Optical printed circuit board and connector technology

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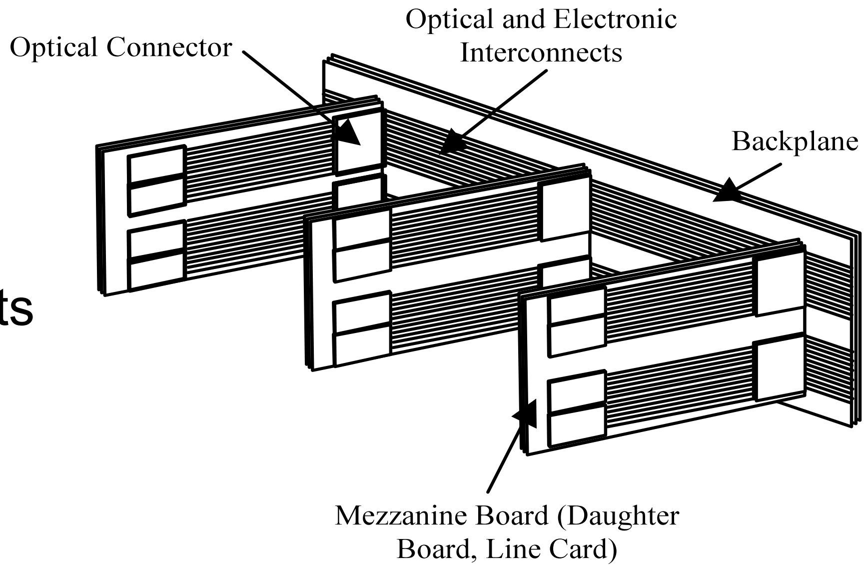
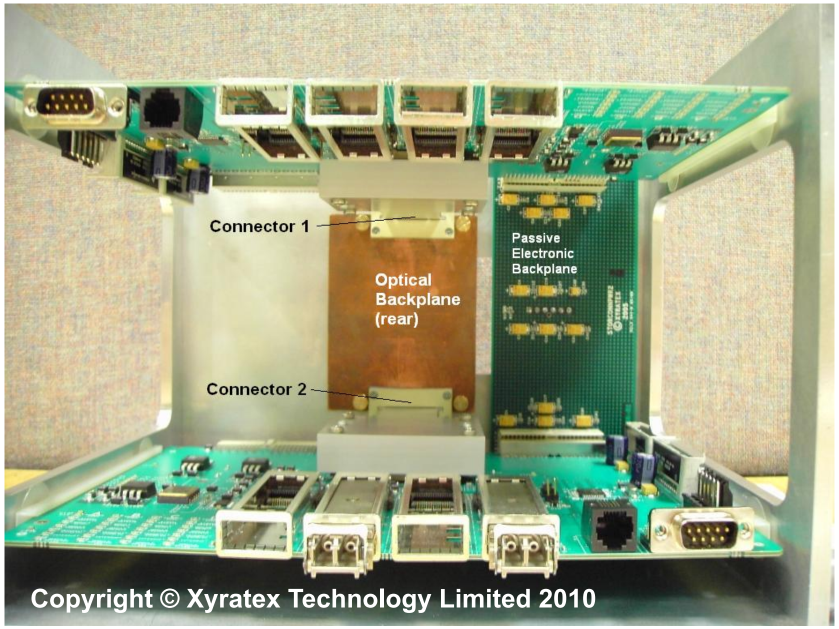
Outline

- 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

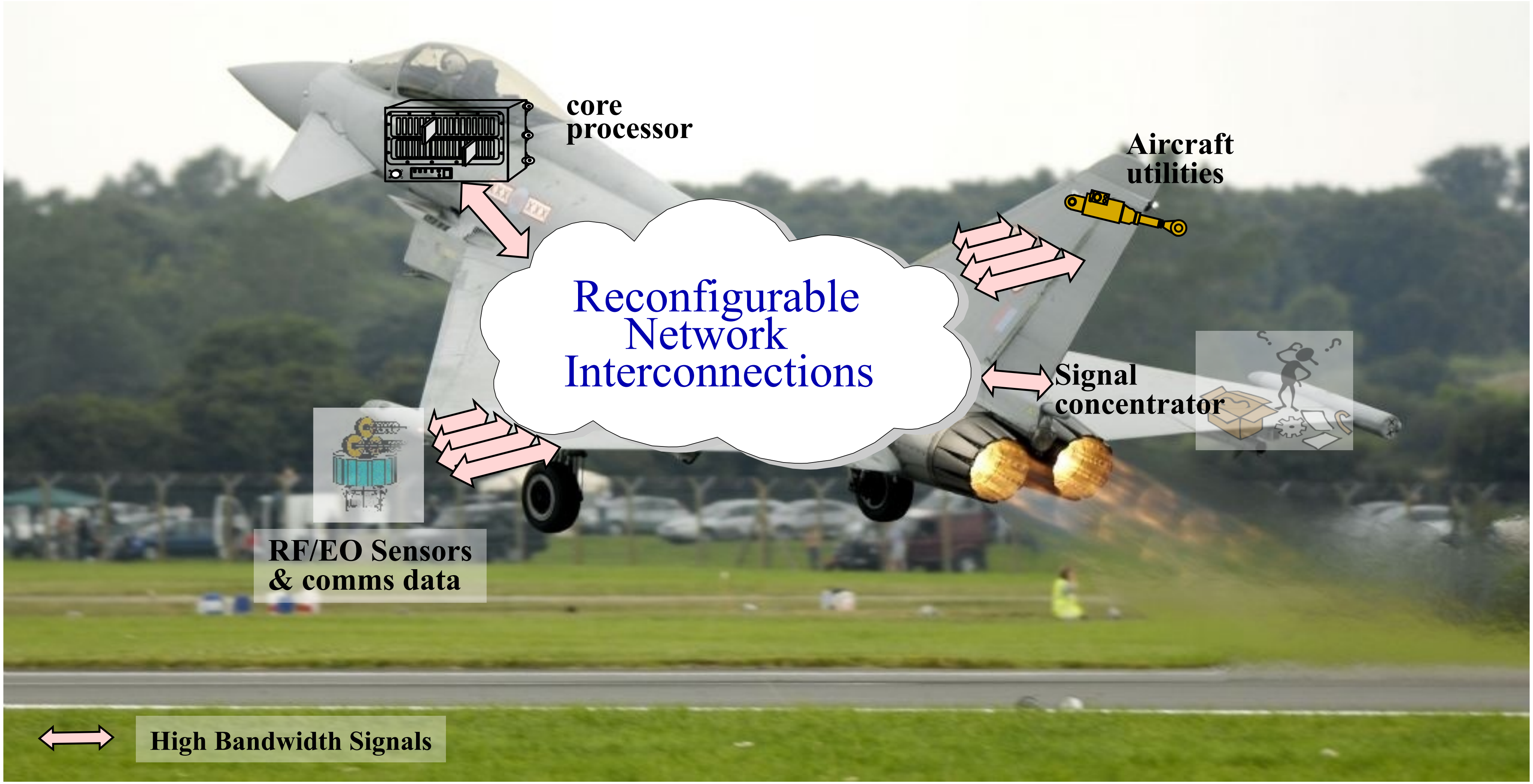
- Optical Waveguides
  - Low loss
  - Low cost
  - Low power consumption
  - Low crosstalk
  - Low clock skew
  - WDM gives higher aggregate bit rate
  - Cannot transmit electrical power

On-board Platform Applications

BAE SYSTEMS

On-board Platform Applications

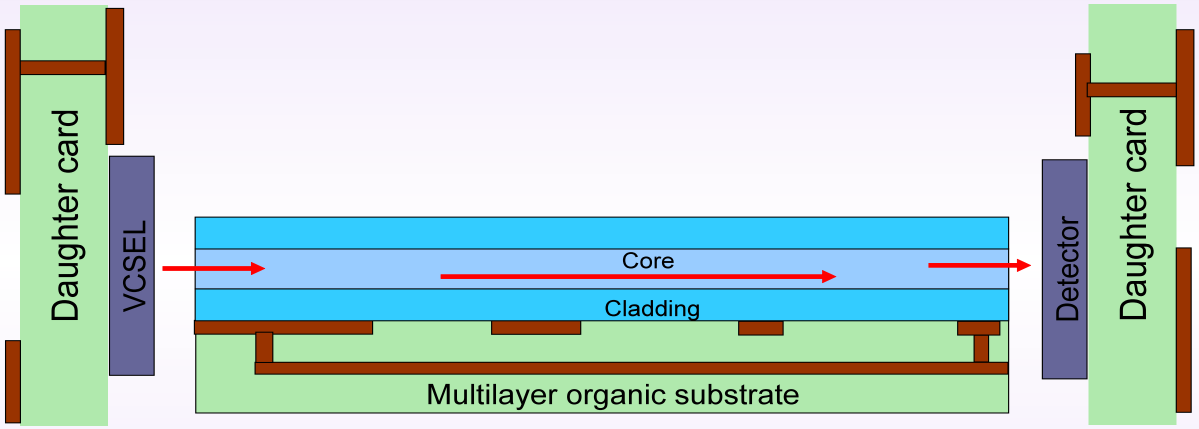
BAE SYSTEMS



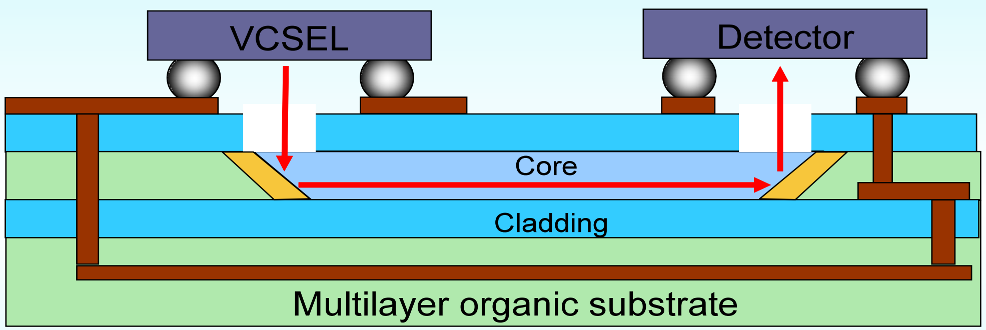
The Integrated Optical and Electronic Interconnect PCB Manufacturing (OPCB) project

- 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

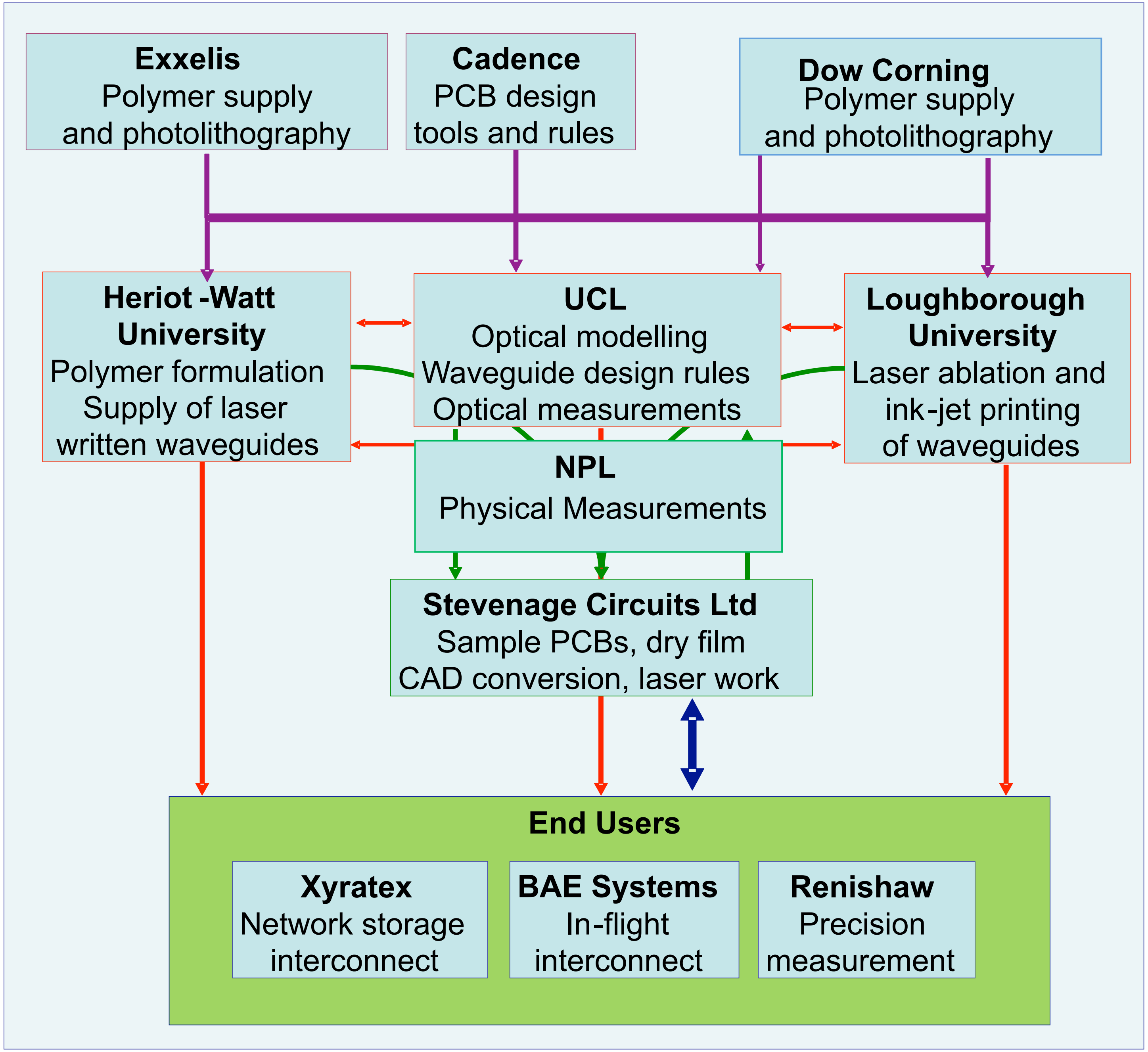
Integration of Optics and Electronics



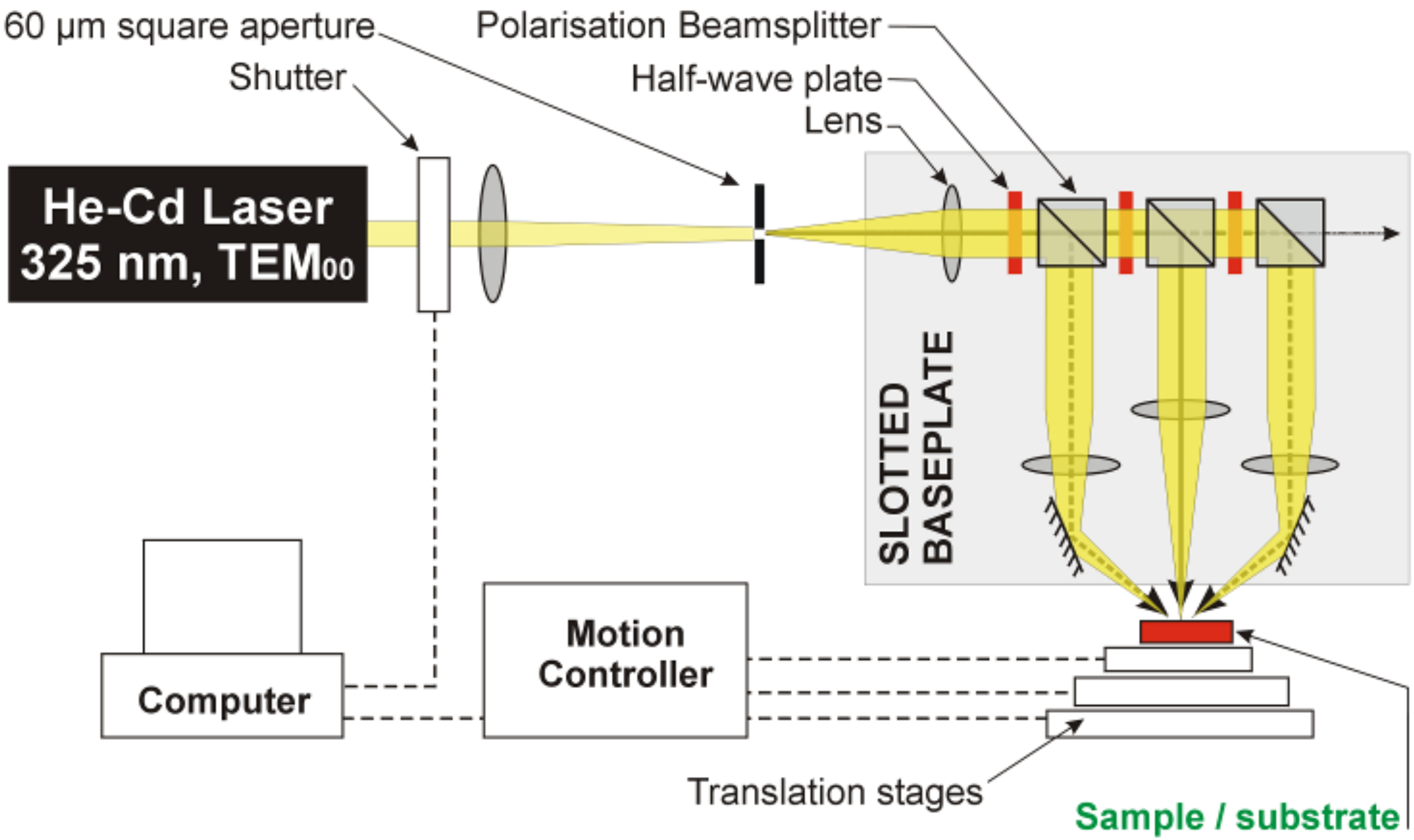
- Backplanes
  - Butt connection of "plug-in" daughter cards
  - In-plane interconnection
- Focus of OPCB project

