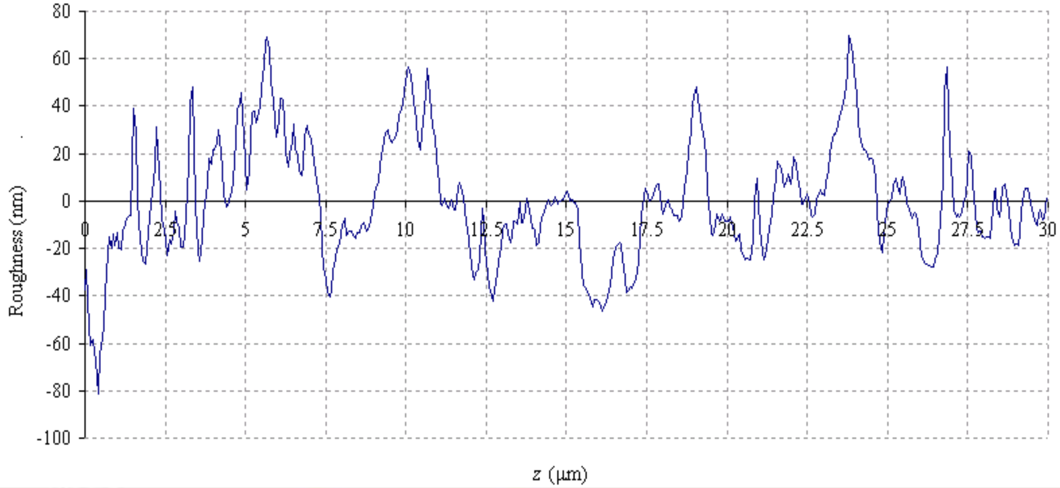
Crosstalk in Chirped Width Waveguide Array



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

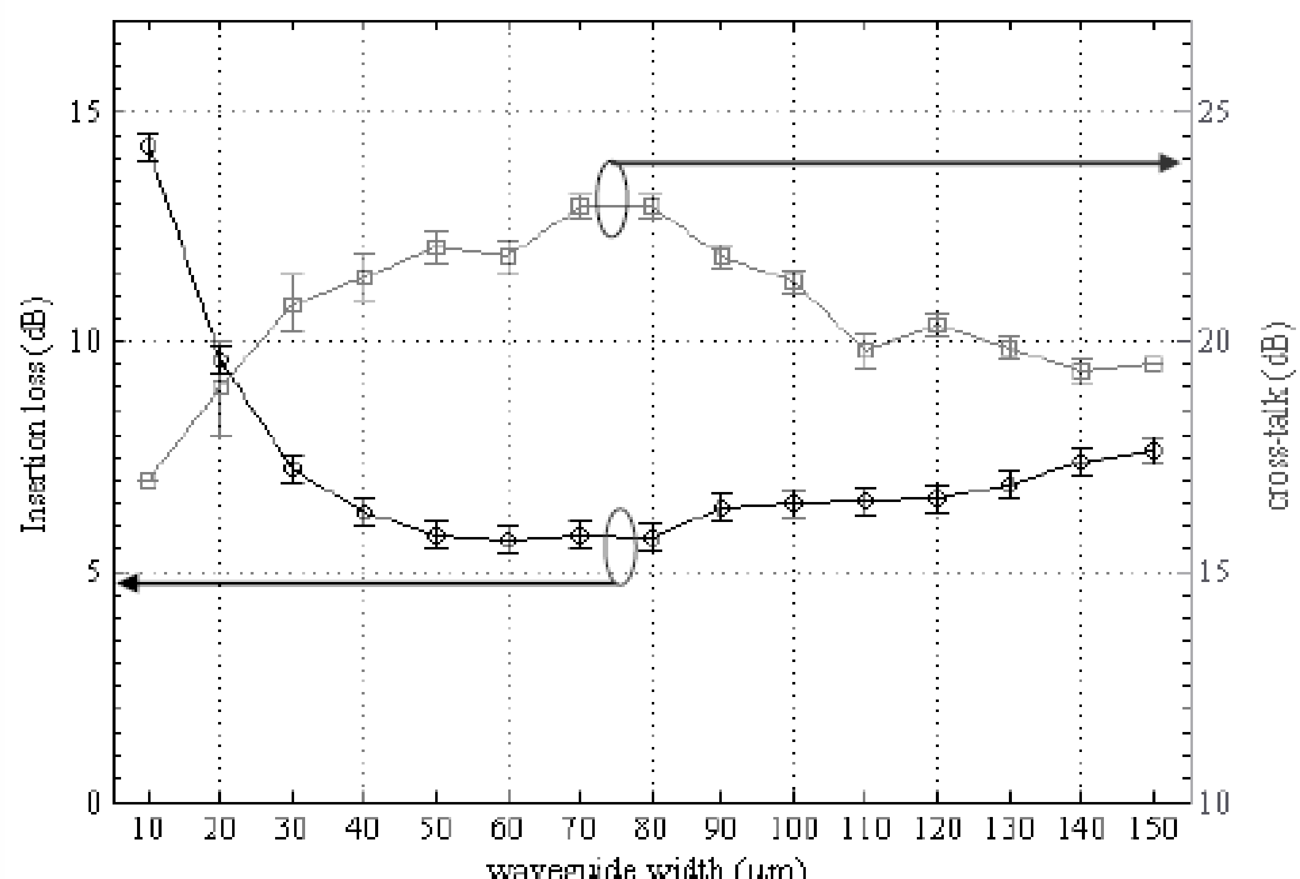
Surface roughness



- RMS side wall roughness: 9 nm to 74 nm

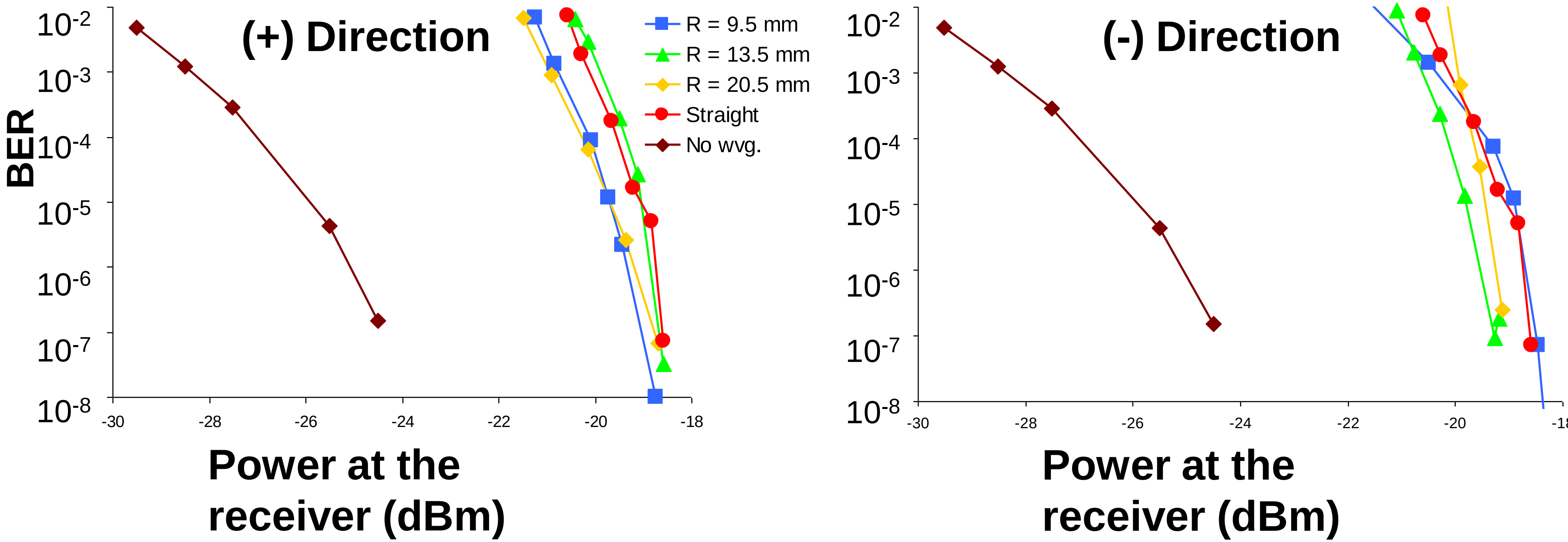
- RMS polished end surface roughness: 26 nm to 192 nm.

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

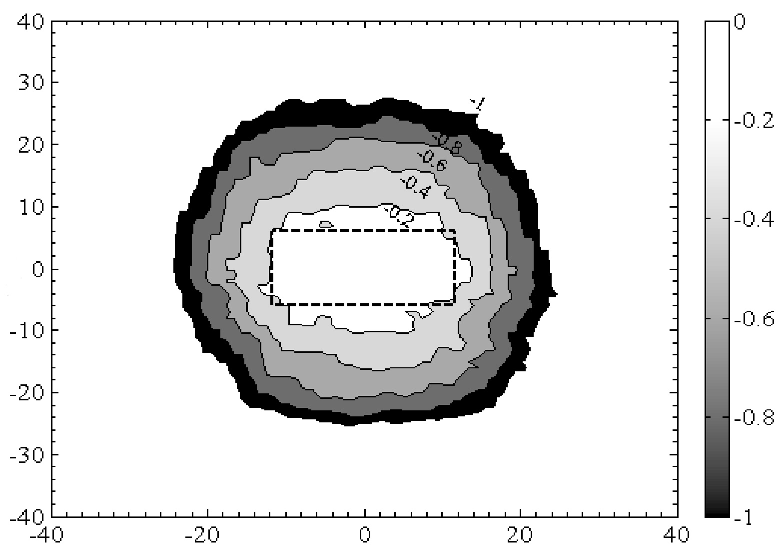


6~7dB for a 70 µm width waveguide

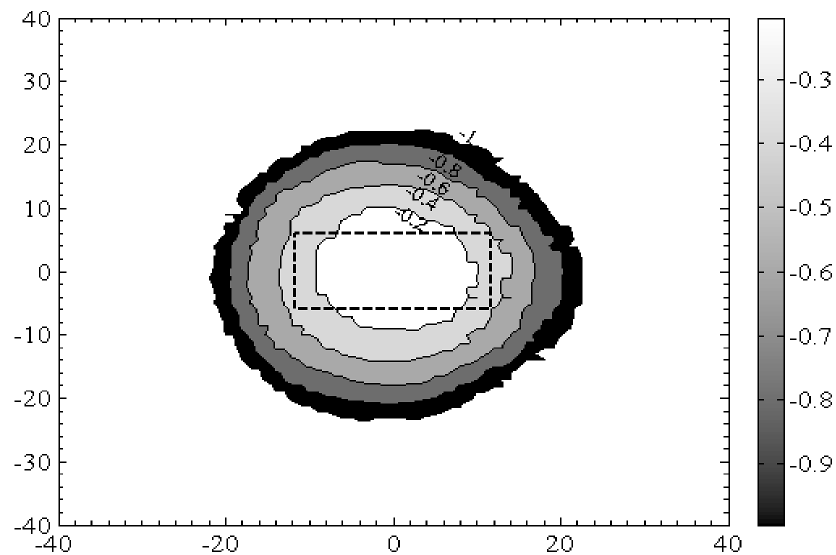
Bit error rate for laterally misaligned 1550 nm 2.5 Gb/s DFB laser