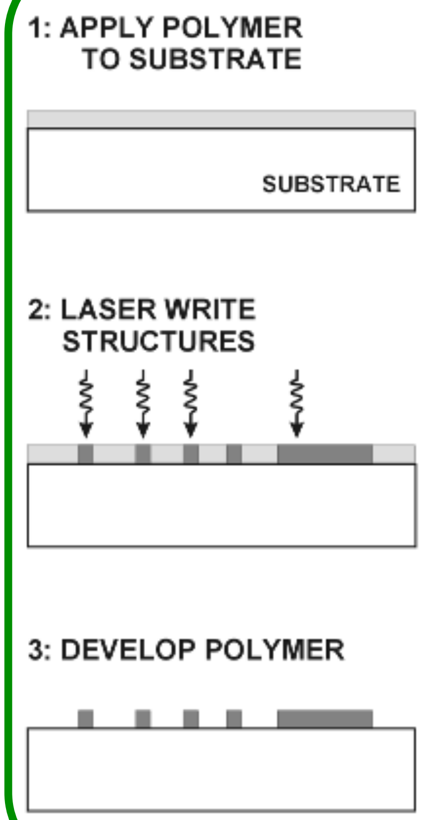


- Out-of-plane connection
  - 45° mirrors
  - Chip to chip connection possible

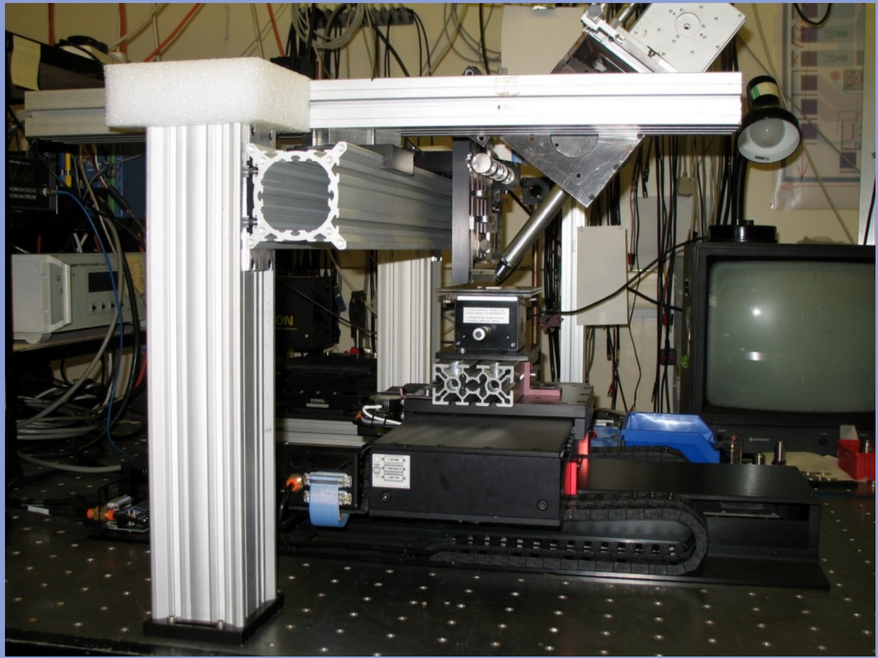

Exxelis
Polymer supply
and photolithography
Cadence
PCB design
tools and rules
Dow Corning
Polymer supply
and photolithography
Heriot -Watt
University
Polymer formulation
Supply of laser
written waveguides
UCL
Optical modelling
Waveguide design rules
Optical measurements
Loughborough
University
Laser 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

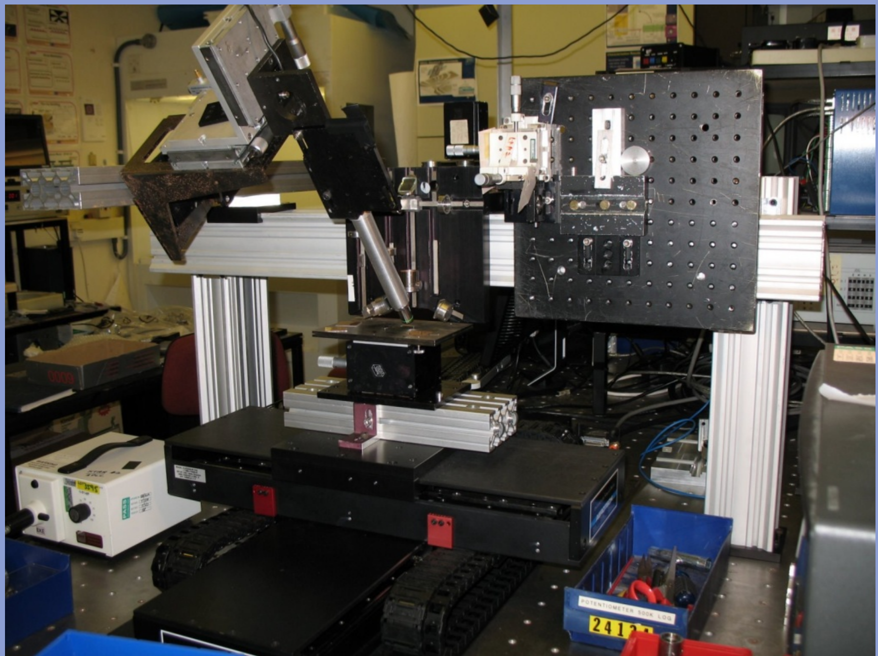
Direct Laser-writing Setup: Schematic

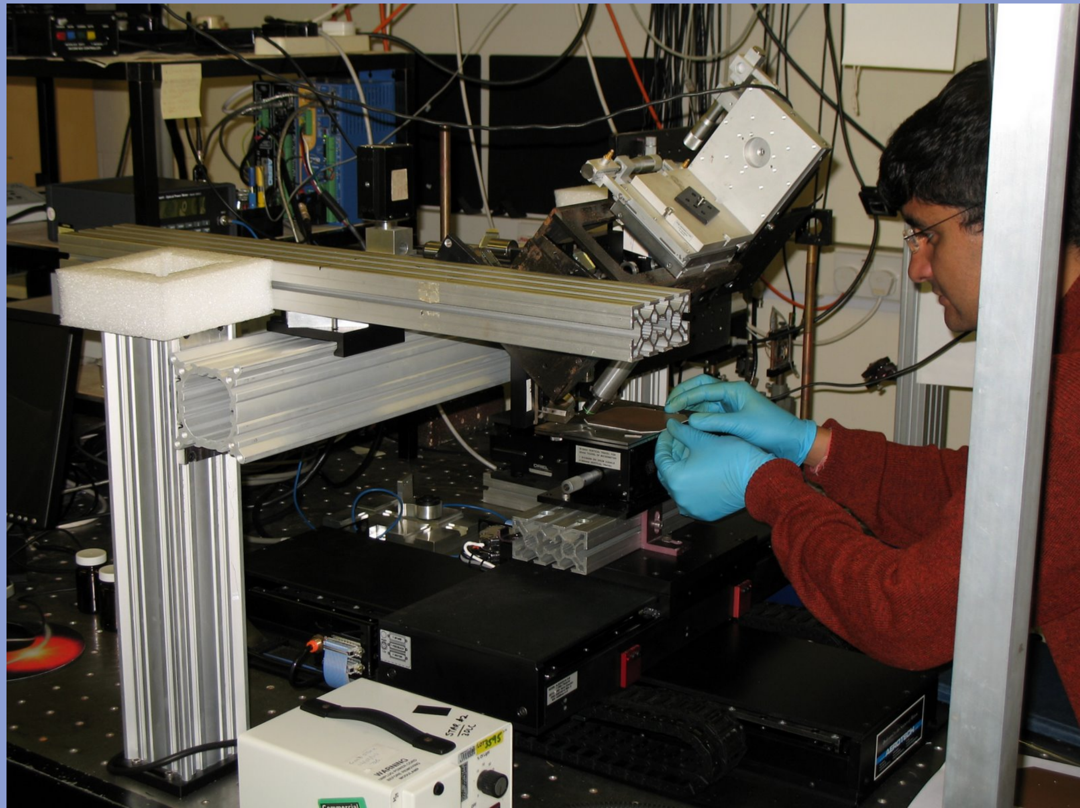




- **Slotted baseplate** mounted vertically over translation, rotation & vertical stages; components held in place with magnets
- By using two opposing 45º beams we minimise the amount of substrate rotation needed

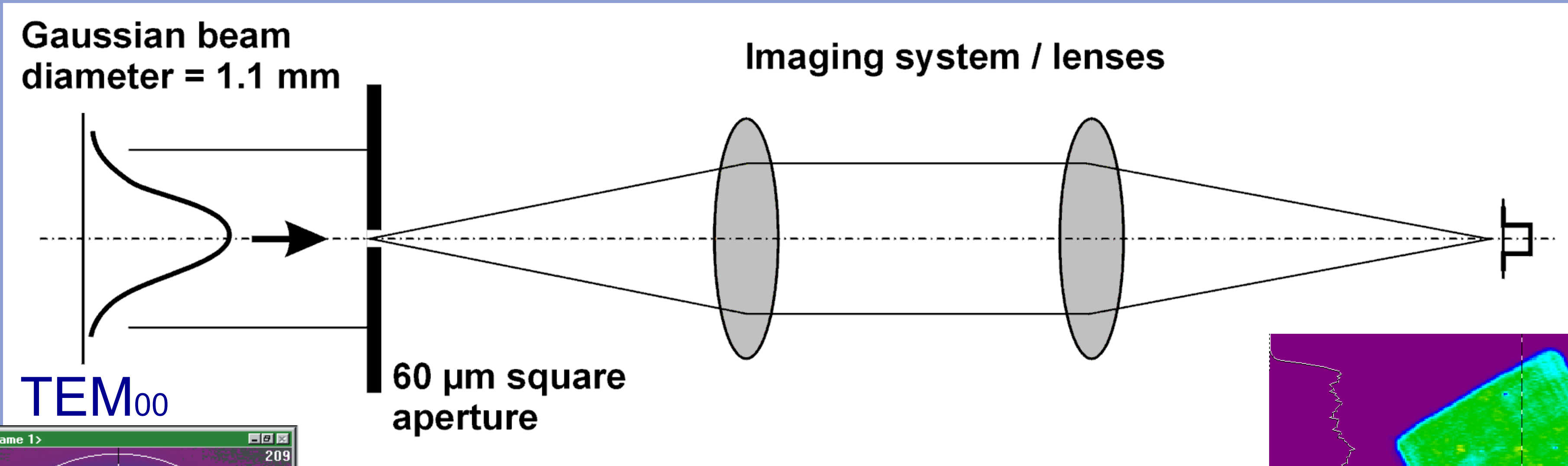


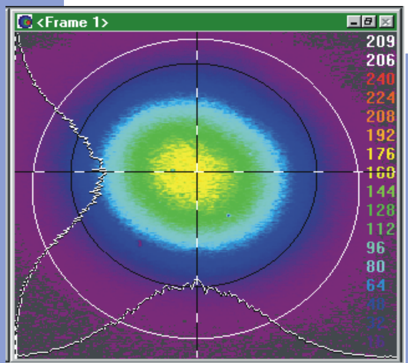


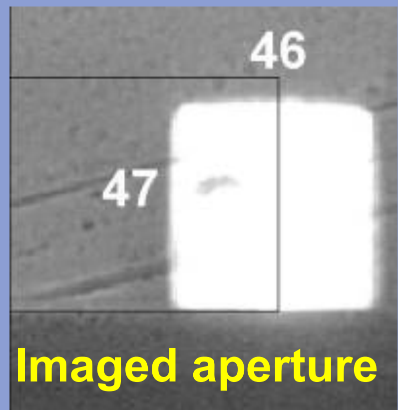


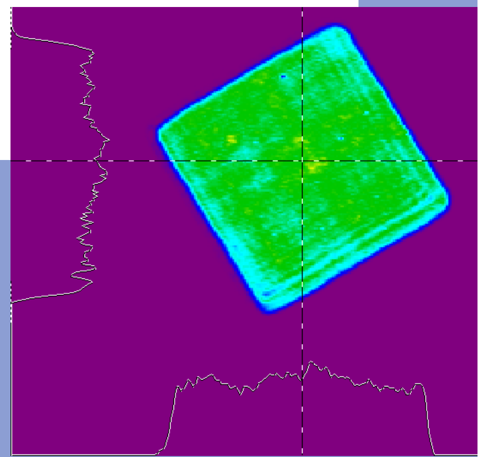
Writing sharply defined features

– flat-top, rectangular laser spot







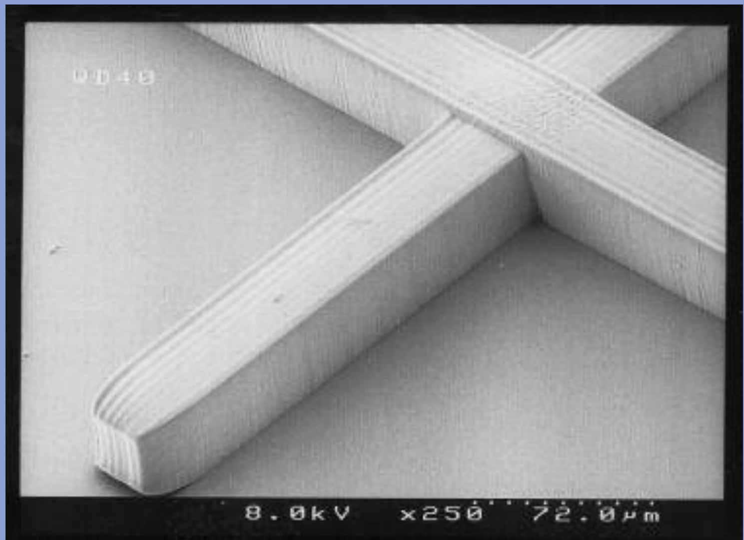


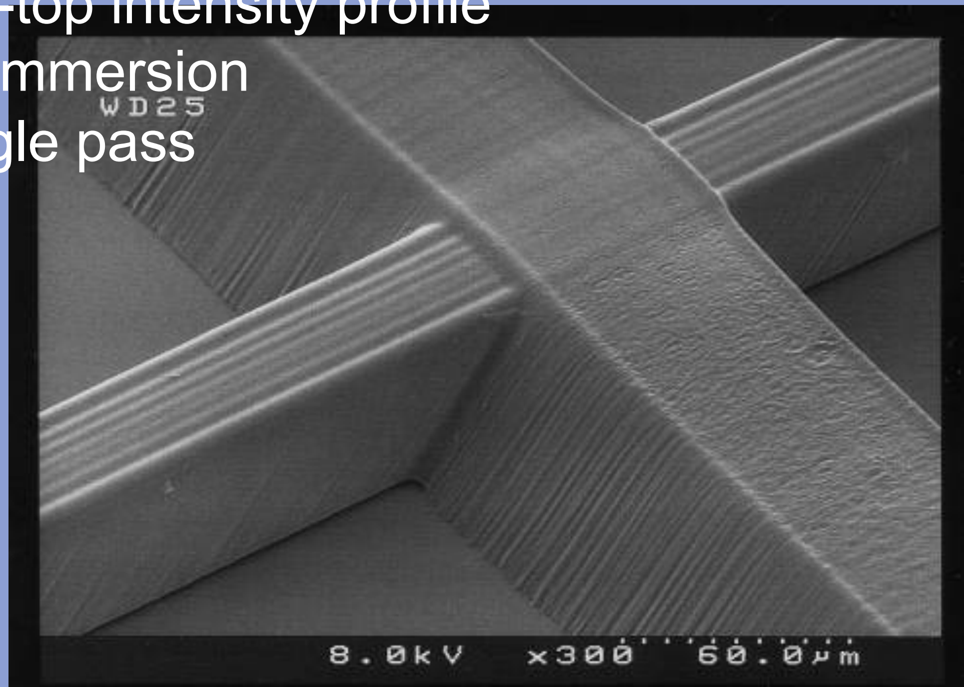
Images of the resulting waveguide core cross-sections

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



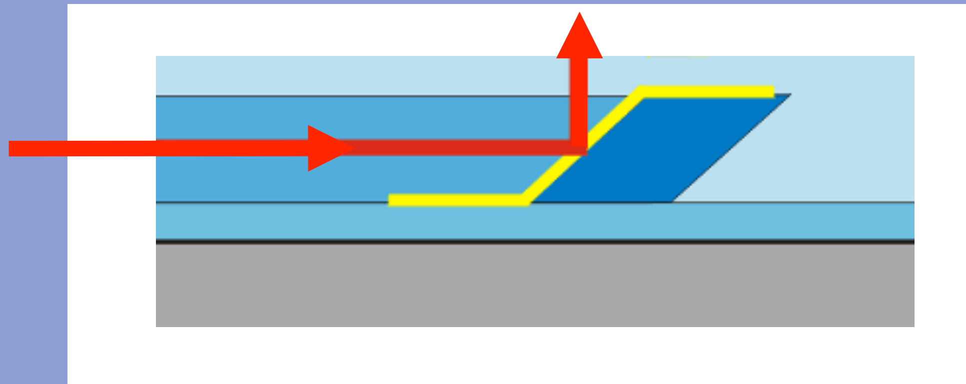


Optical microscope image showing end on view of the 45º surfaces

Waveguide terminated with 45-deg mirror

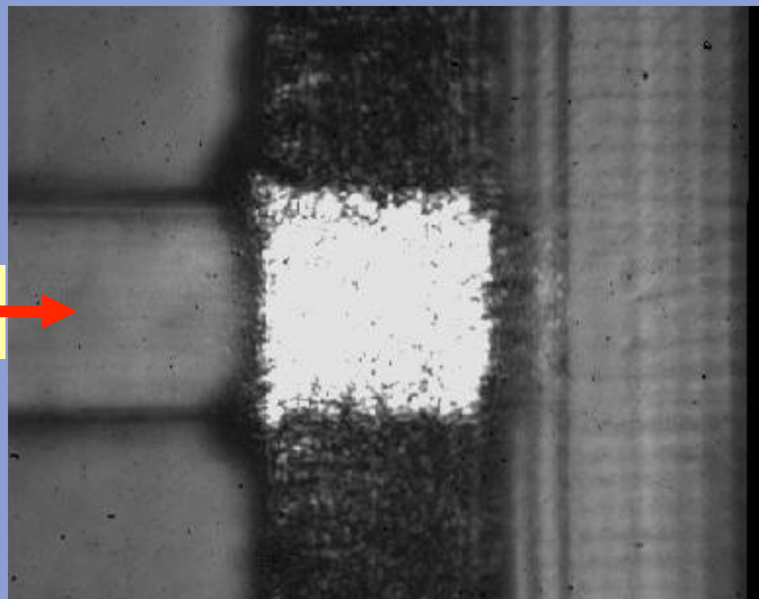
Out-of-plane coupling,

using 45-deg mirror (silver)



Microscope image looking
down on mirror
coupling light towards camera

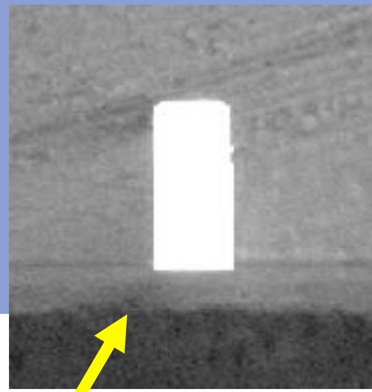
OPTICAL INPUT

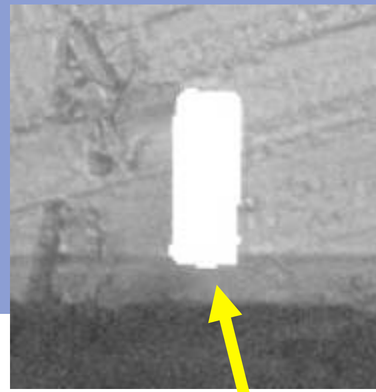


Results with a Gaussian spot profile (2)

Laser-writing Parameters:

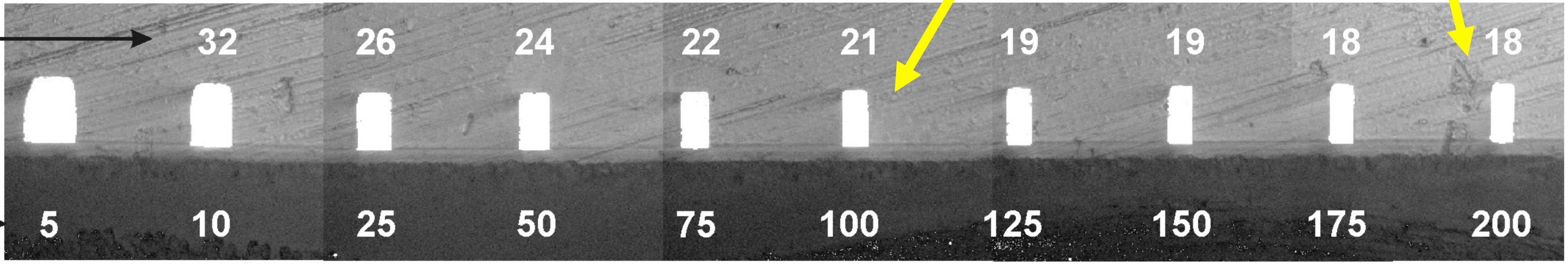
- Profile: Gaussian, 1 mm $1/e^2$ TEM_{00} beam with 40 mm EFL lens
- Optical power available: ~9 mW
- Cores written in air
- Variable writing speed





Approximate height of waveguide cores: 45 - 50 µm

Approximate width (µm)



Writing speed (mm/s)

(Waveguide cores on a 125 µm pitch)

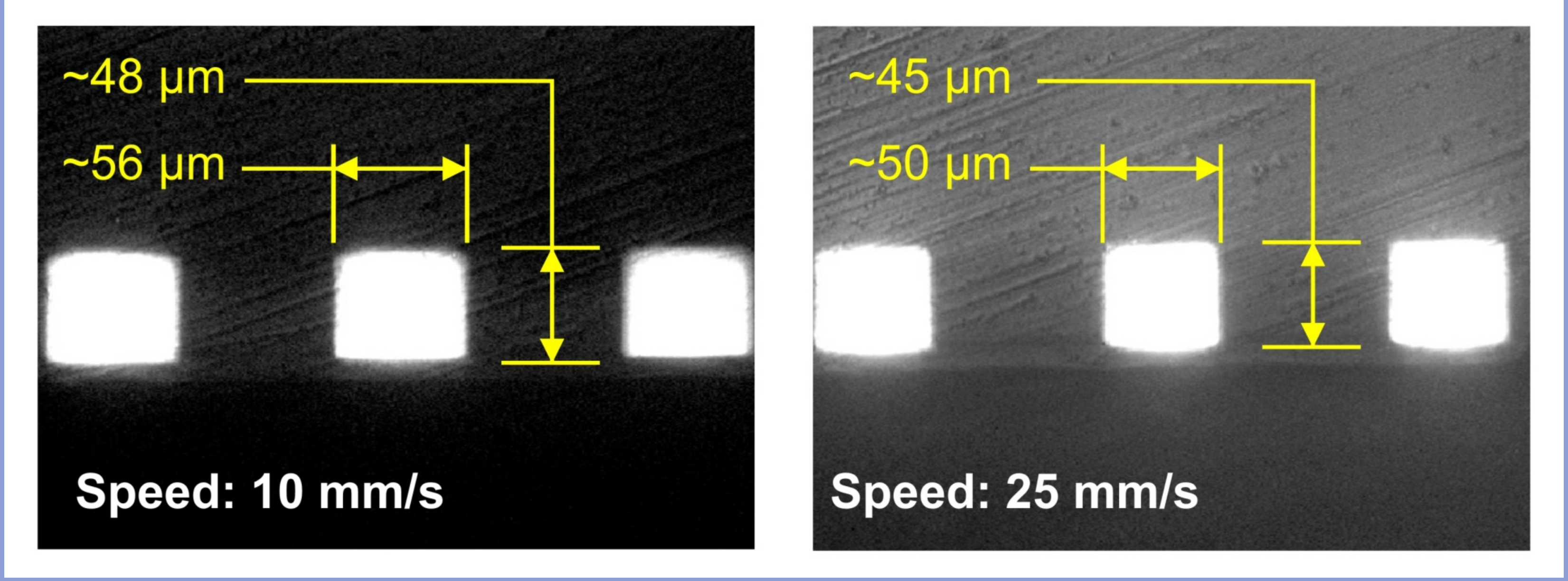
Results with an imaged circular aperture

Laser-writing Parameters:

– Profile: imaged aperture, 100 µm diameter,
illuminated by Gaussian truncated at ~50% peak,
0.5 magnification onto writing plane

– Optical power available for writing: ~2 mW

– Cores written in air, on a 125 µm pitch



End-on view of back-illuminated guides

Large Board Processing: Writing

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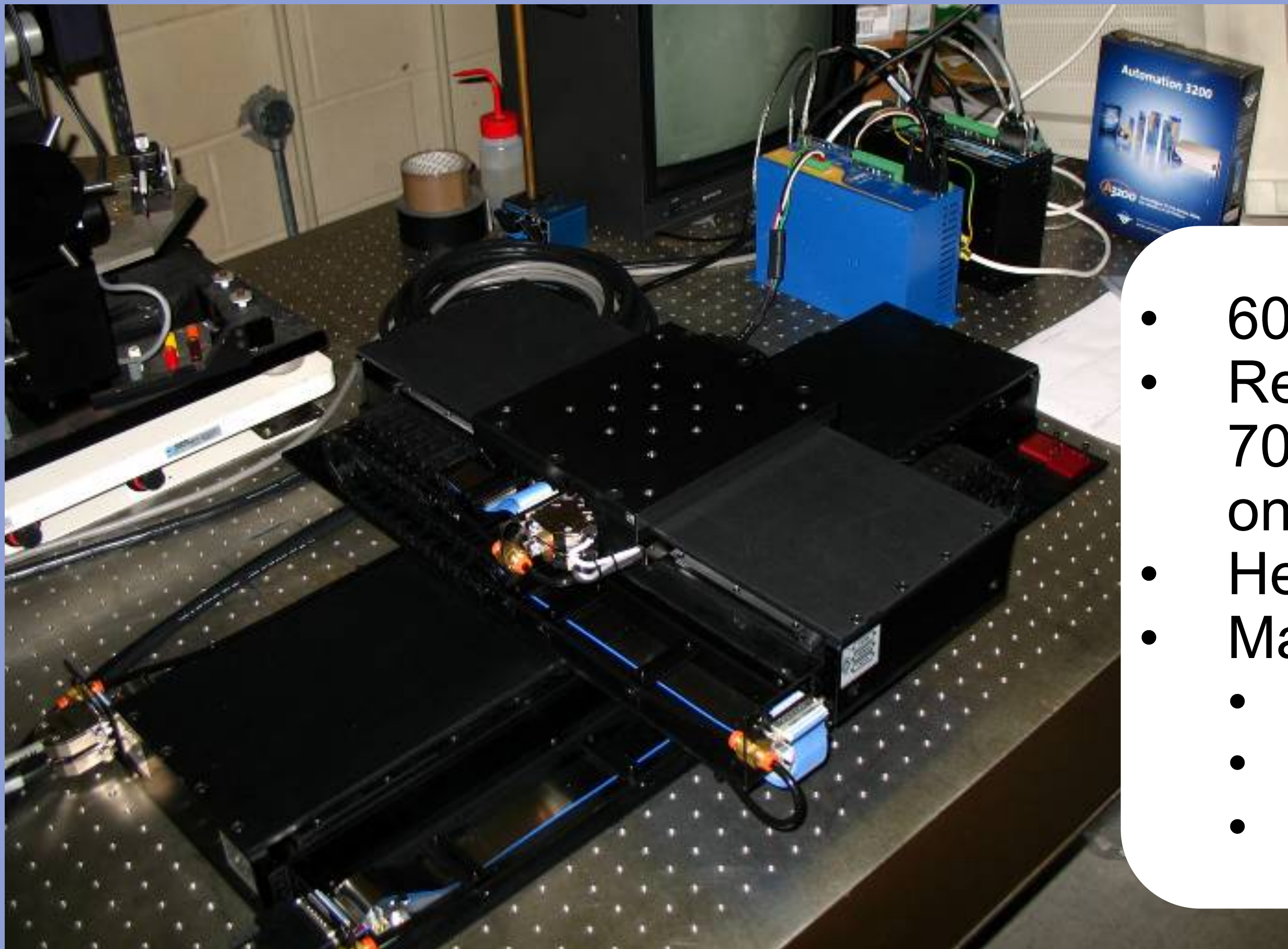
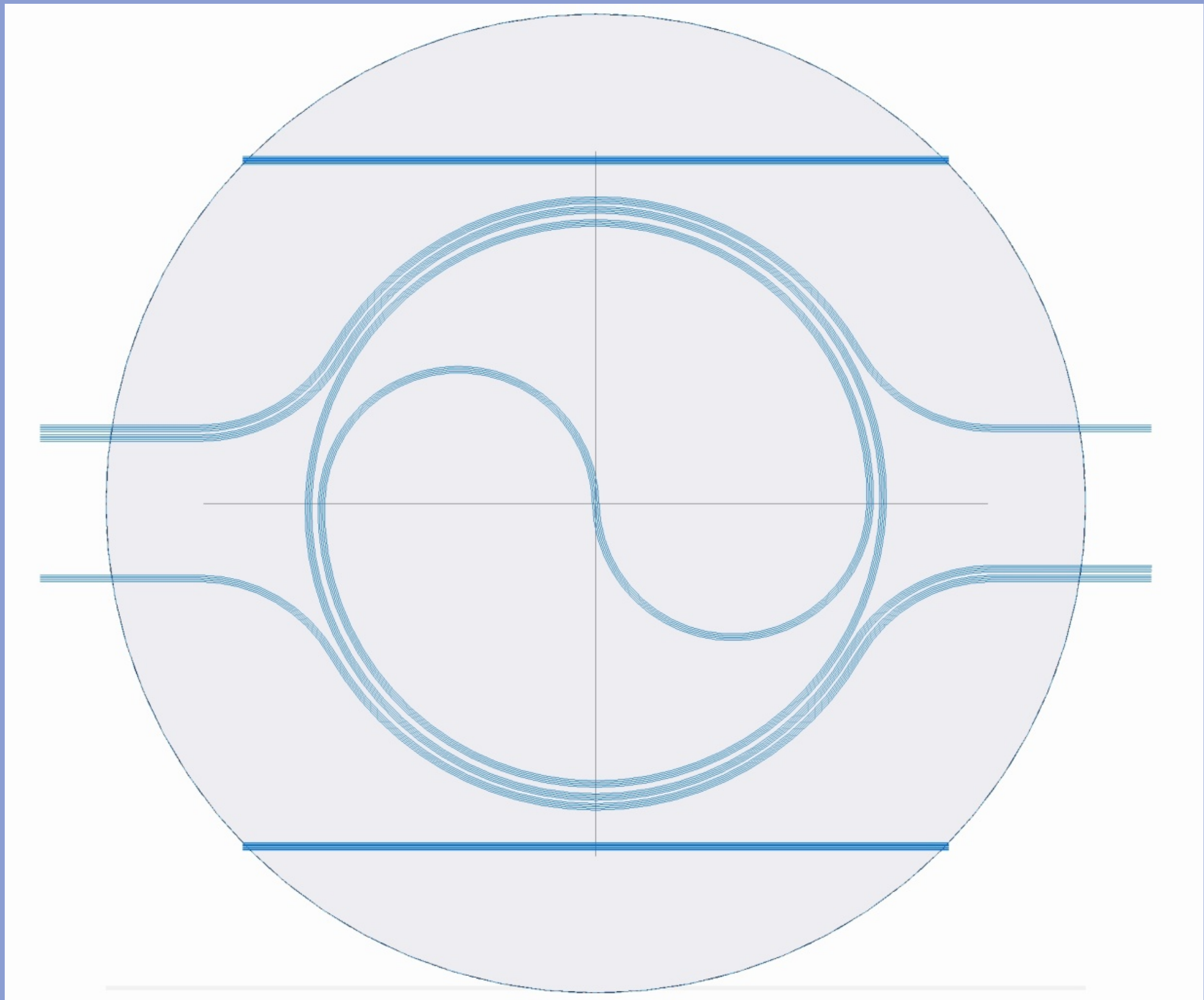
- Stationary "writing head" with board moved using Aerotech sub-μm precision stages
- Waveguide trajectories produced using CAD program