Contour map of VCSEL and PD misalignment



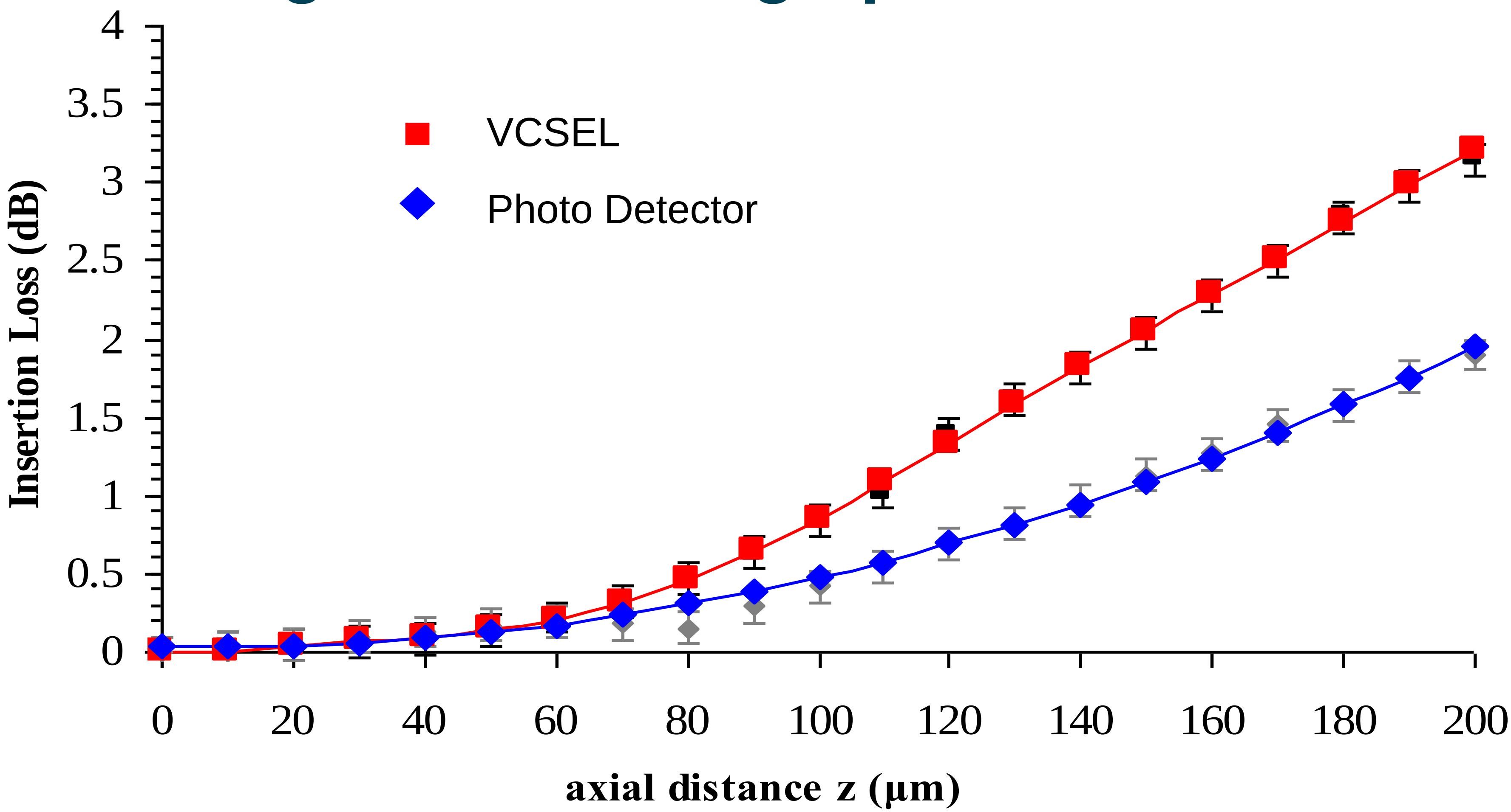
(a) Contour map of relative insertion loss compared to the maximum coupling position for VCSEL misalignment at z = 0.



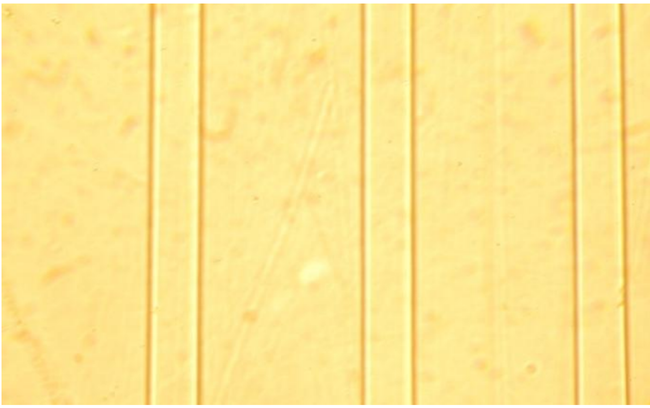
(b) Same for PD misalignment at *z* = 0. Resolution step was *Δx* = *Δy* = 1 µm.

- 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

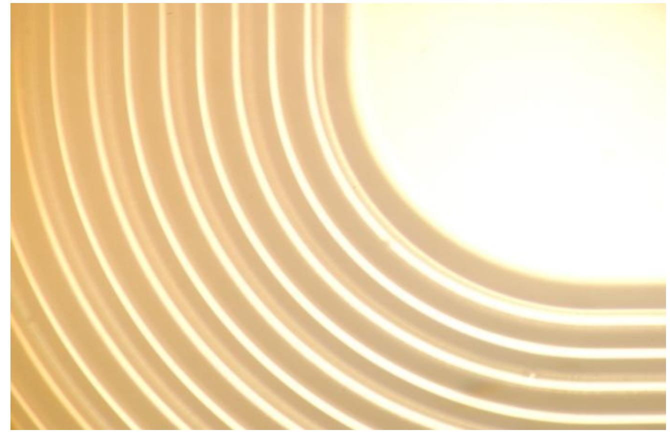
Coupling Loss for VCSEL and PD for misalignments along optic axis



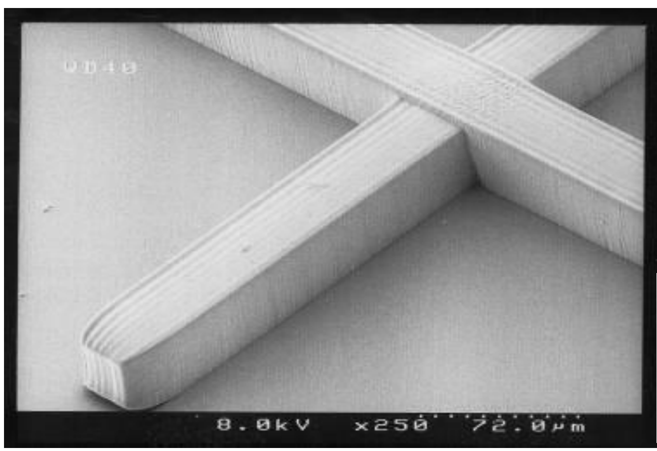
Fabrication Techniques and Waveguides Samples



Straight waveguides – Optical InterLinks



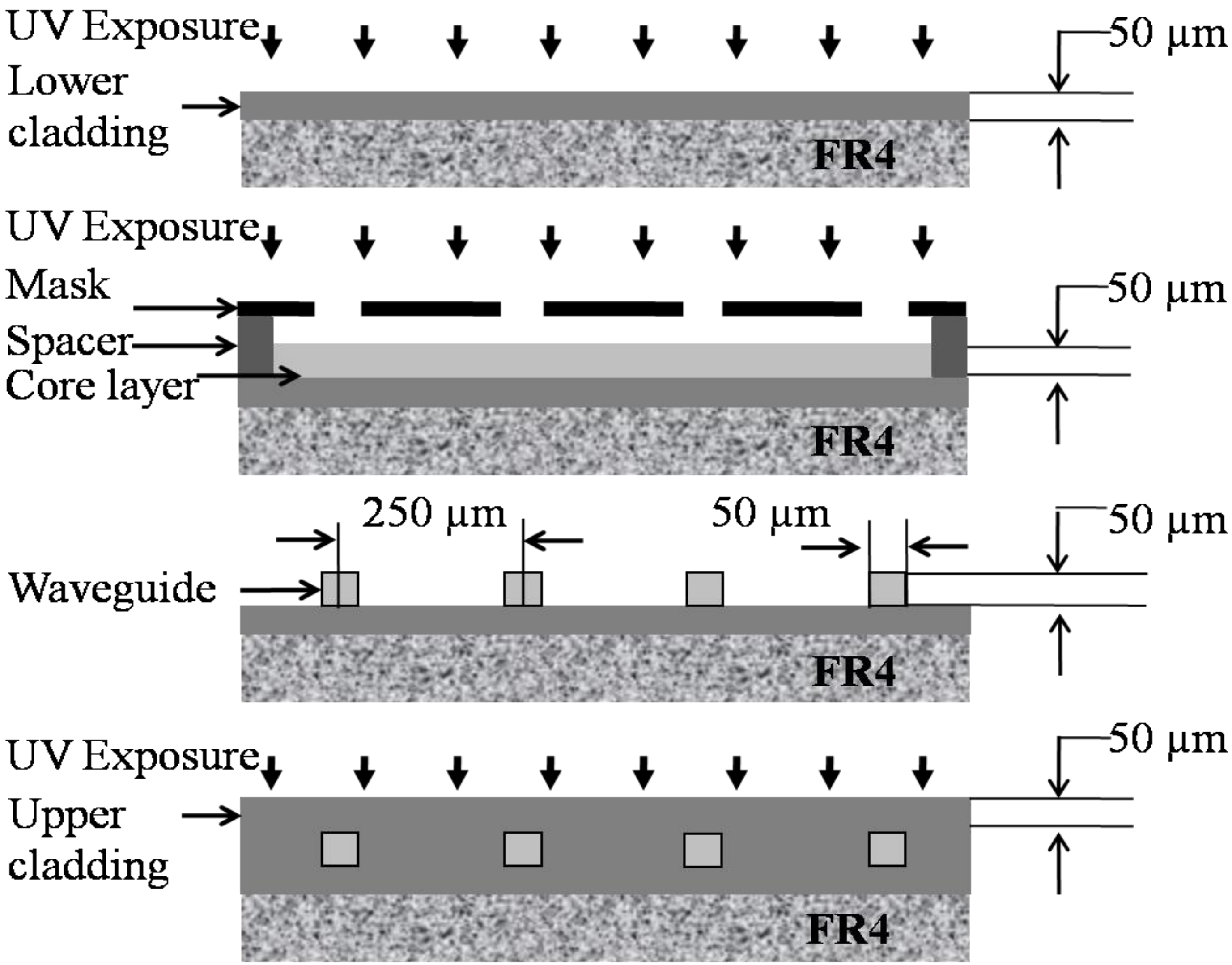
90° Crossings – Dow Corning



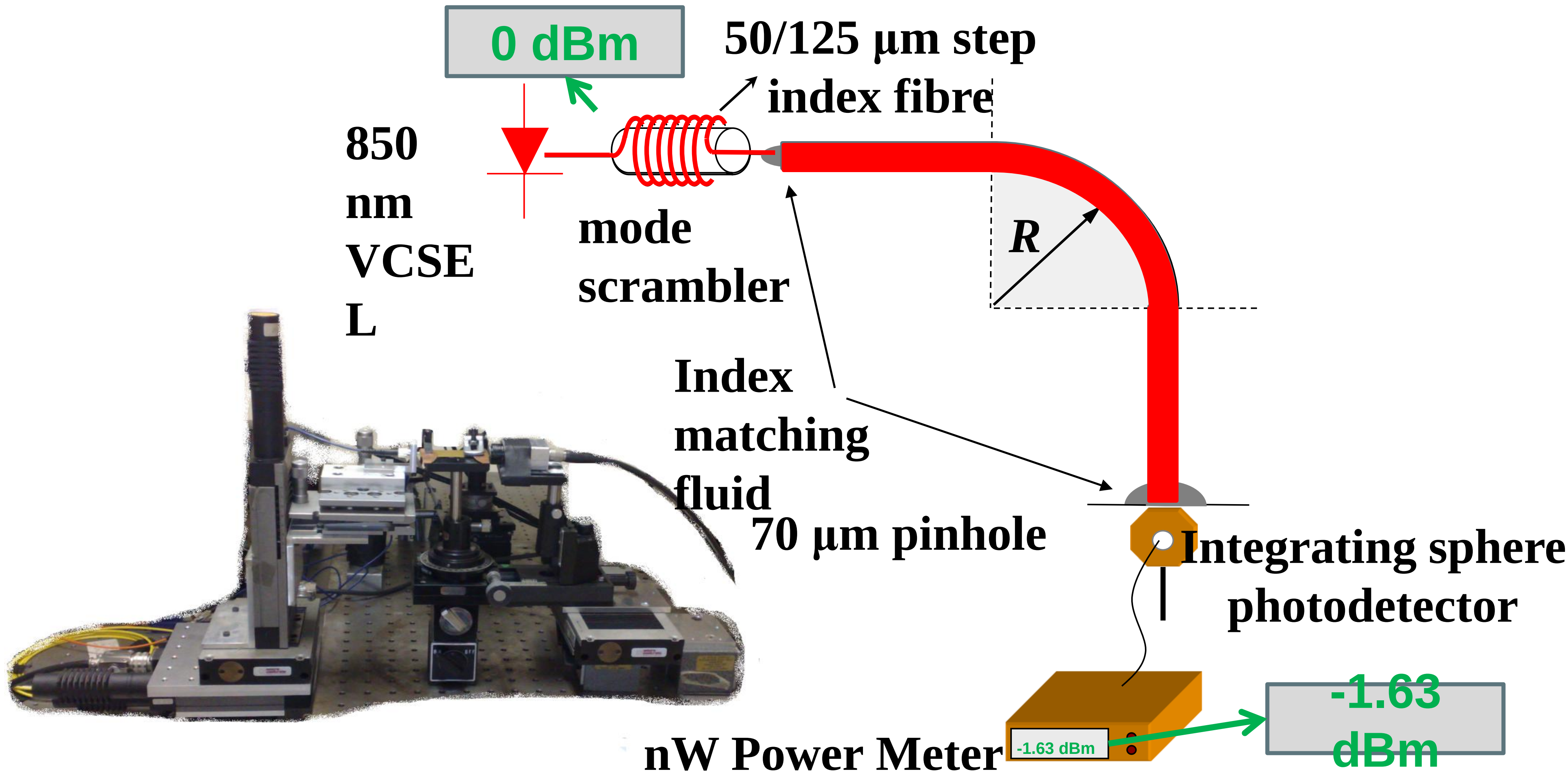
90° Crossings – Heriot Watt University

50° Crossings – Exxelis

Photolithographic Fabrication of Waveguides



Optical Loss Measurement



VCSEL Array for Crosstalk Measurement

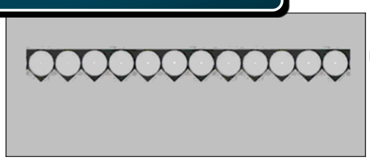
PIN Array

Source: Microsemi Corporation

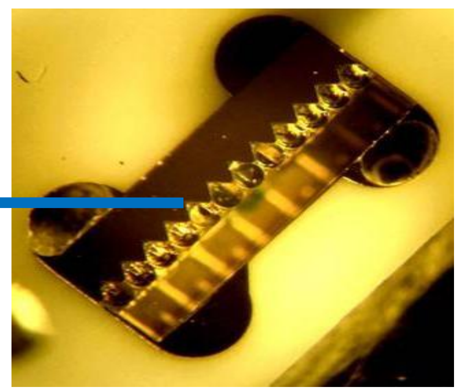
VCSEL Array

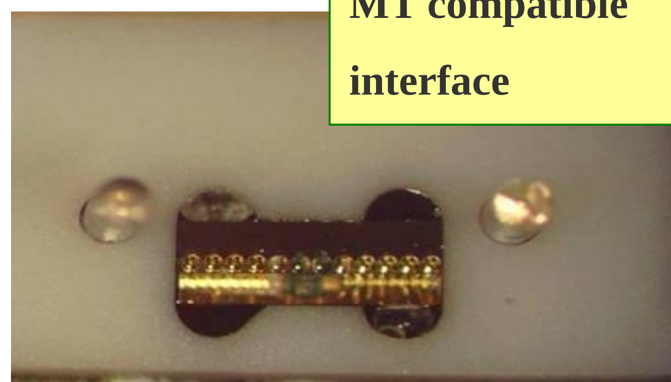
Source: ULM Photonics GmbH

GRIN Lens Array



Source: GRINTech GmbH

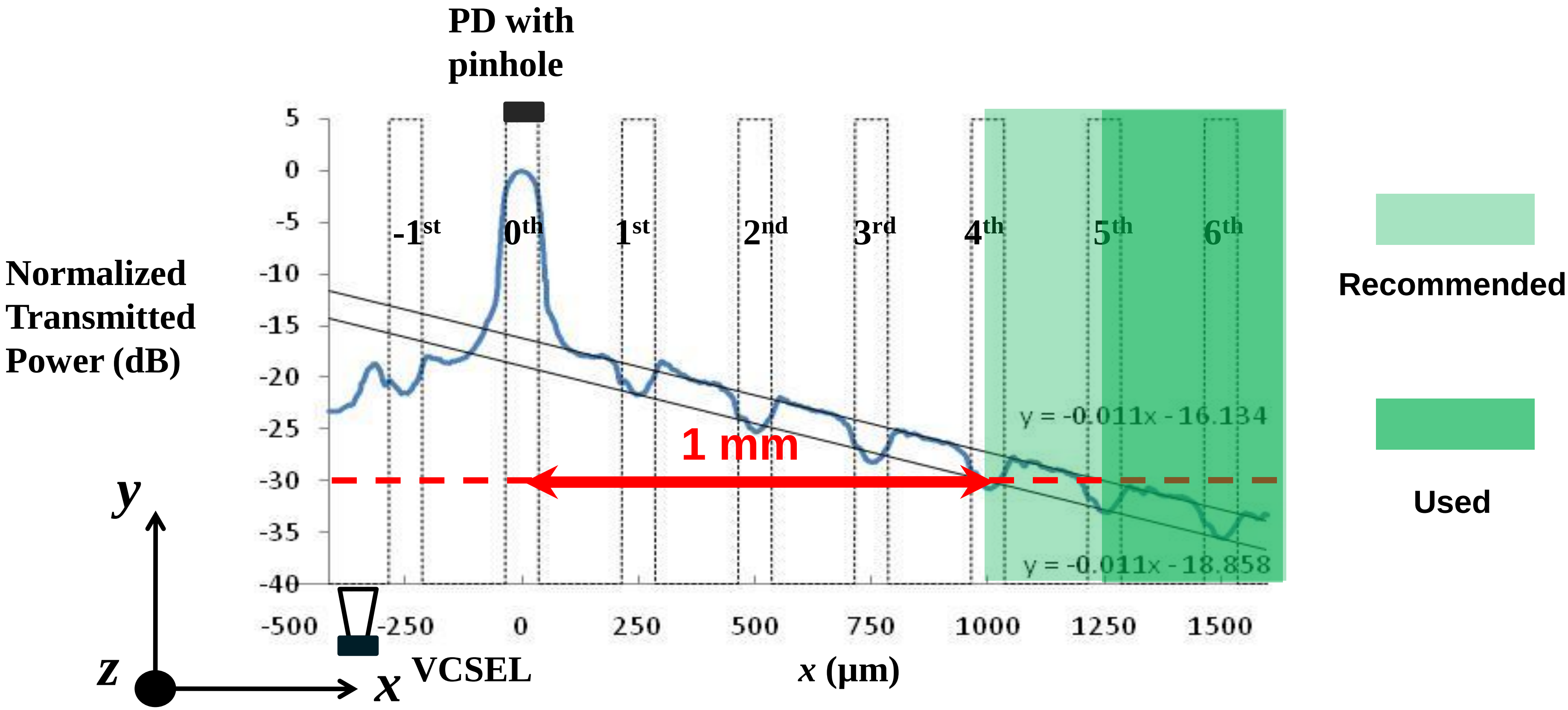




MT compatible interface

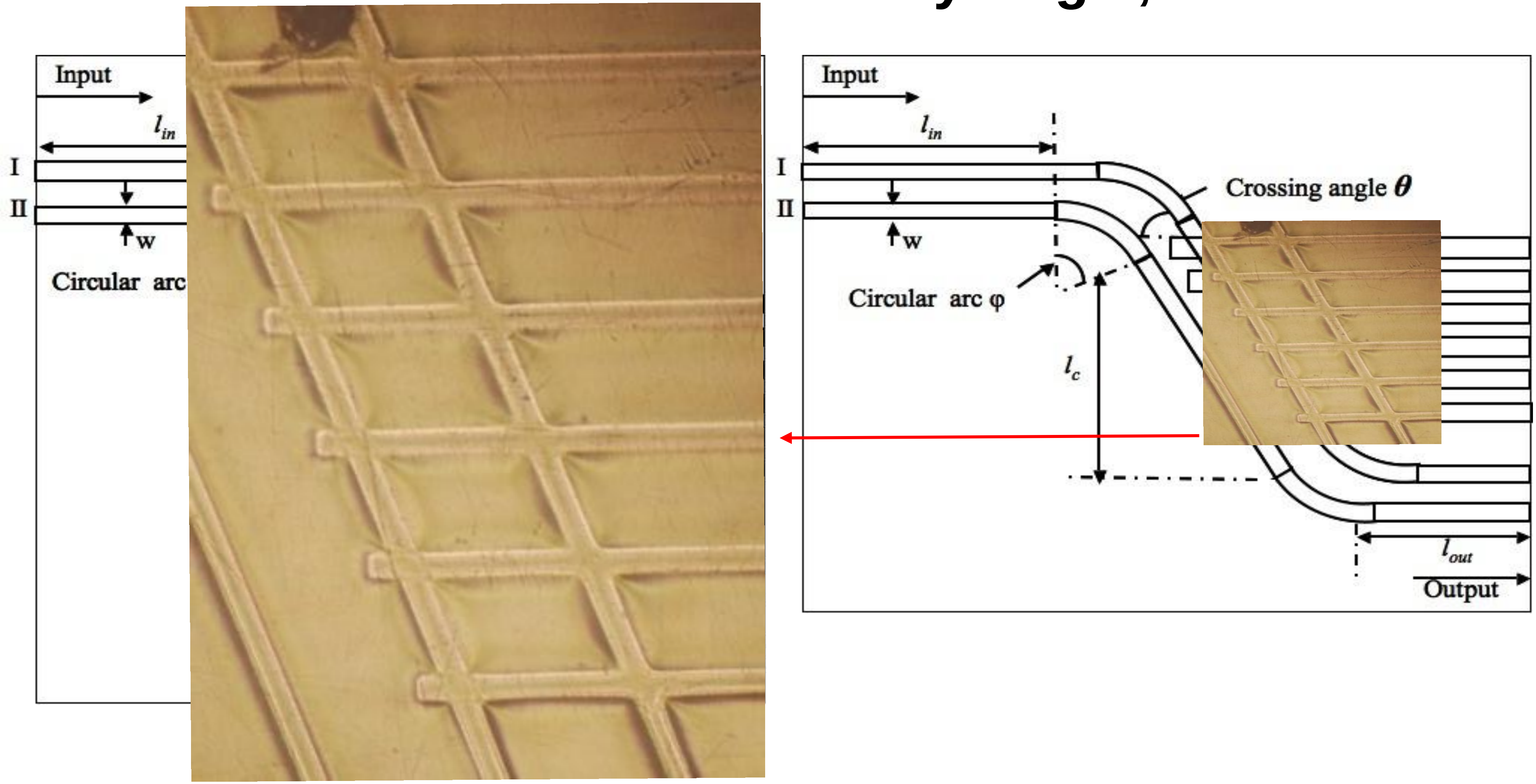