- 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

Test Structures

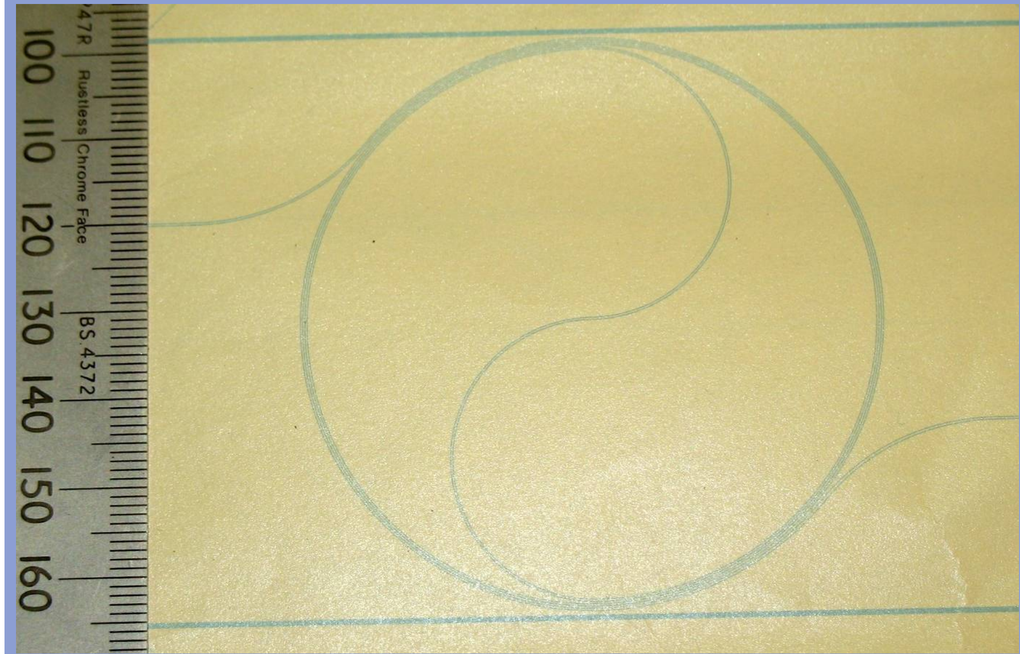


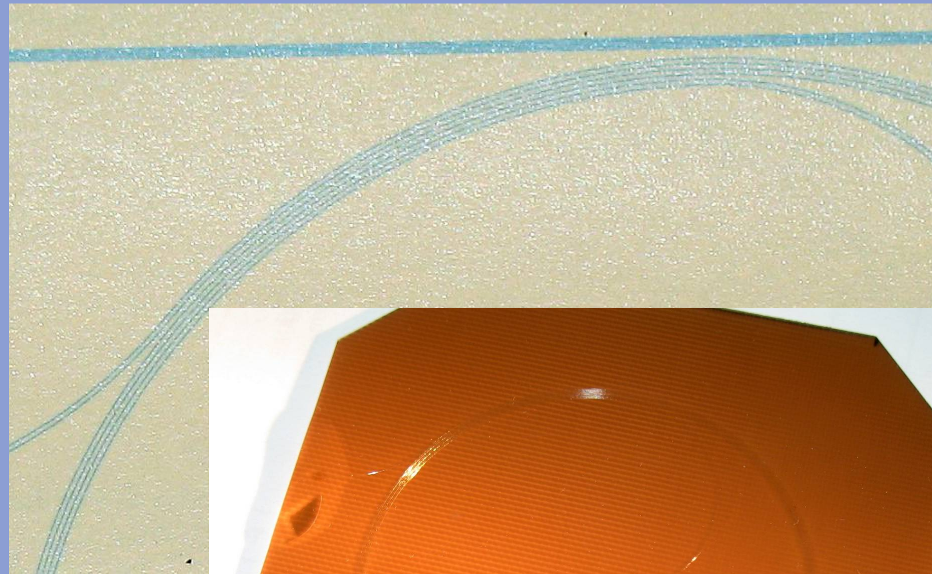
Spirals:
x5, 250 µm pitch
700 mm long

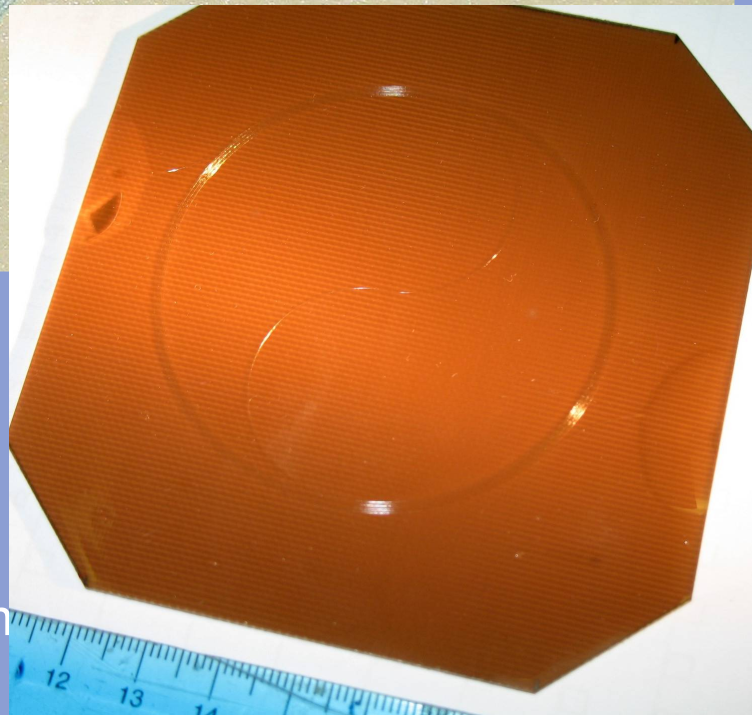
Curves:
x10, 250 µm pitch
170 mm long

Straights:
x20, 125 µm pitch
100 mm long

Large area writing: Spiral Test Structure





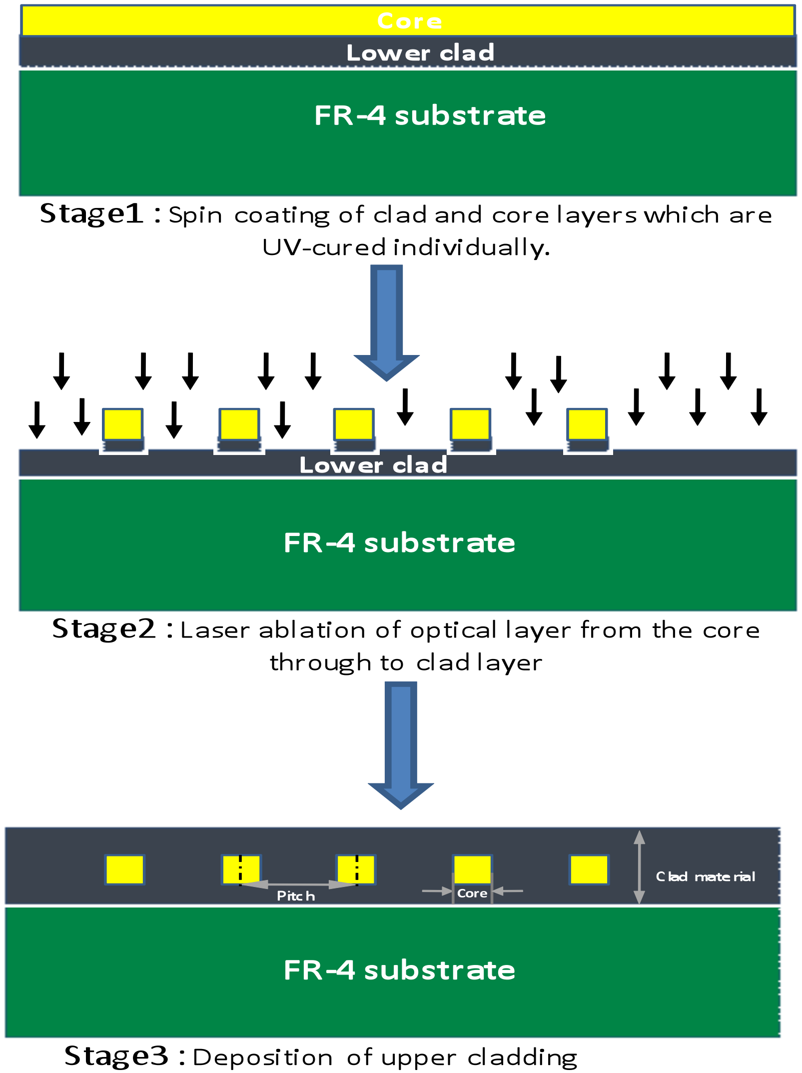


- The guides shown include two parallel spirals plus a number of "straight through" waveguides
- Each spiral has a total path length of ~650 mm
- Minimum bend radius is 16 mm (input/output regions & spiral reversal). Large radius is ~ 32 mm
- Spiral cores are on a 250 μm pitch,
  straight waveguides are on a 125 μm pitch

Laser Ablation of Optical Waveguides

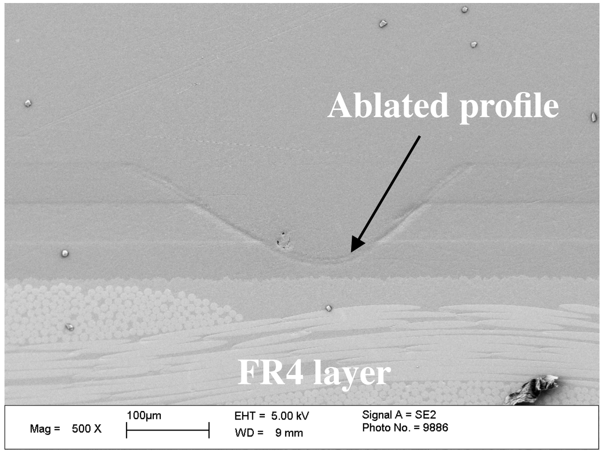
- Research
  - Straight waveguides
  - 2D & 3D integrated mirrors
- Approach
  - Excimer laser – Loughborough
  - CO_2 laser - Loughborough
  - UV Nd:YAG – Stevenage Circuits Ltd
- Optical polymer
  - Truemode® – Exxelis
  - Polysiloxane – Dow Corning

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

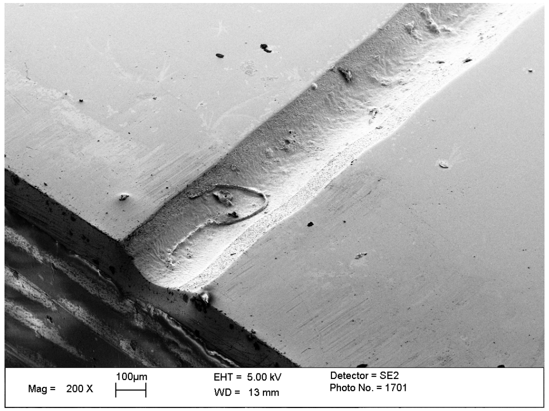


Machining of Optical Polymer with CO_2 Laser

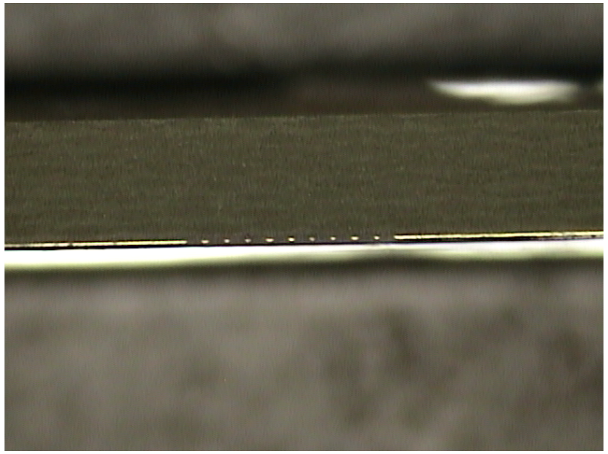
- System
  - 10 Watt(max.) power CW beam
  - Wavelength = 10.6 µm (infrared)
- Process
  - Thermally-dominated ablation process
- Machining quality
  - Curved profile
  - Waveguide fabrication underway



Side view of machined trench



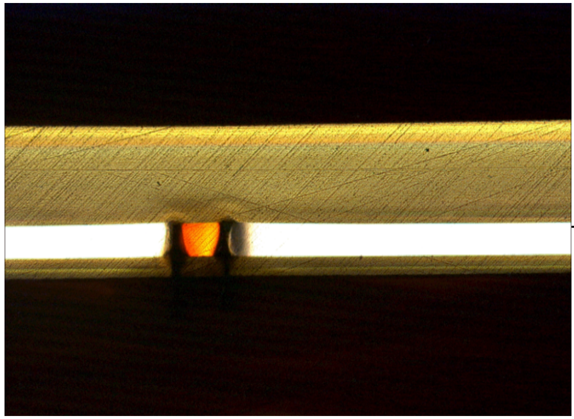
Machined trench



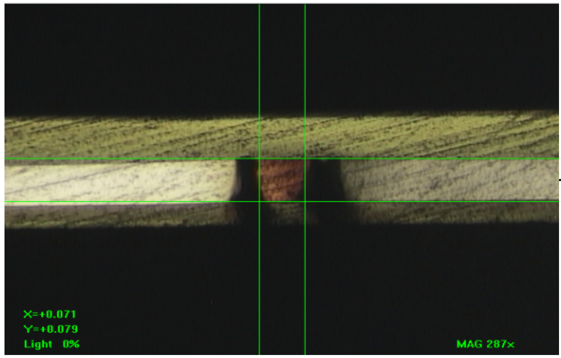
Waveguides (side view)

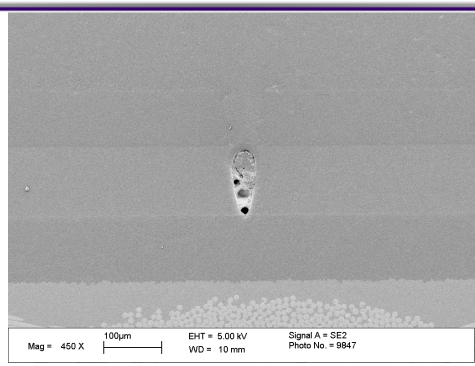
Loughborough University

UV Nd:YAG machining in collaboration with Stevenage Circuits Ltd

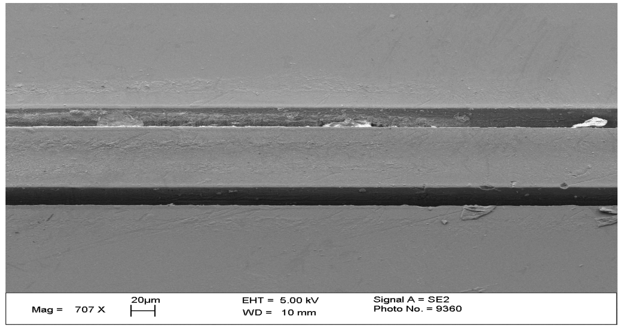


- **Waveguide of 71 µm x 79 µm fabricated using UV Nd:YAG**
- **Waveguide detected using back lighting**