xyratex

Design Rules for Inter-waveguide Cross Talk

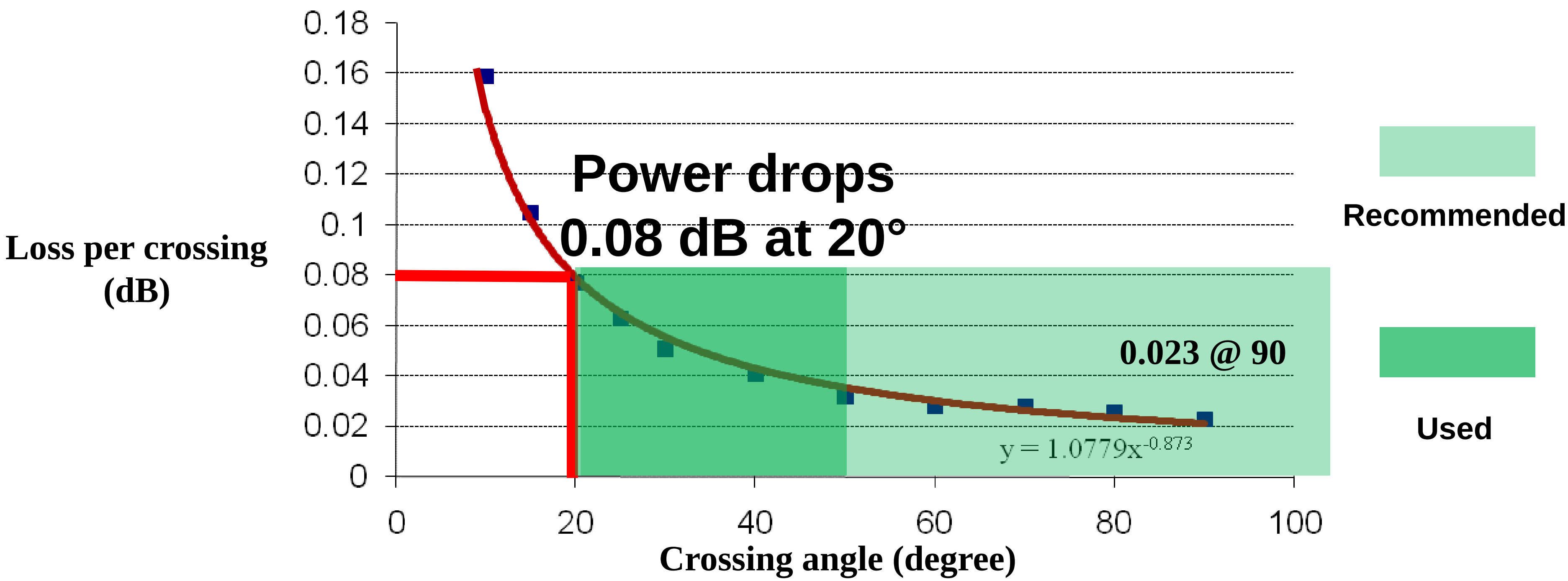


- 70 µm × 70 µm waveguide cross sections and 10 cm long
- In the cladding power drops linearly at a rate of 0.011 dB/µm
- Crosstalk reduced to -30 dB for waveguides 1 mm apart

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

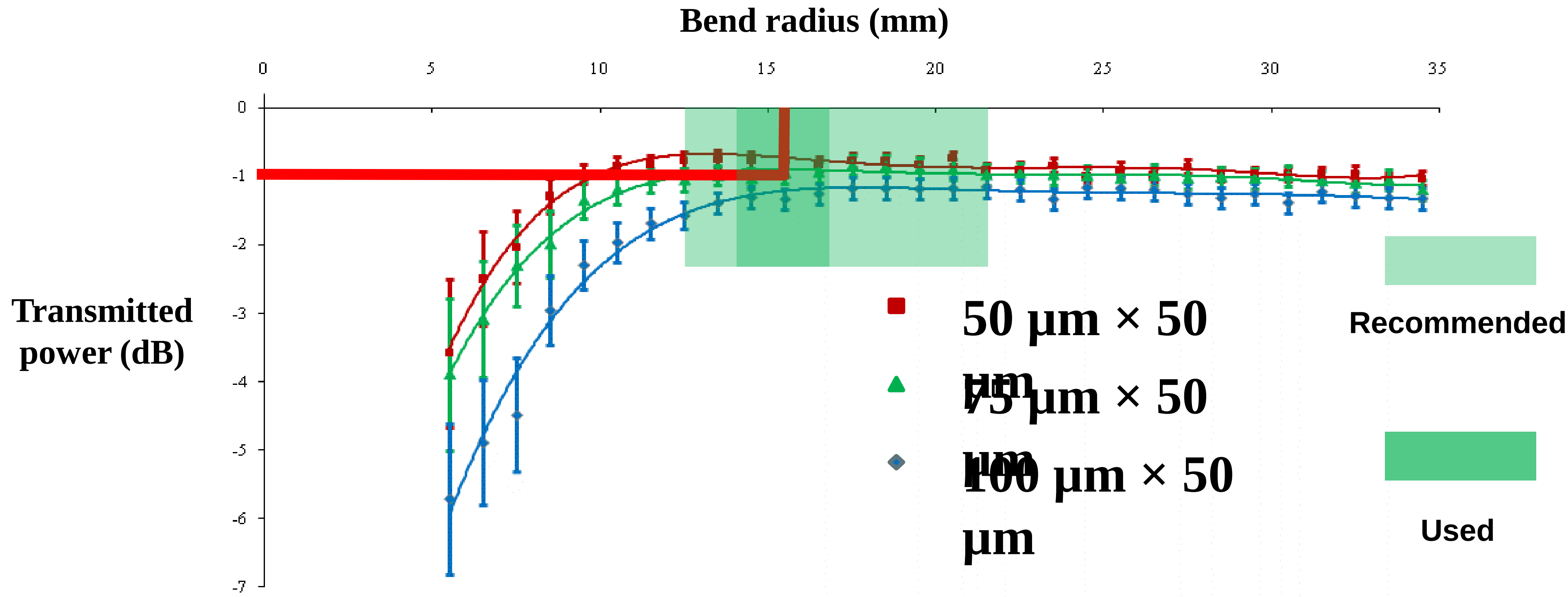


Design Rules for Arbitrary Angle Crossings



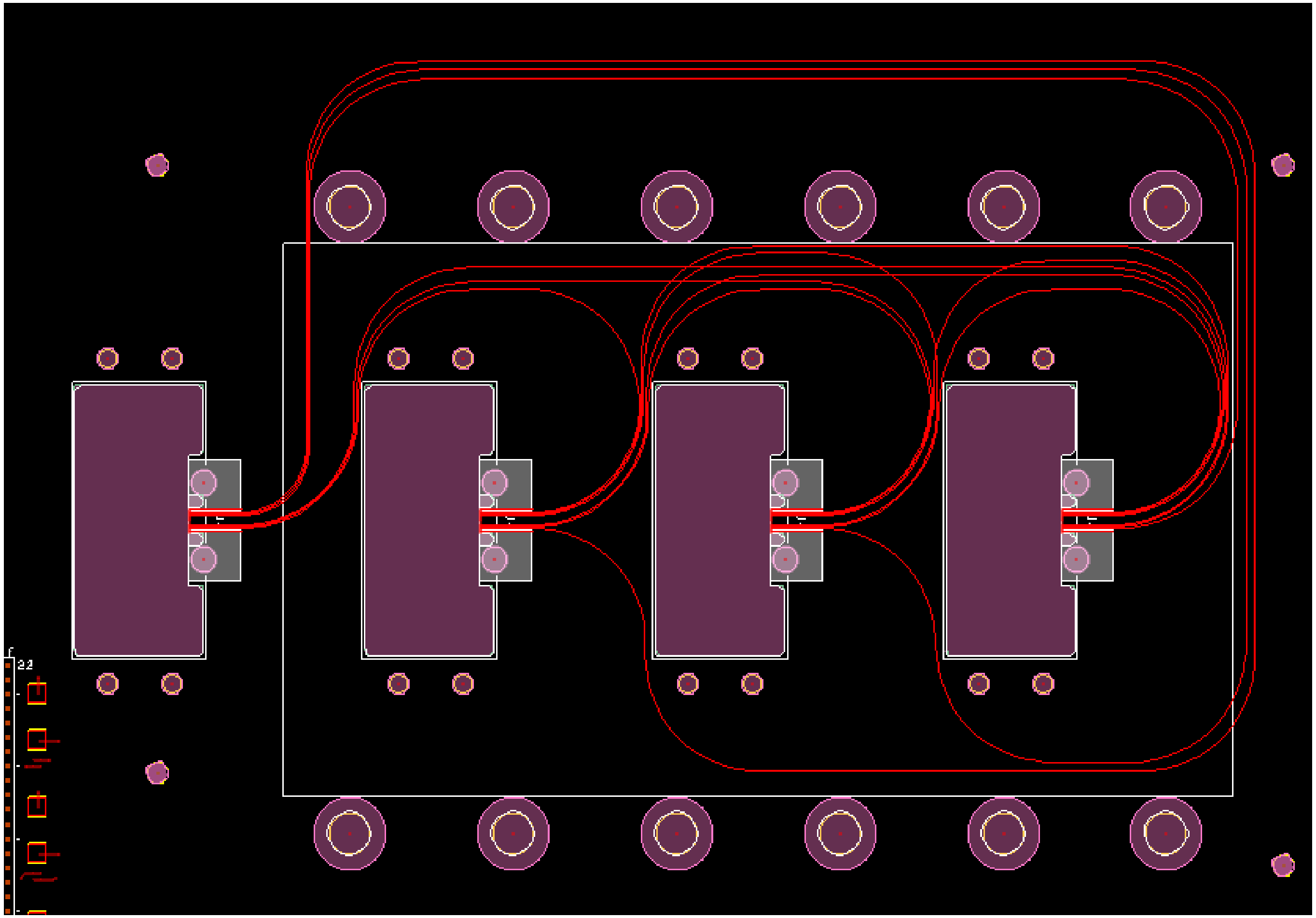
- Loss of 0.023 dB per 90° crossing consistent with other reports
- The output power dropped by 0.5% at each 90° crossing
- The loss per crossing (L_c) depends on crossing angle (θ), $L_c = 1.0779 \cdot \theta^{-0.8727}$

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

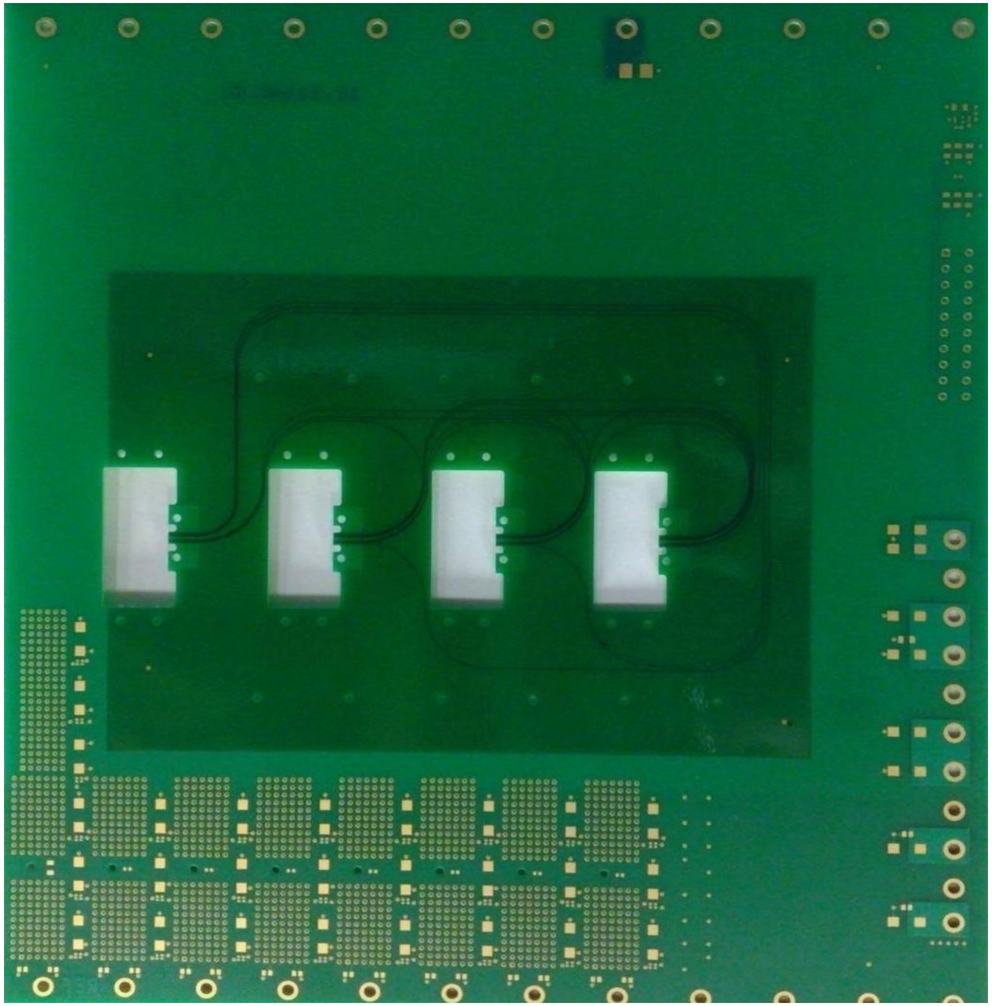


Fully connected waveguide layout using design rules

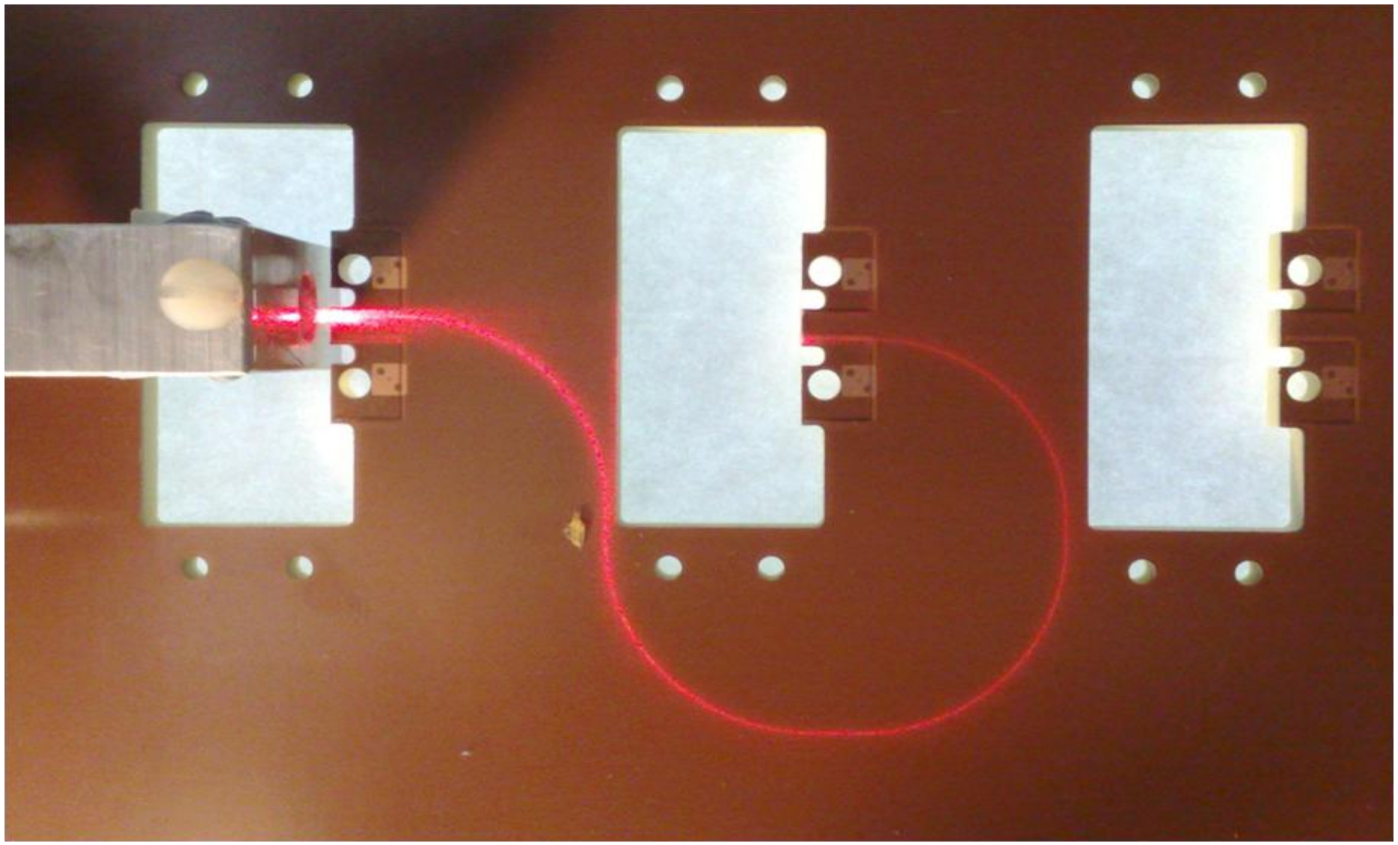
Power Budget

<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>

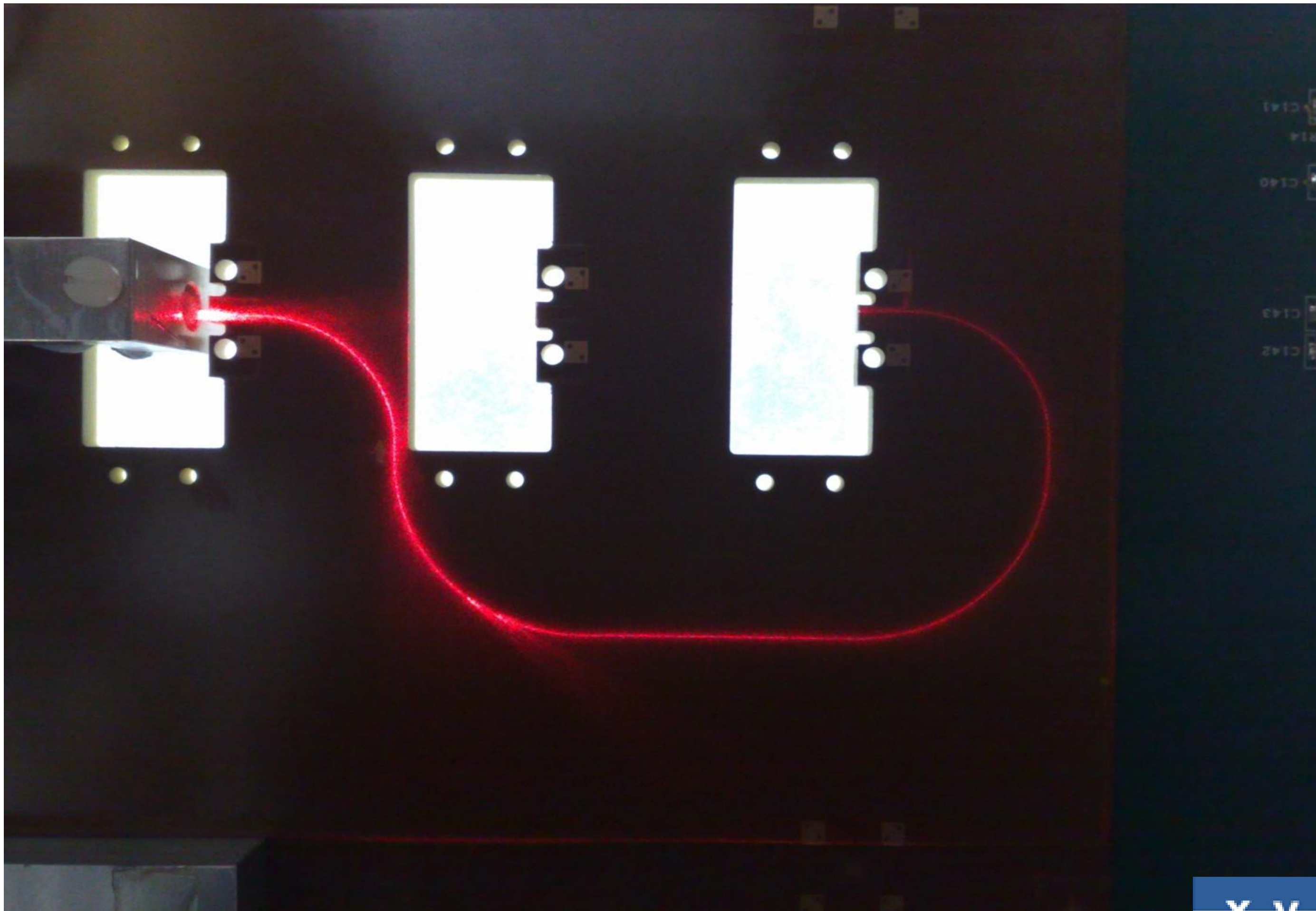
Demonstrator Dummy Board



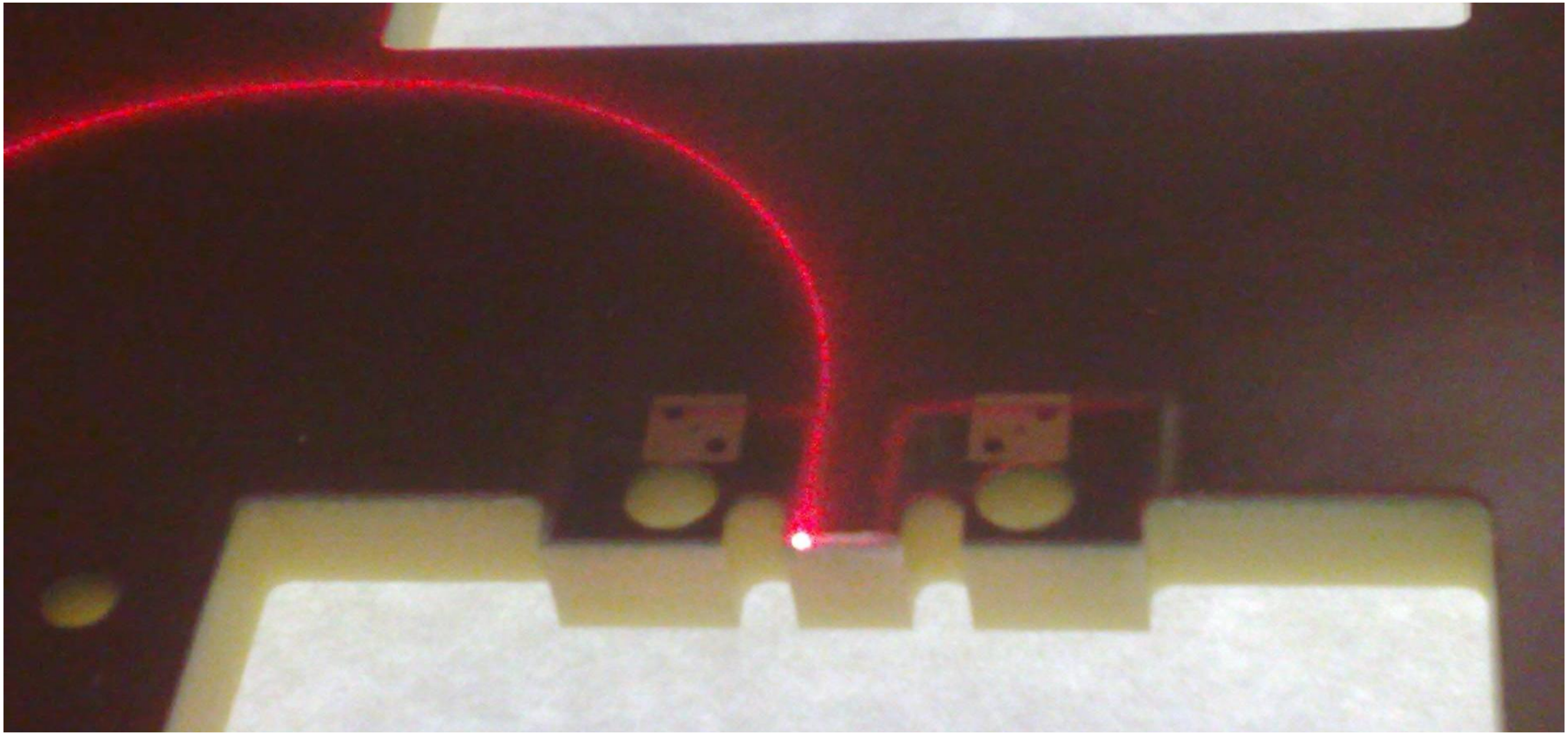
The Shortest Waveguide Illuminated by Red Laser