Side view

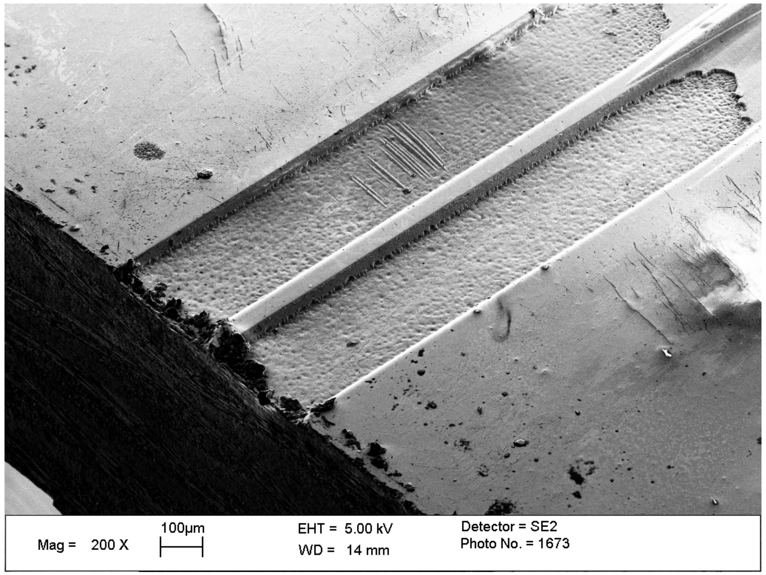


Plan view

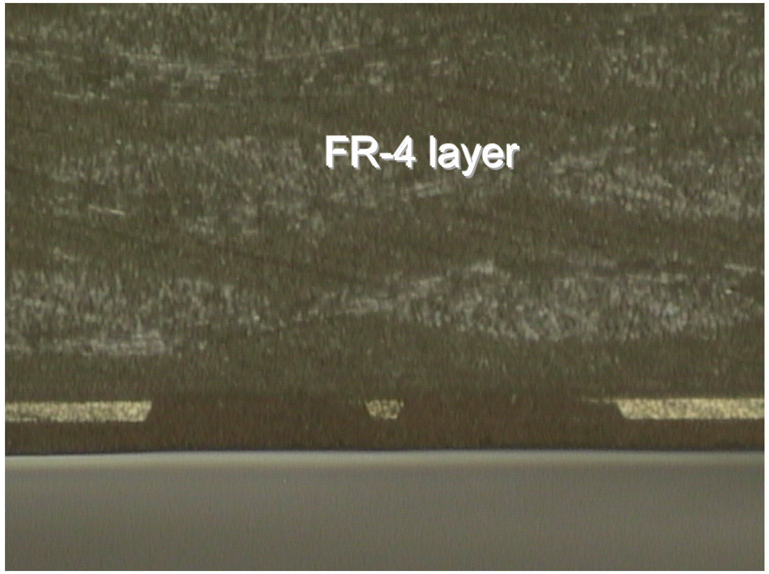
- System
  - 355 nm (UV) Pulsed laser with 60 ns pulse width and Gaussian beam (TEM_{00}) or “Tophat” profile at Stevenage Circuits Ltd.
- Process
  - Photochemically-dominated ablation process.
- Waveguide quality
  - Minimum Heat Affected Zone
  - Propagation loss measurement underway

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.



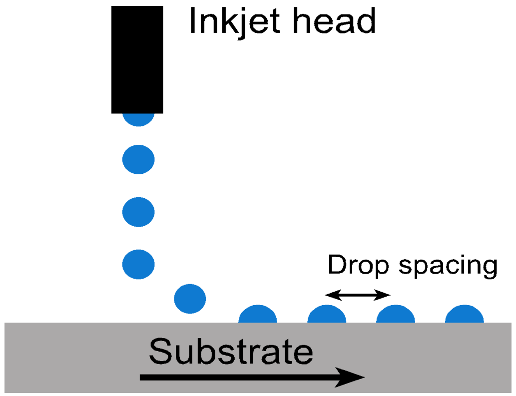
Machined trenches



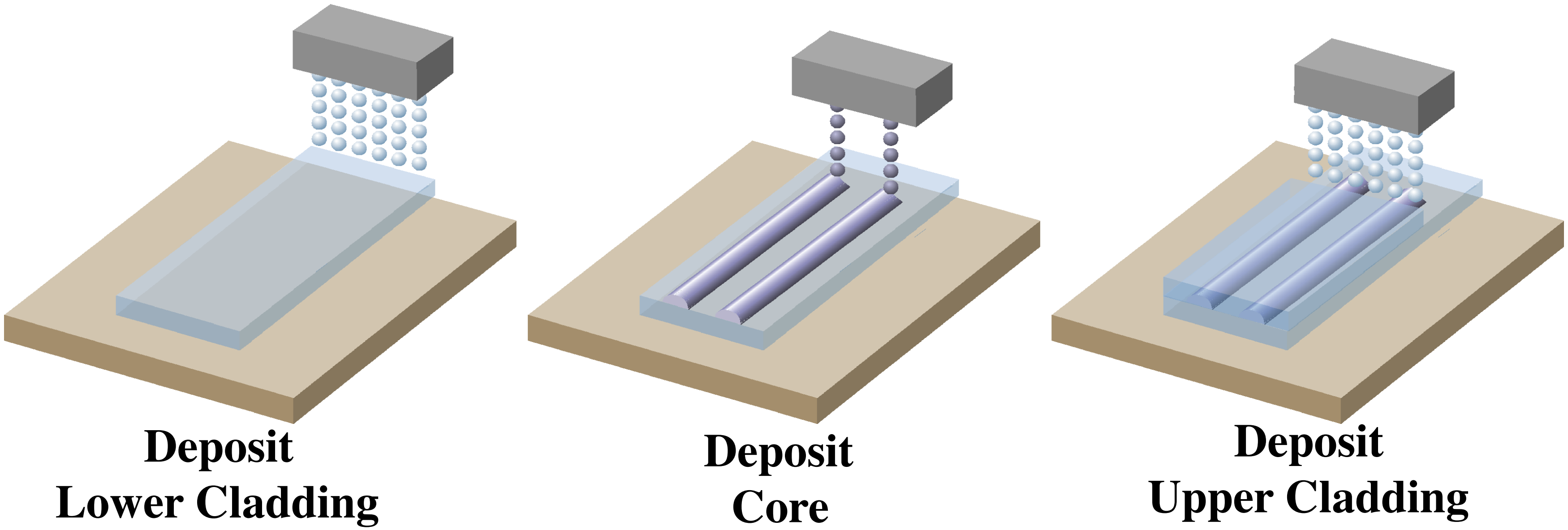
Waveguide structure

Loughborough University

Inkjetting as a Route to Waveguide Deposition

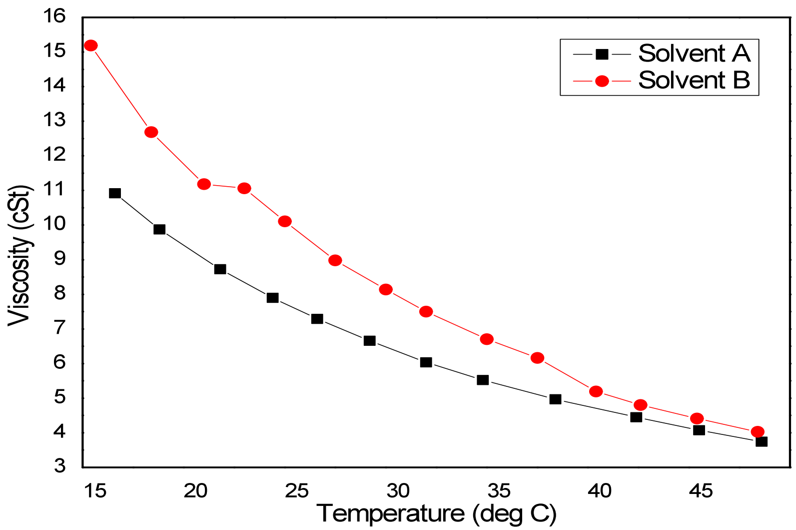


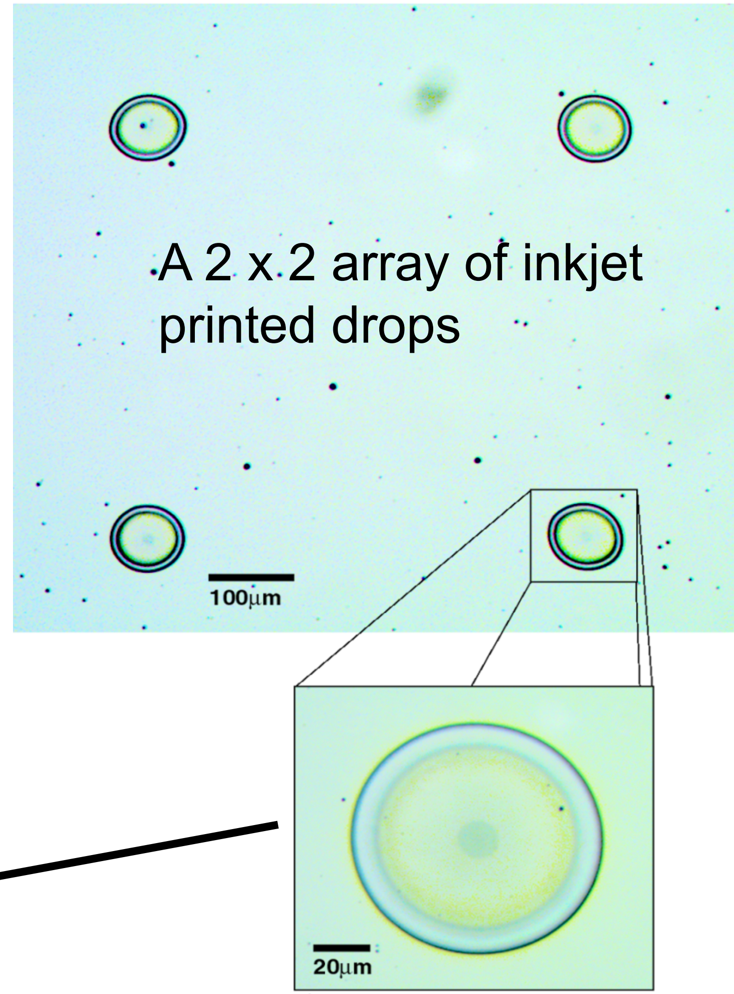
- Print polymer then UV cure
- Advantages:
  - controlled, selective deposition of core and clad
  - less wastage: picolitre volumes
  - large area printing
  - low cost



Challenges of Inkjet Deposition

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

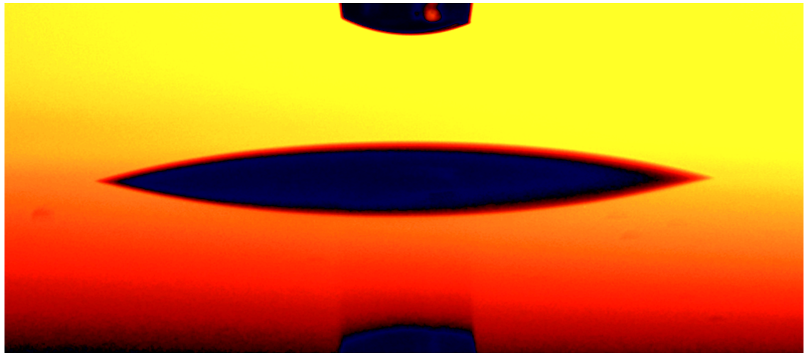




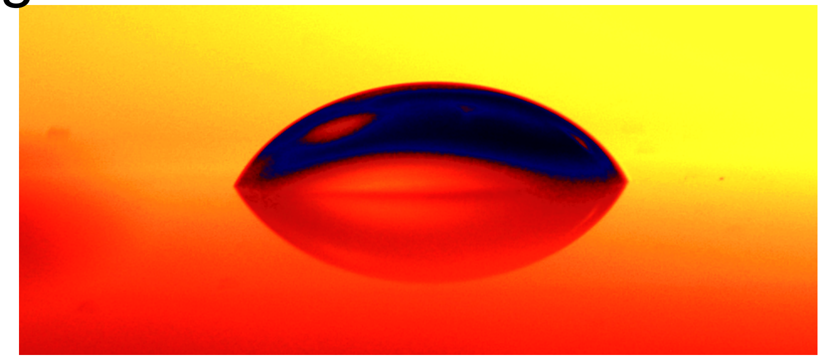
Cross-section of dried droplet “coffee-stain” effect

Changing Surface Wettability

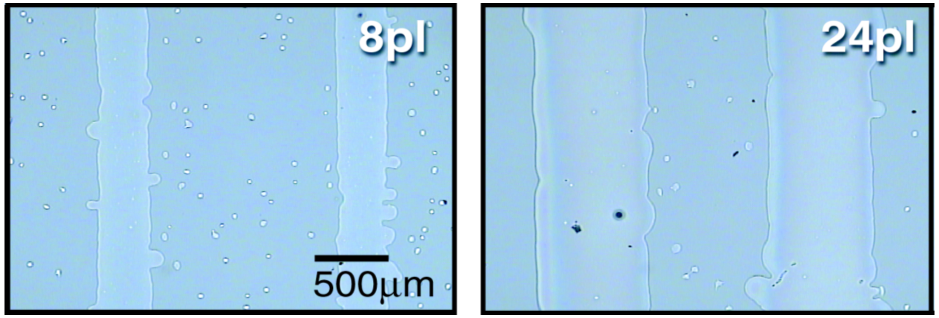
Contact Angles



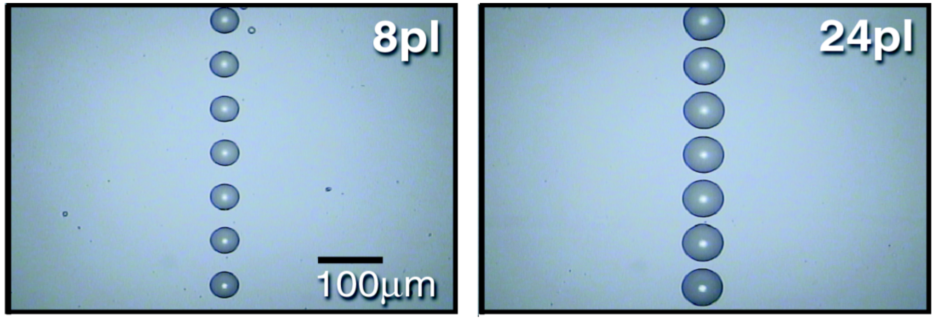
Core material on cladding



Core material on modified glass surface (hydrophobic)



Large wetting - broad inkjetted lines

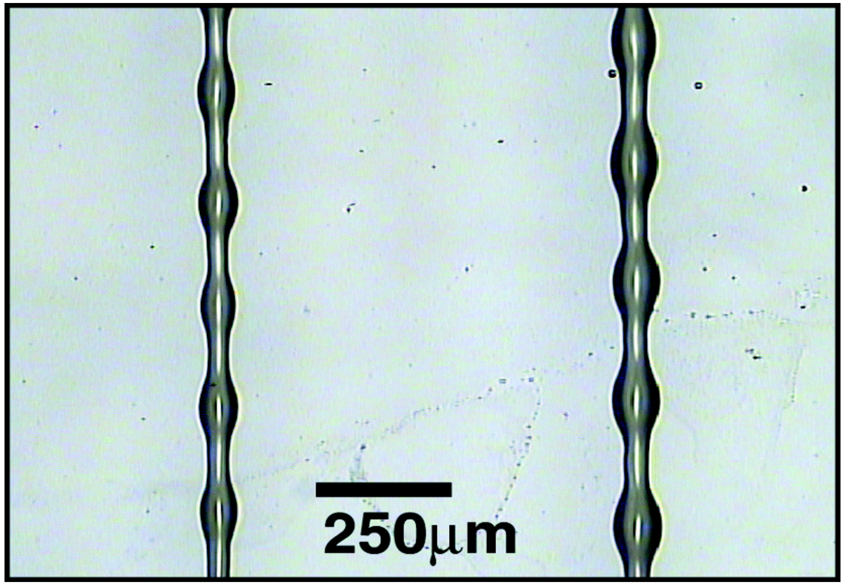


Reduced wetting – discrete droplets

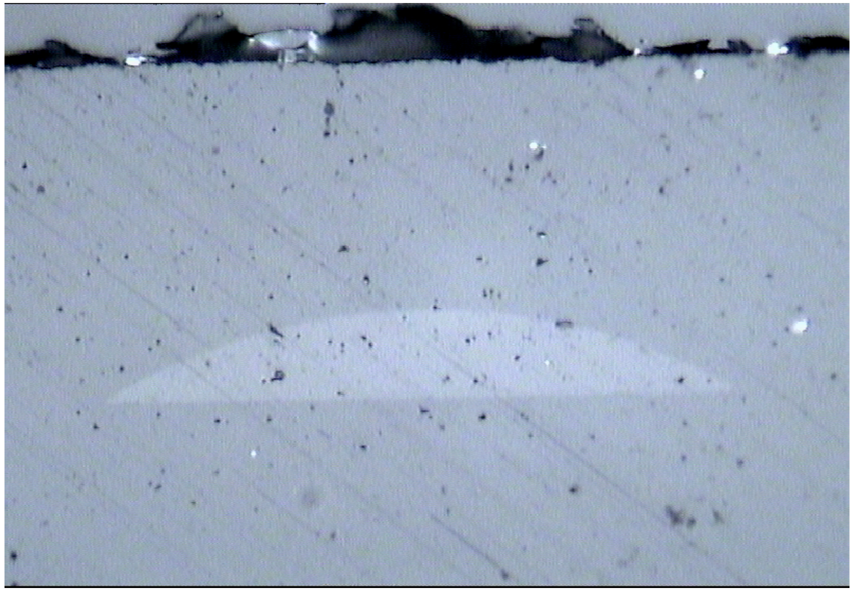
Identical inkjetting conditions - spreading inhibited on modified surface

Loughborough University

Towards Stable Structures



Stable line structures with periodic features

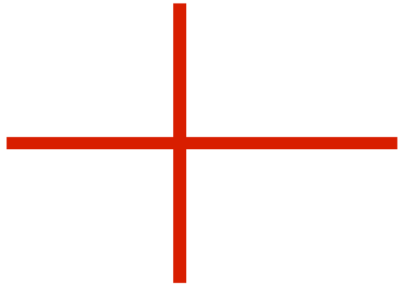


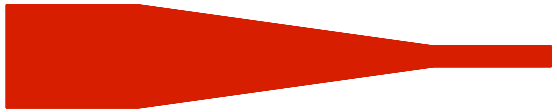
Cross section of inkjetted core material surrounded by cladding (width 80 microns)

A balance between wettability, line stability and adhesion

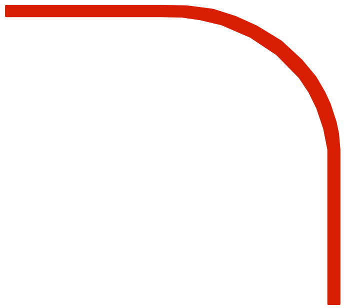
Waveguide components and measurements

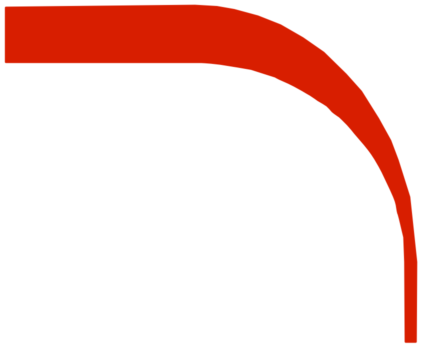
- Straight waveguides 480 mm x 70 µm x 70 µm
- Bends with a range of radii
- Crossings
- Spiral waveguides
- Tapered waveguides
- Bent tapered waveguides



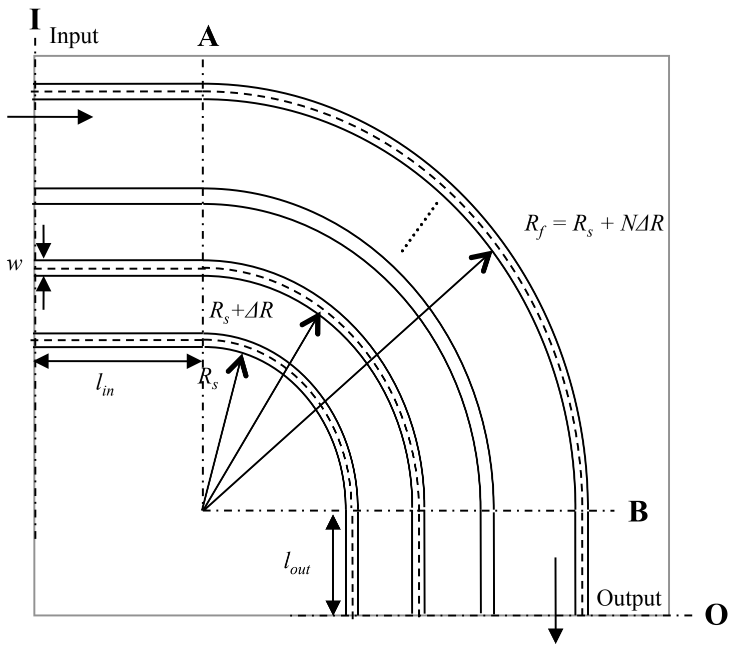


- Loss
- Crosstalk
- Misalignment tolerance
- Surface Roughness
- Bit Error Rate, Eye Diagram

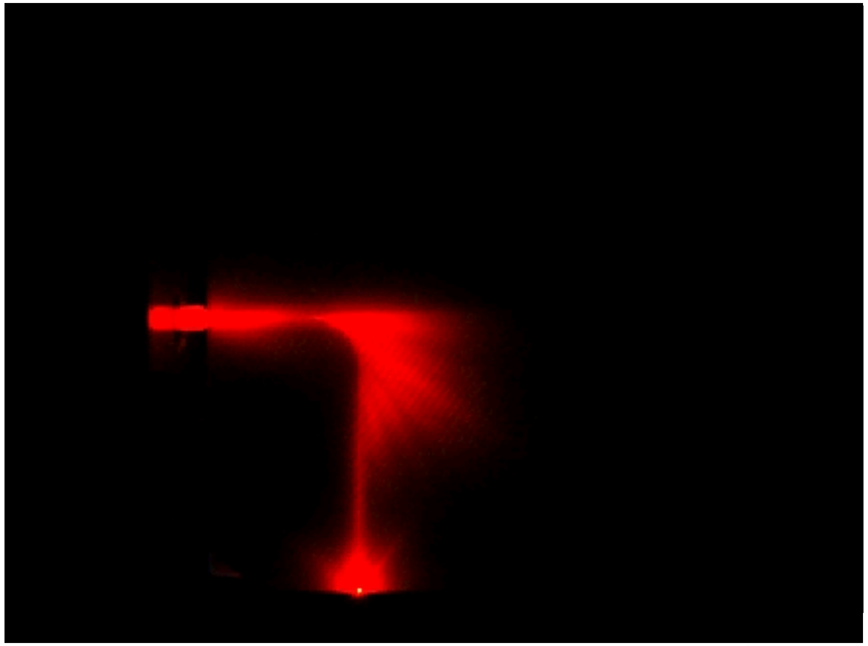




Optical Power Loss in 90° Waveguide Bends



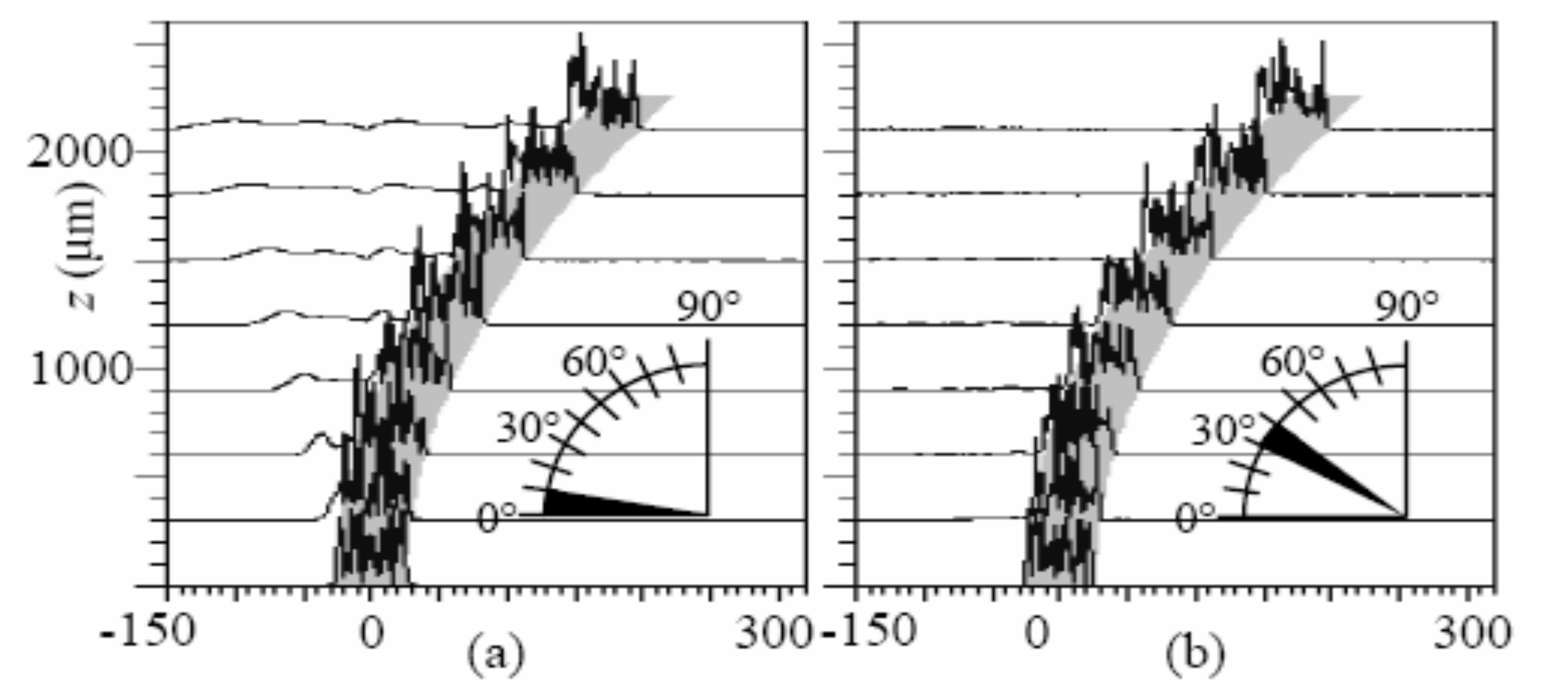
Schematic diagram of one set of curved waveguides.



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

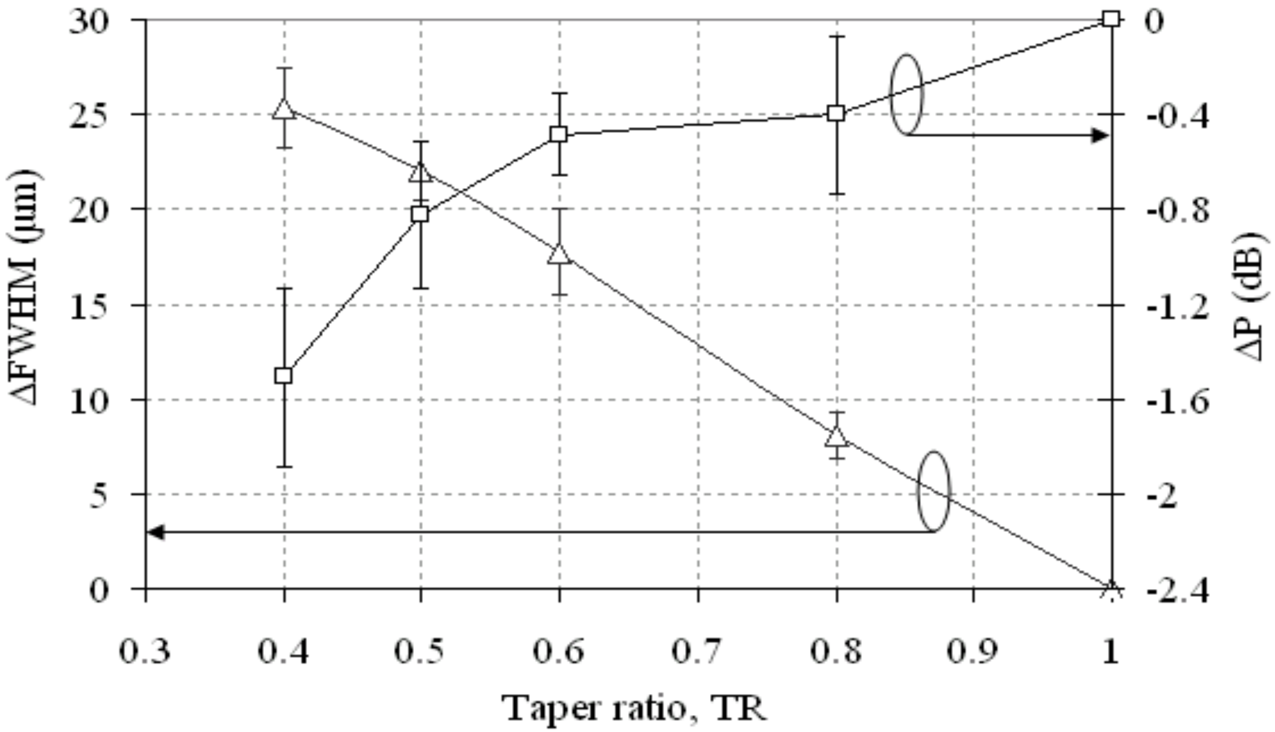


w = 50 μm, R = 13 mm

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

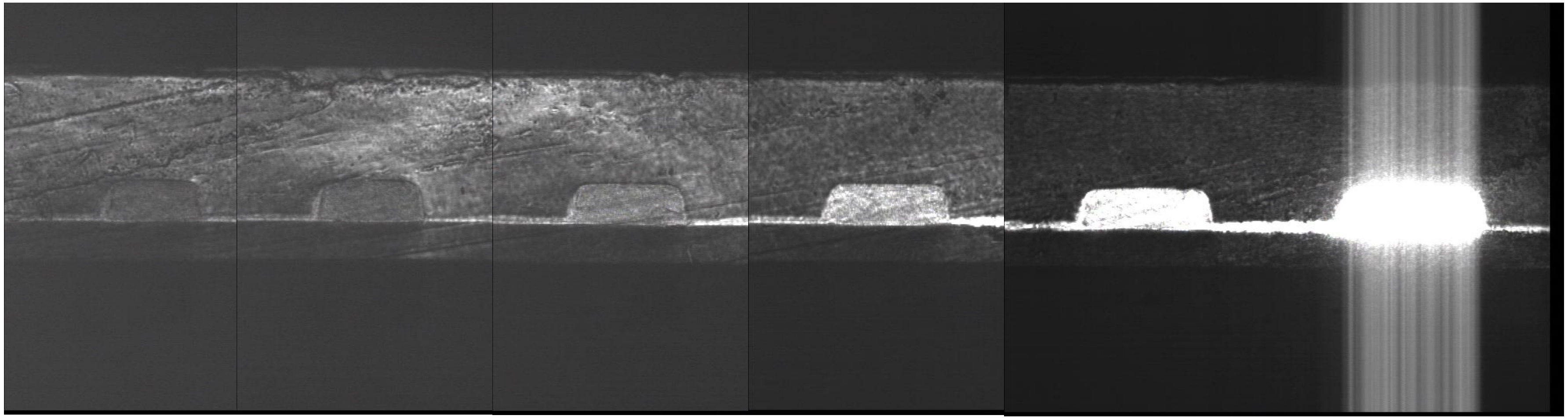
(right picture) in the 30° to 40° degree segment.