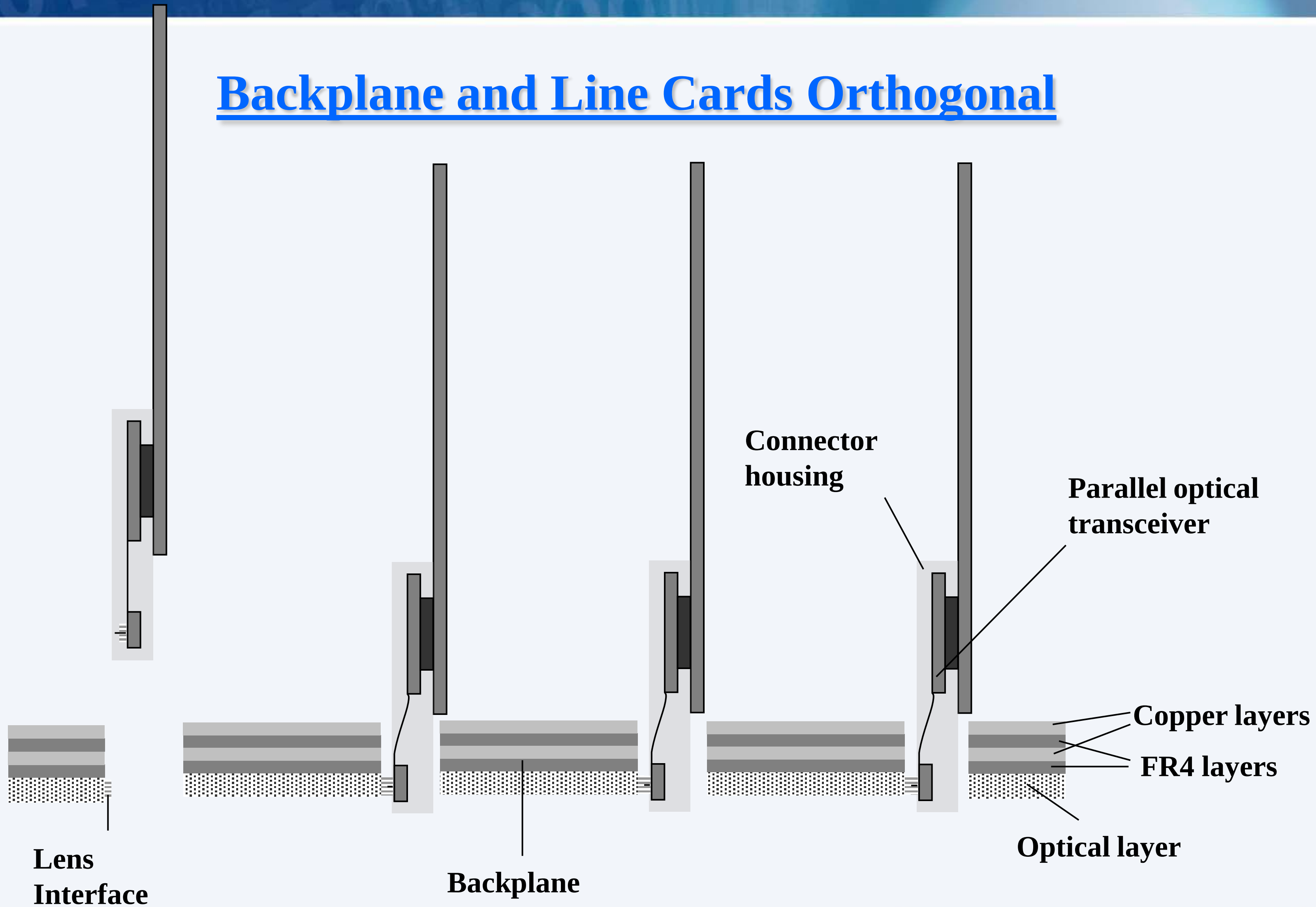
Waveguide with 2 Crossings Connected 1^{st} to 3^{rd} Linecard Interconnect



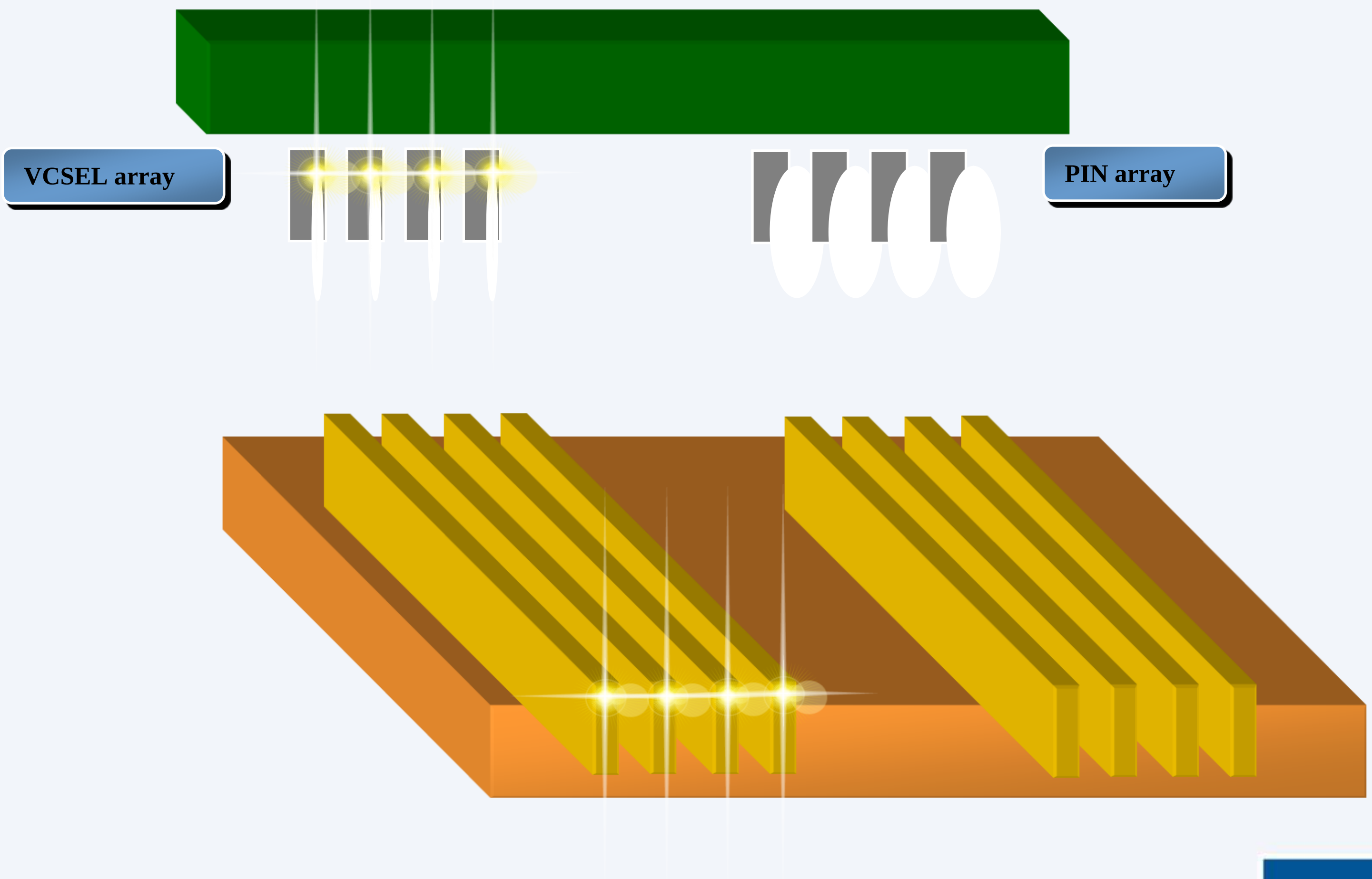
Output Facet of the Waveguide Interconnection