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

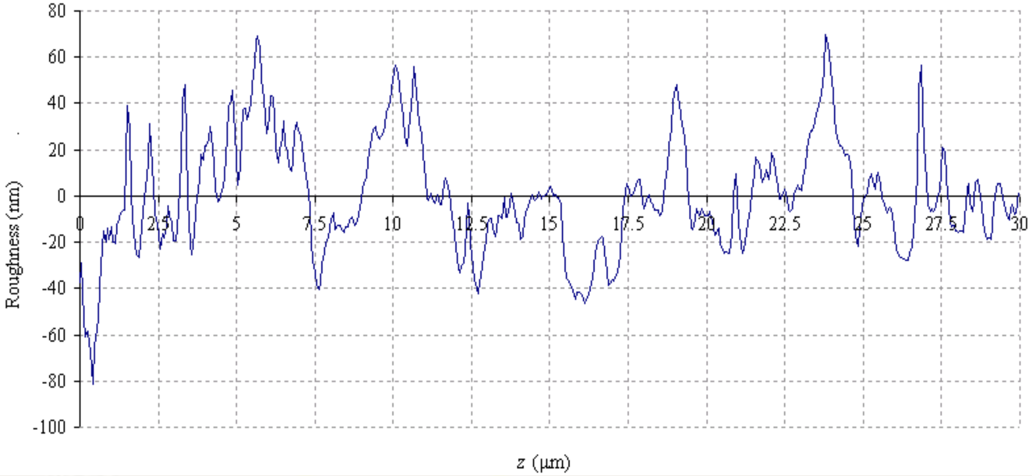
Crosstalk in Chirped Width Waveguide Array



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

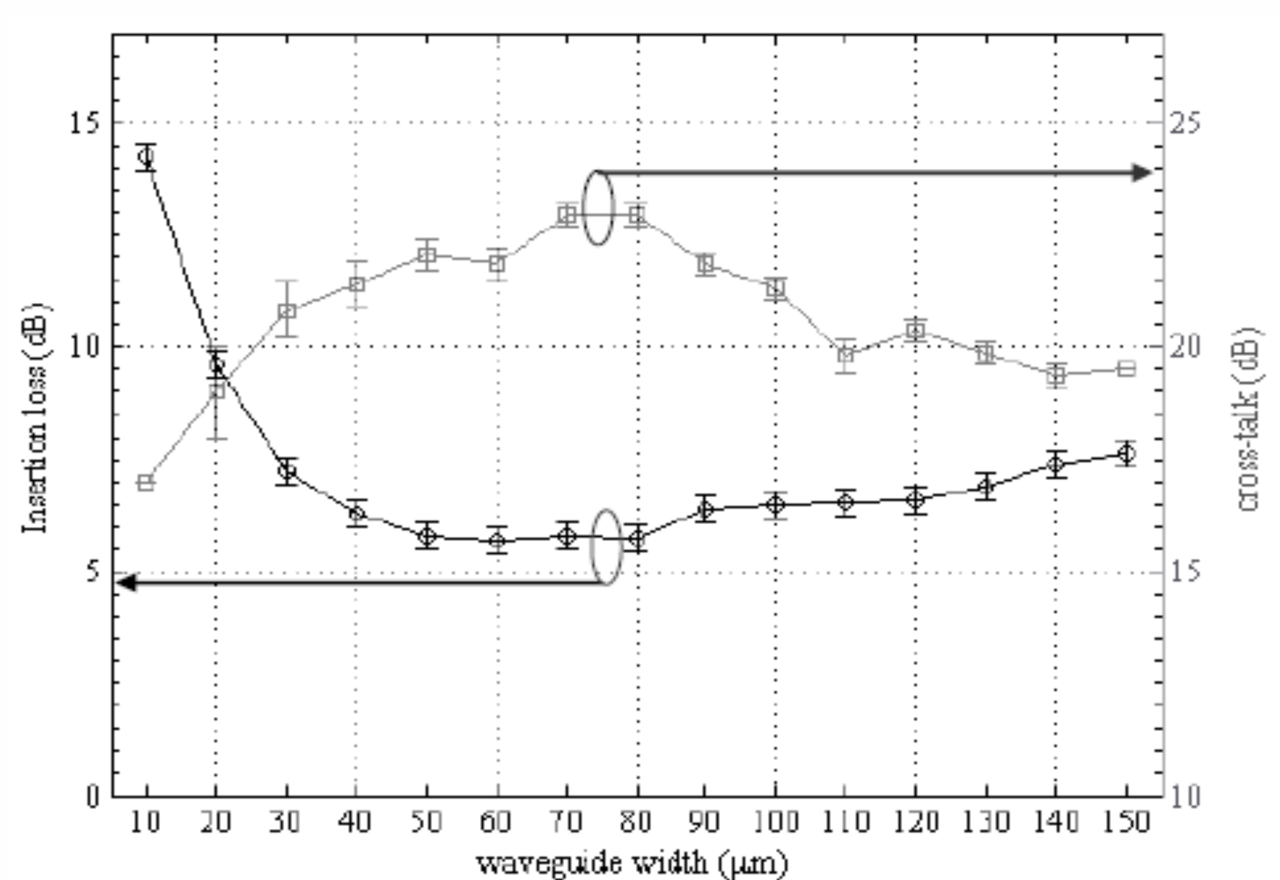
- Light launched from VCSEL imaged via a GRIN lens into 50 µm x 150 µm waveguide
- Photolithographically fabricated chirped with waveguide array
- Photomosaic with increased camera gain towards left

Surface roughness



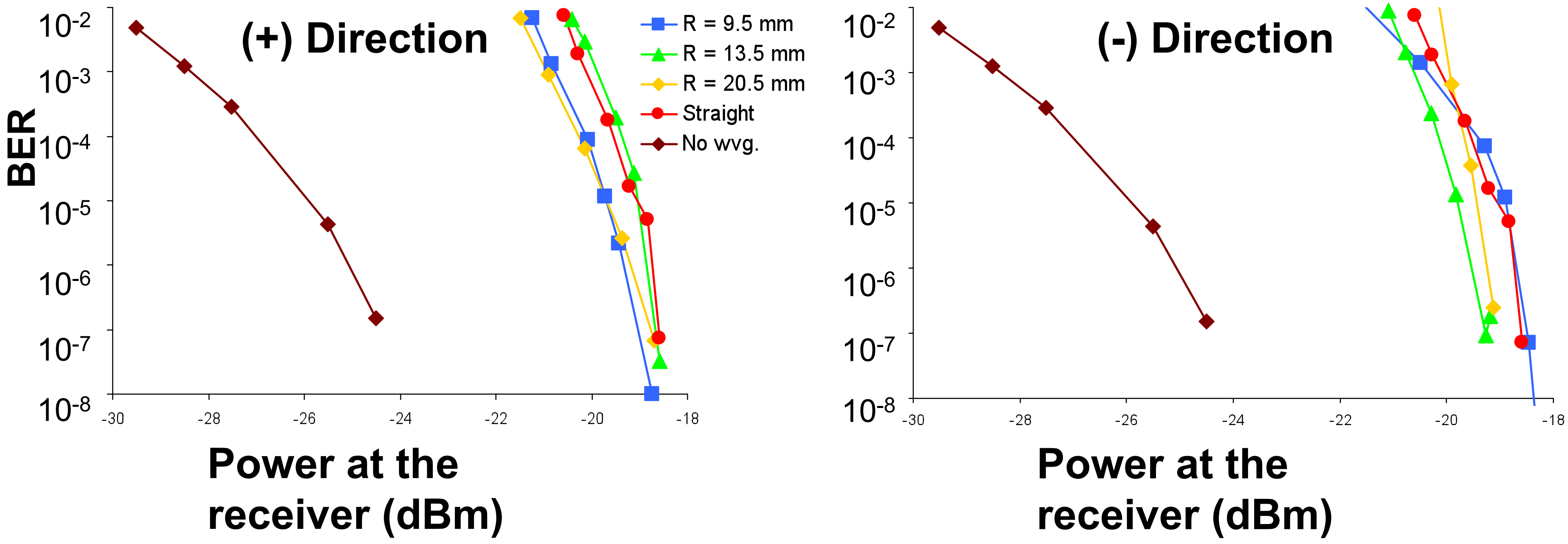
- RMS side wall roughness: 9 nm to 74 nm
- RMS polished end surface roughness: 26 nm to 192 nm.

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

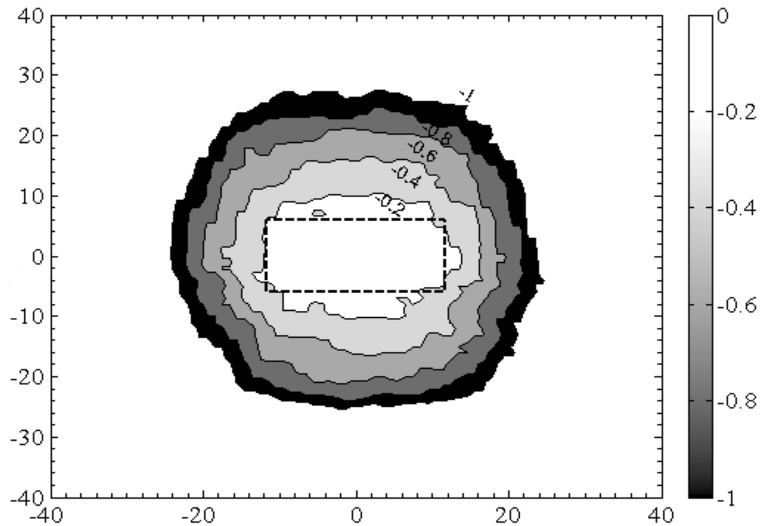


6~7dB for a 70 µm width waveguide

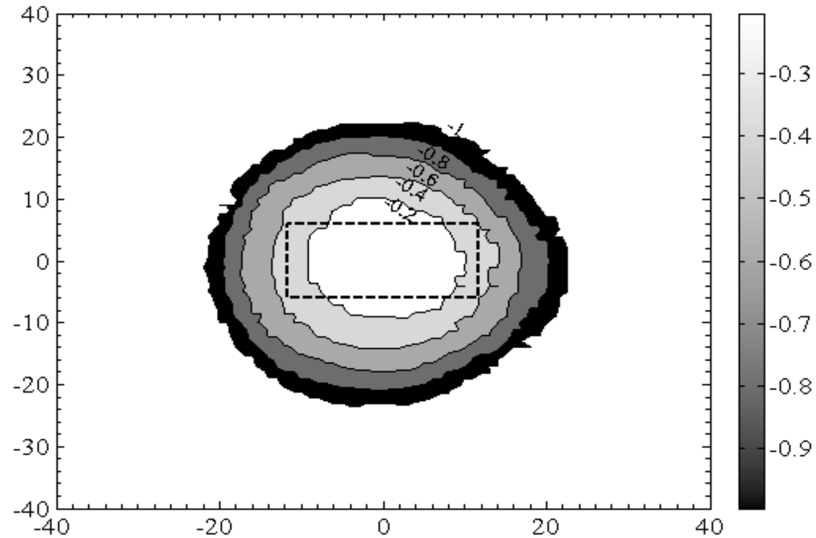
Bit error rate for laterally misaligned 1550 nm 2.5 Gb/s DFB laser



Contour map of VCSEL and PD misalignment



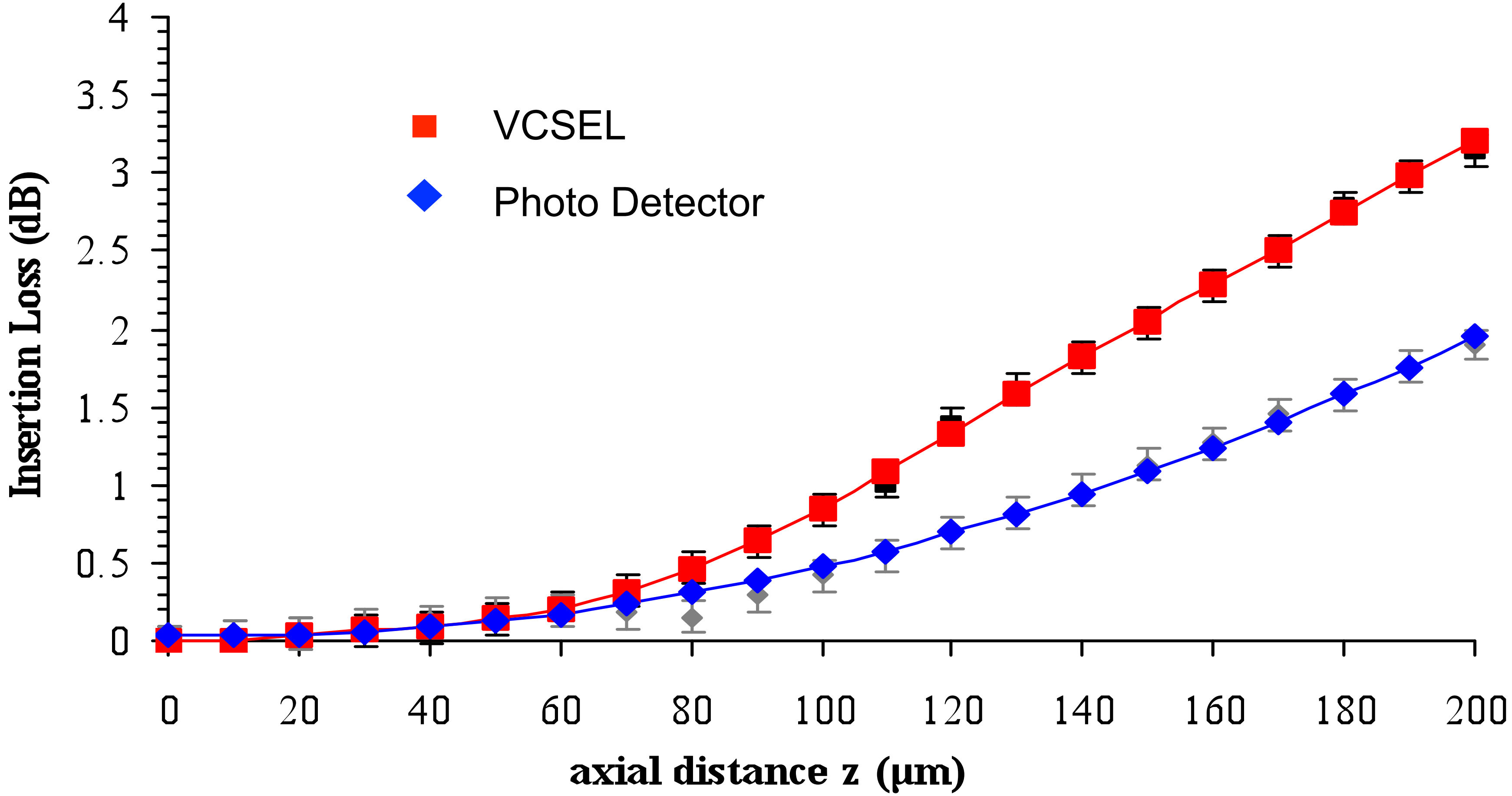
(a) Contour map of relative insertion loss compared to the maximum coupling position for VCSEL misalignment at z = 0.



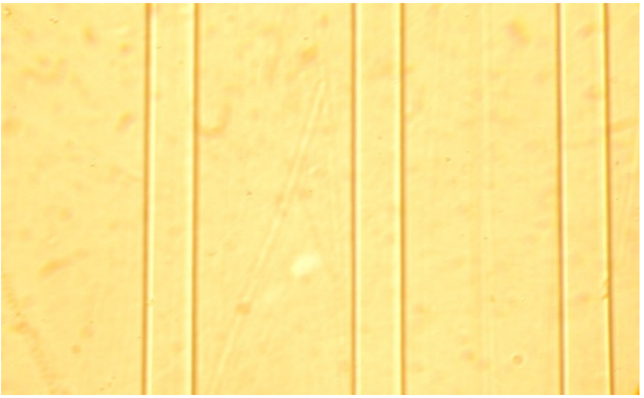
(b) Same for PD misalignment at *z* = 0. Resolution step was $\Delta x = \Delta y = 1$ µm.