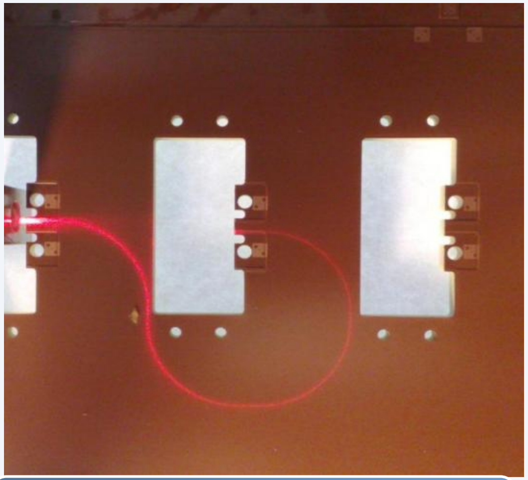


Backplane and Line Cards Orthogonal



Butt-coupled connection approach without 90º deflection optics

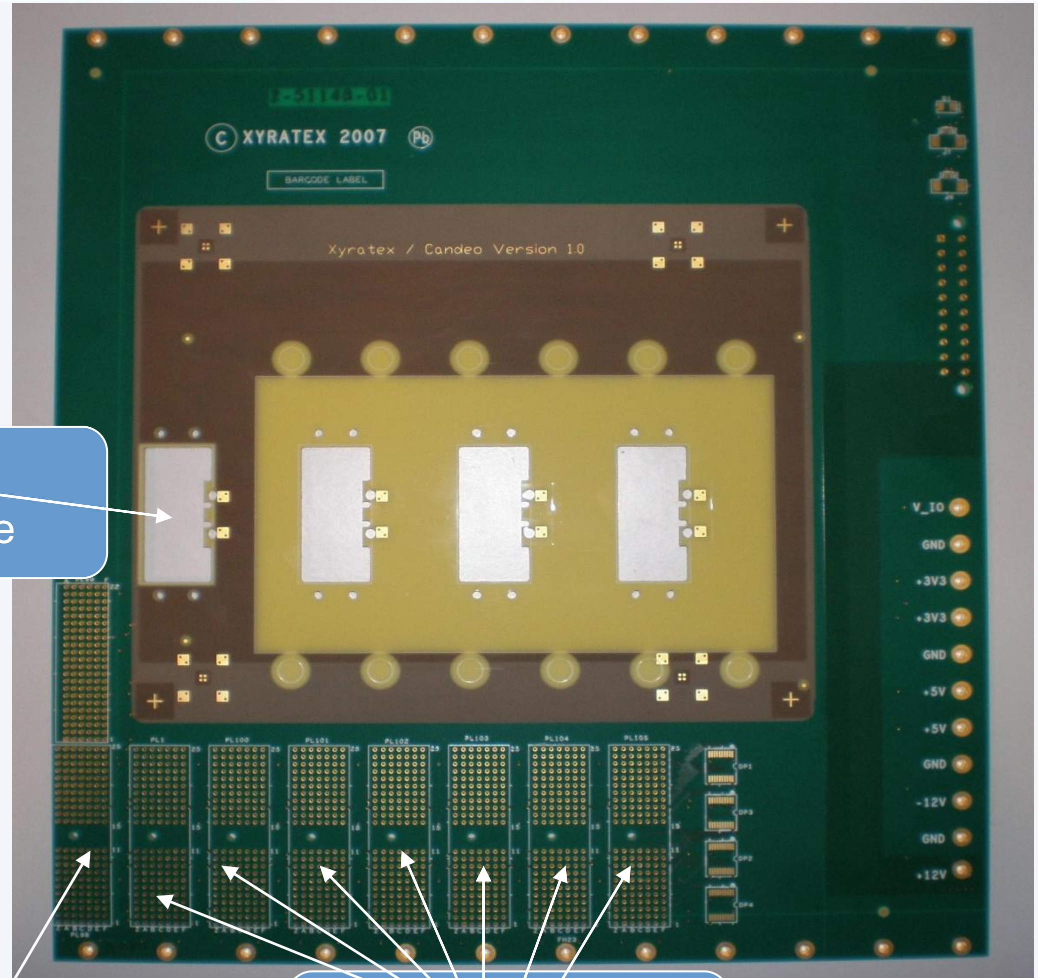




Waveguide illuminated through butt-coupled fibre connection

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
- ❑Electrical C-PCI connector slots for SBC and line cards
- ❑ 1 polymeric optical layer for high speed 10 GbE traffic
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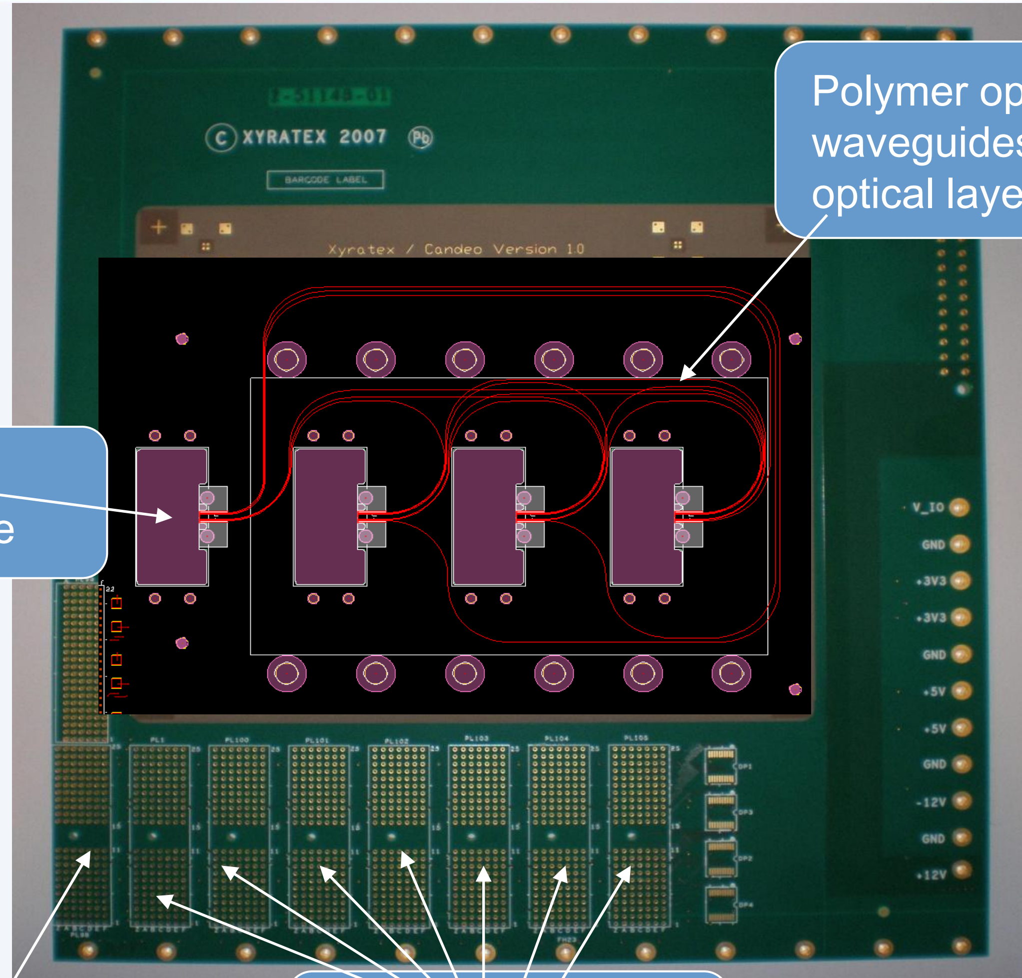
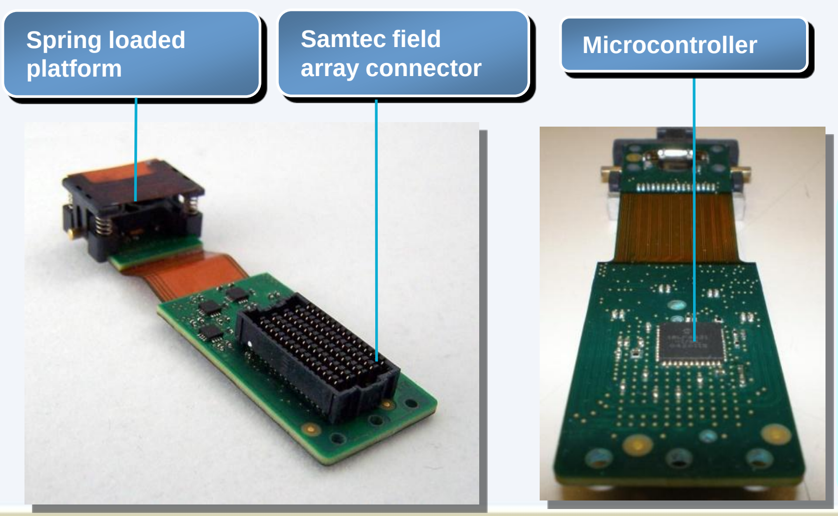
- ❑ Dedicated point-to-point optical waveguide architecture



PARALLEL OPTICAL PCB CONNECTOR MODULE

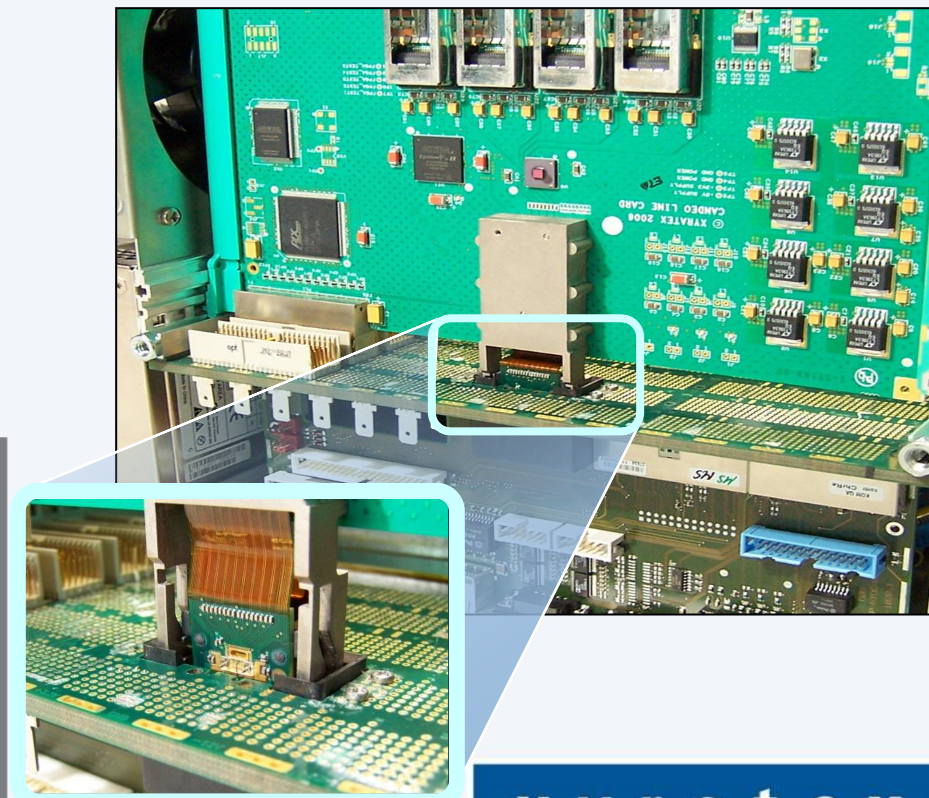
Parallel optical transceiver circuit

- ❑ Small form factor quad parallel optical transceiver
- ❑ Microcontroller supporting I^2C interface
- ❑ Samtec "*SEARAY™*" open pin field array connector
- ❑ Spring loaded platform for optical engagement mechanism
- ❑ Custom heatsink for photonic drivers



Backplane connector module

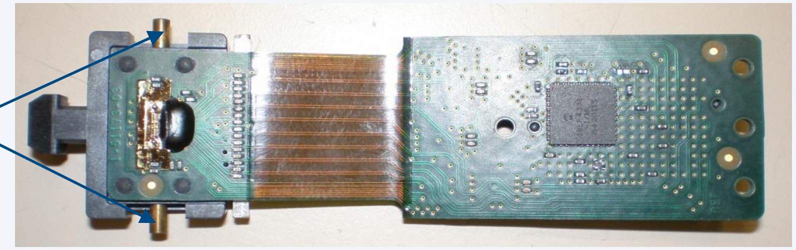
- ❑ Samtec / Xyratex collaborate to develop optical PCB connector
- ❑ 1 stage insertion engagement mechanism developed
- ❑ Xyratex transceiver integrated into connector module

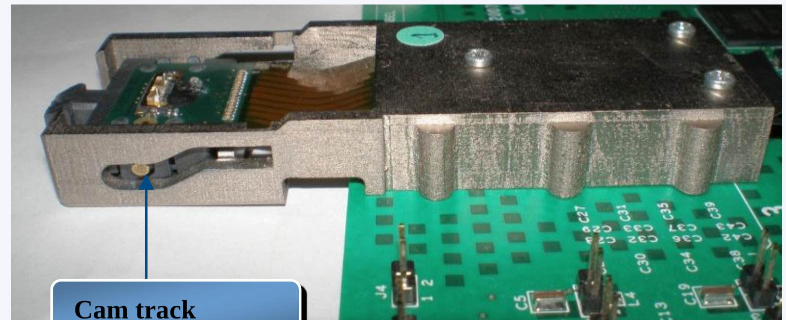


xyratex

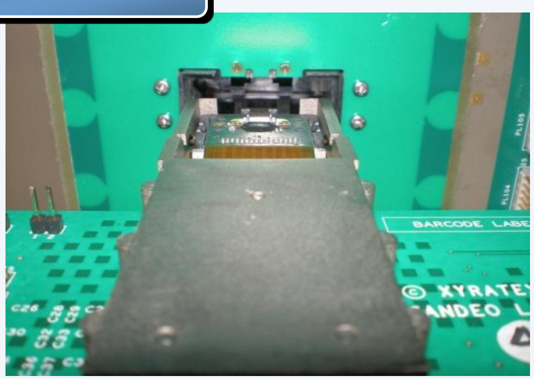
Engagement process

- Optical transceiver interface floats
- Backplane receptacle “funnels” connector
- Cam followers force optical interface up
- Optical transceiver lens butt-couples to backplane lens

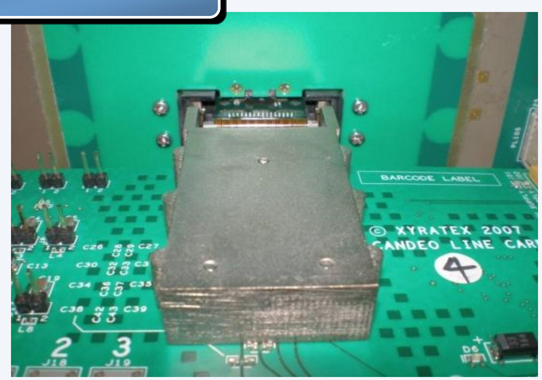




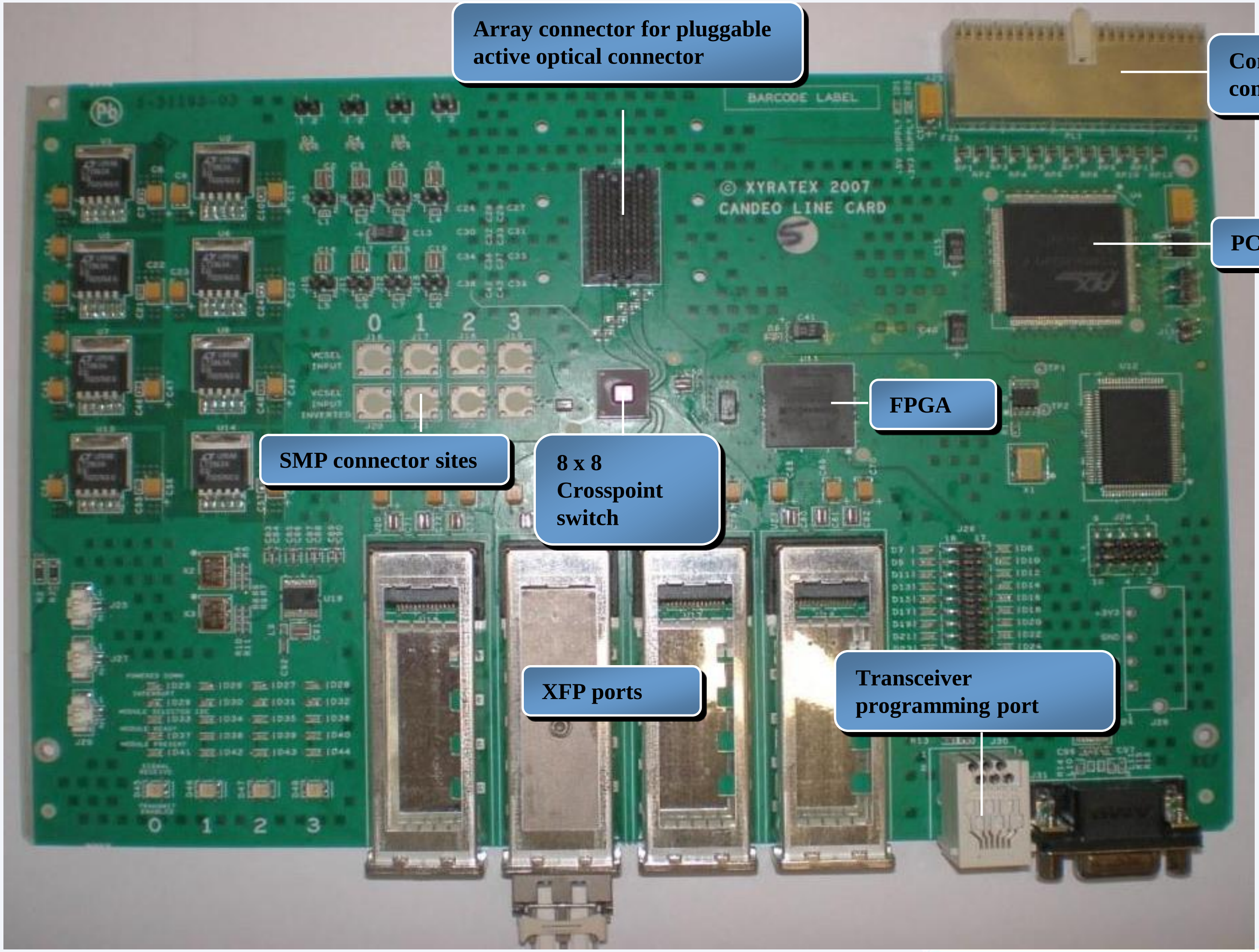
Undocked



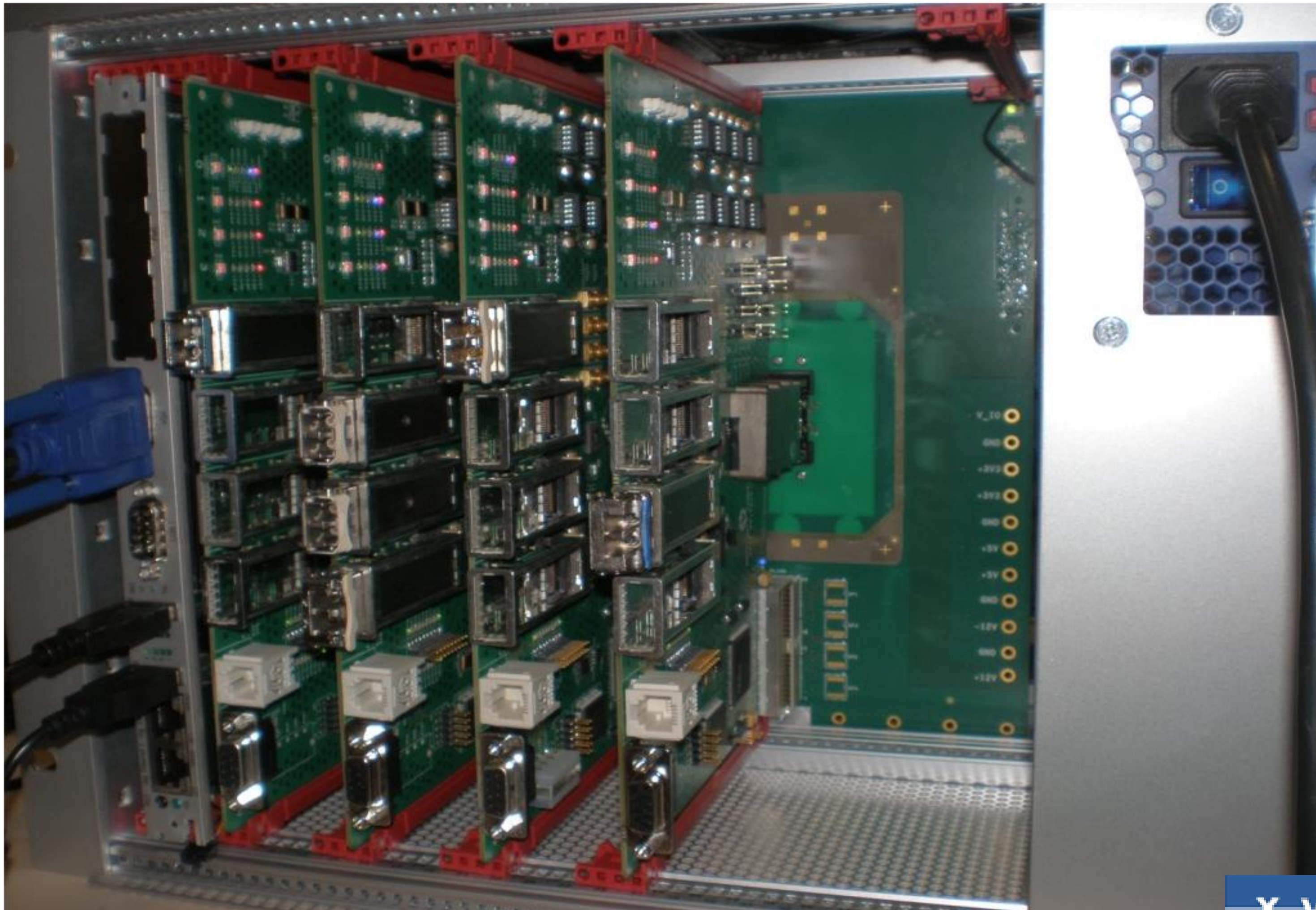
Docked



High Speed Switching Line Card



Demonstrator with Optical Interconnects



Electro-optical backplane

Pluggable optical backplane connectors

Compact PCI chassis

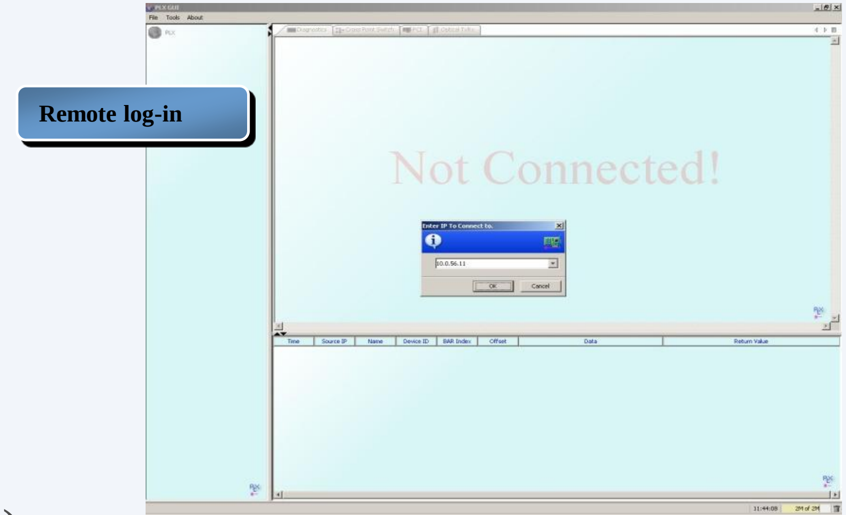
High speed switch line cards

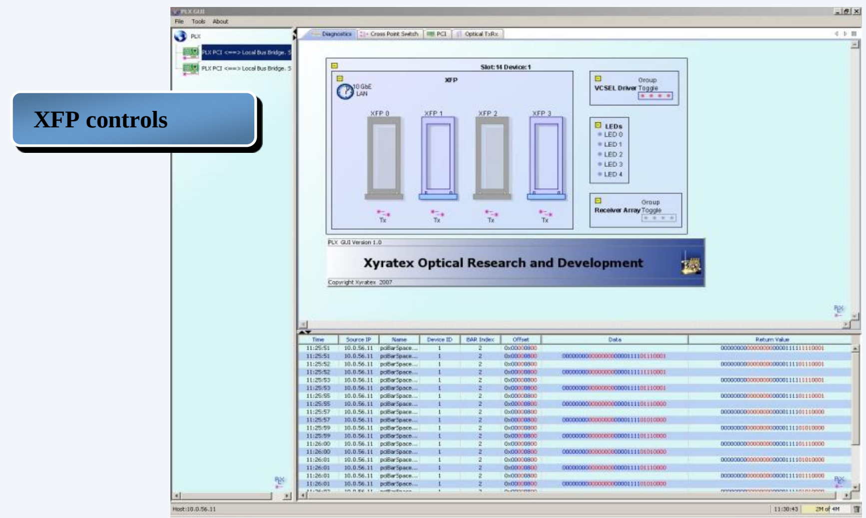
XFP front end

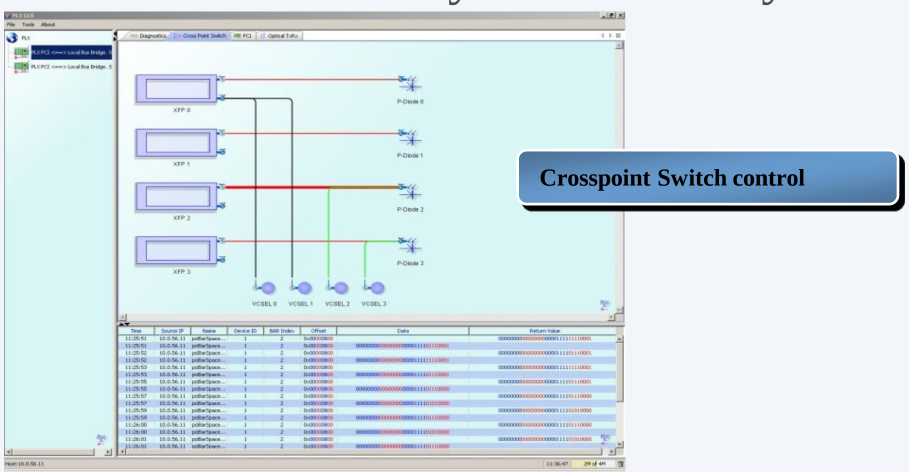
Single board computer

GUI control interface

- ❑ Remote admin
- ❑ XFP control
- ❑ Crosspoint switch configuration
- ❑ Full transceiver control (VCSEL/PIN settings)
- ❑ Selectable between any line card in system







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  - Henry White
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  - Dougal Stewart, Jonathan Calver, Jeremy Rygate, Steve Payne
- **Xyratex Technology Ltd., UK**
  - Dave Milward, Richard Pitwon, Ken Hopkins
- **Exxelis Ltd**
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