- 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

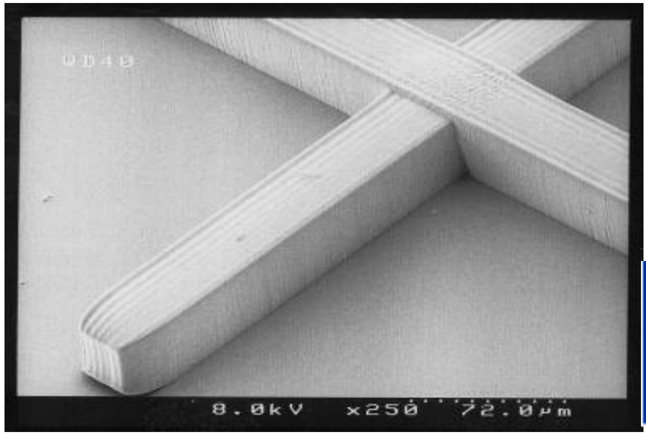


Fabrication Techniques and Waveguides Samples



Straight waveguides – Optical InterLinks

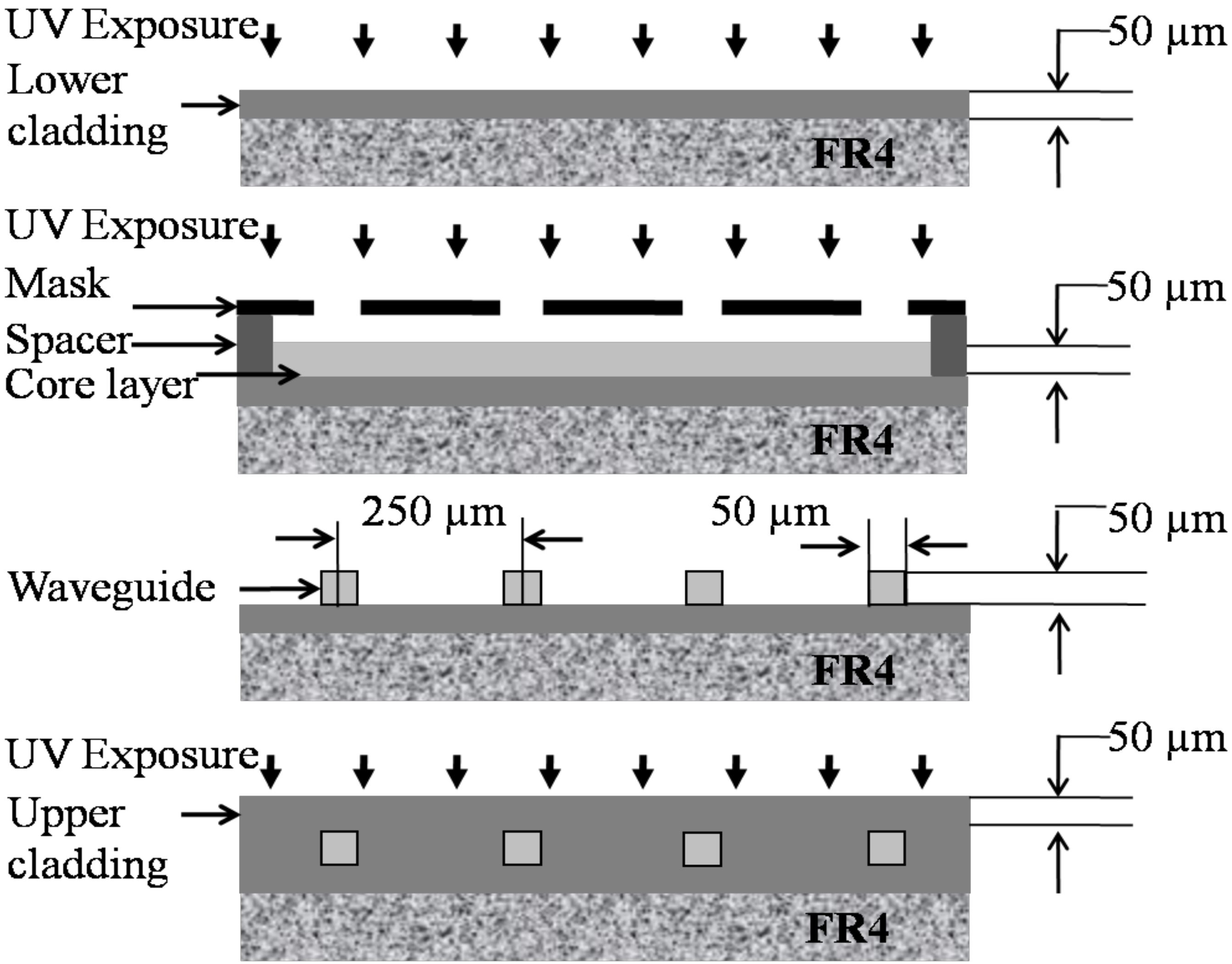
90° Crossings – Dow Corning



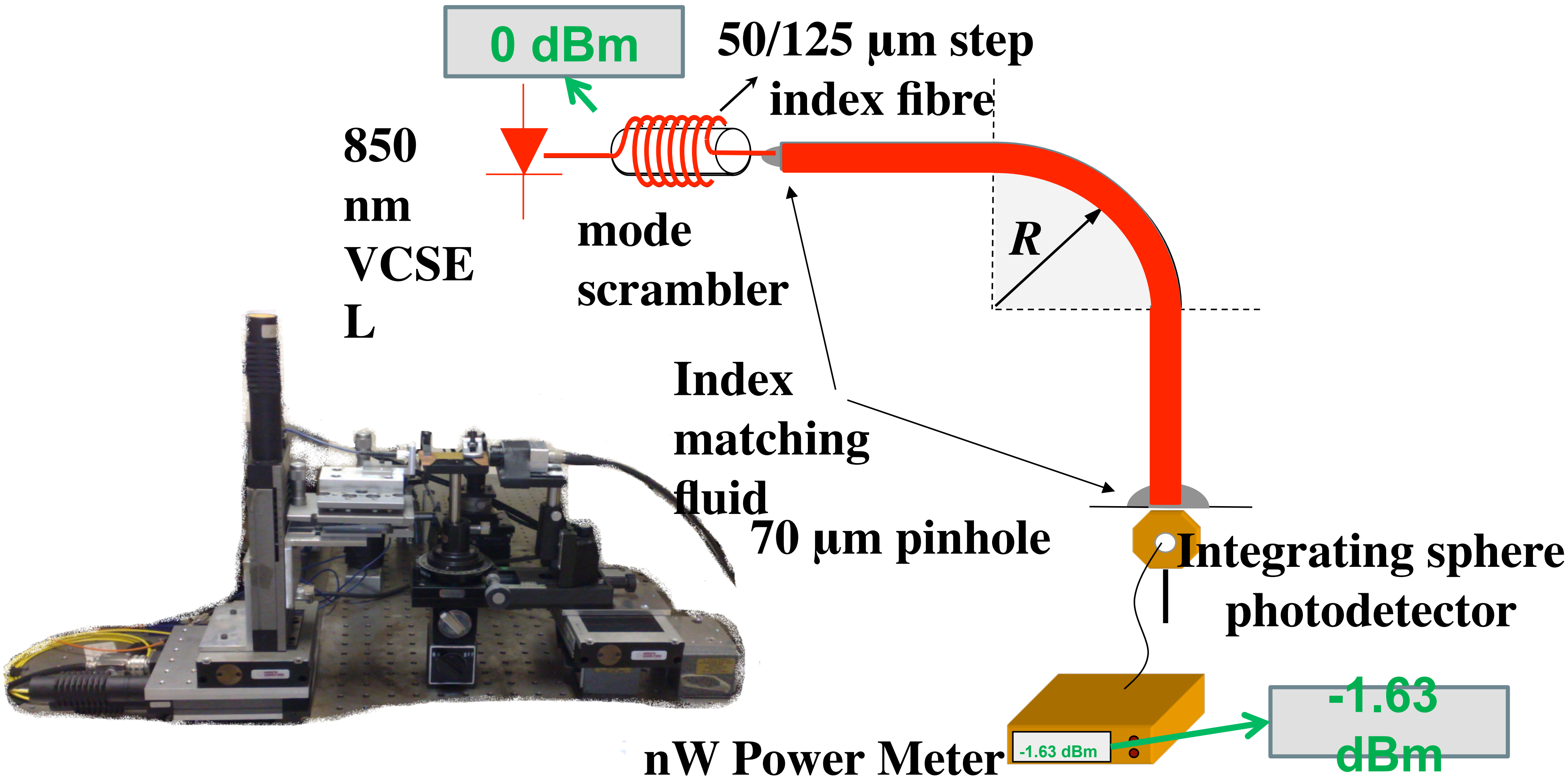
90° Crossings – Heriot Watt University

50° Crossings – Exxelis

Photolithographic Fabrication of Waveguides

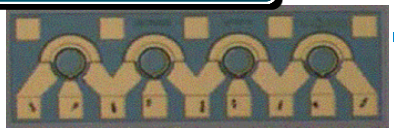


Optical Loss Measurement



VCSEL Array for Crosstalk Measurement

PIN Array

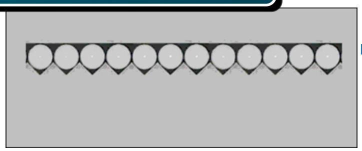


Source: Microsemi Corporation

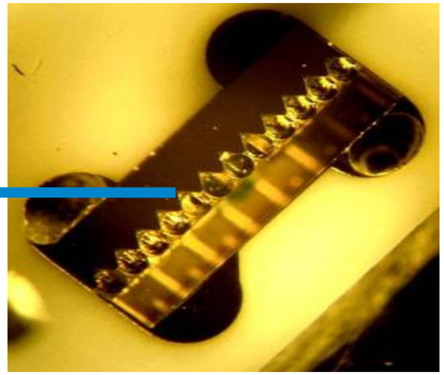
VCSEL Array

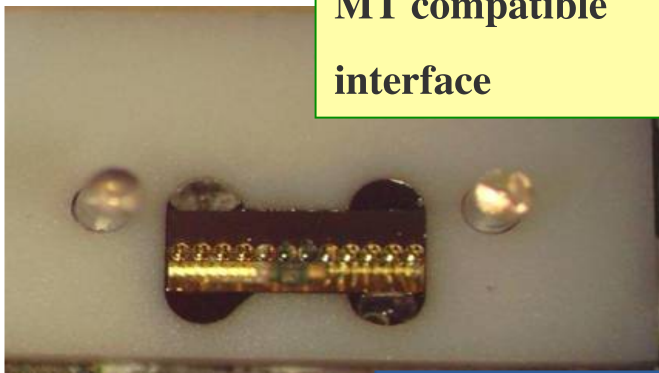
Source: ULM Photonics GmbH

GRIN Lens Array



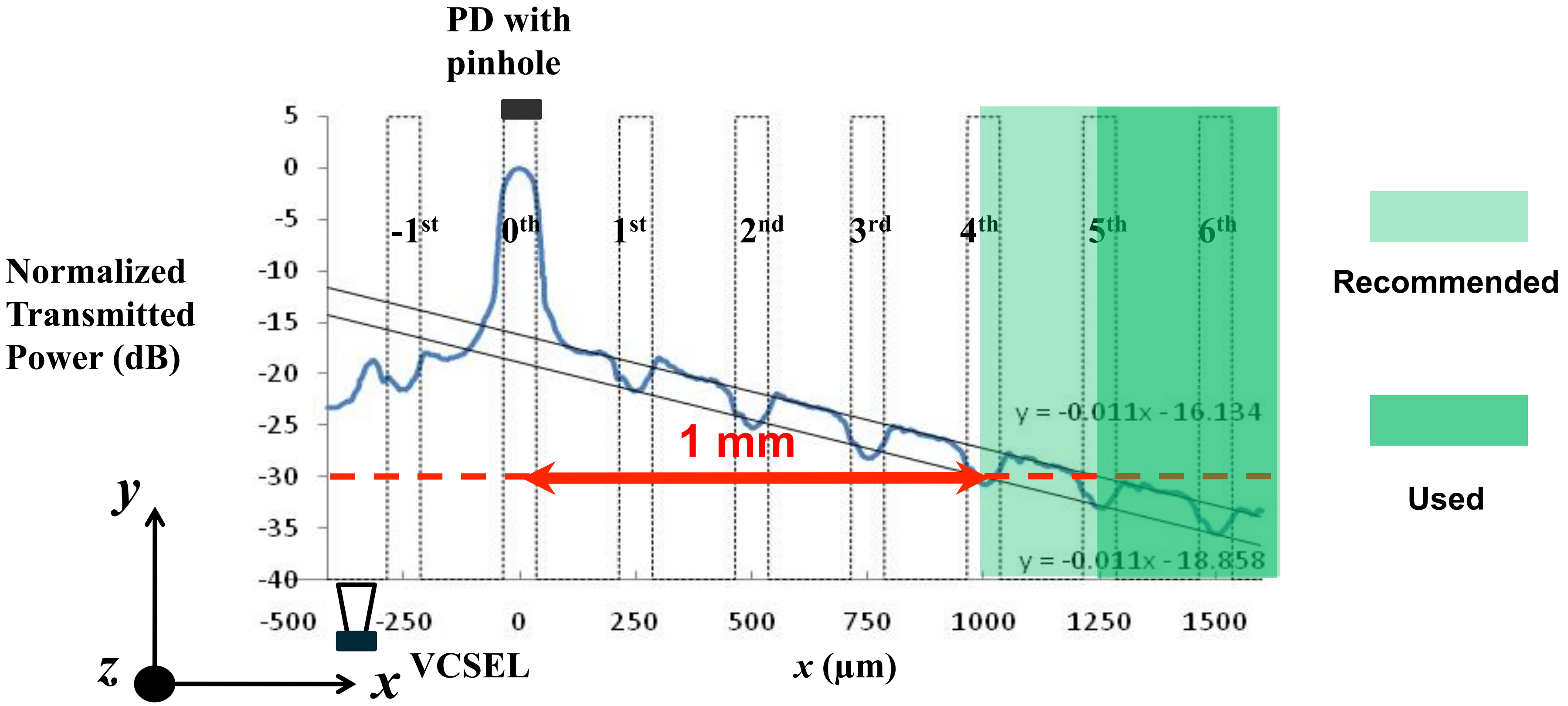
Source: GRINTech GmbH





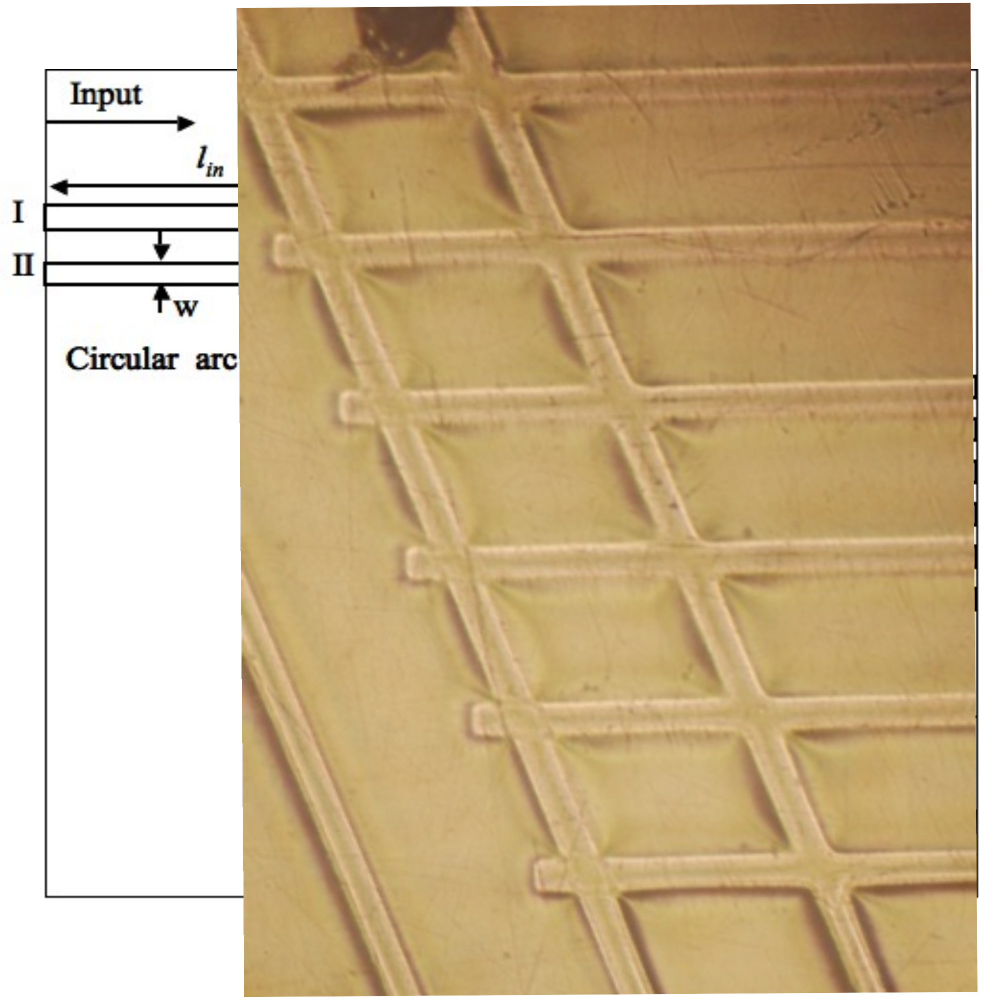
MT compatible interface

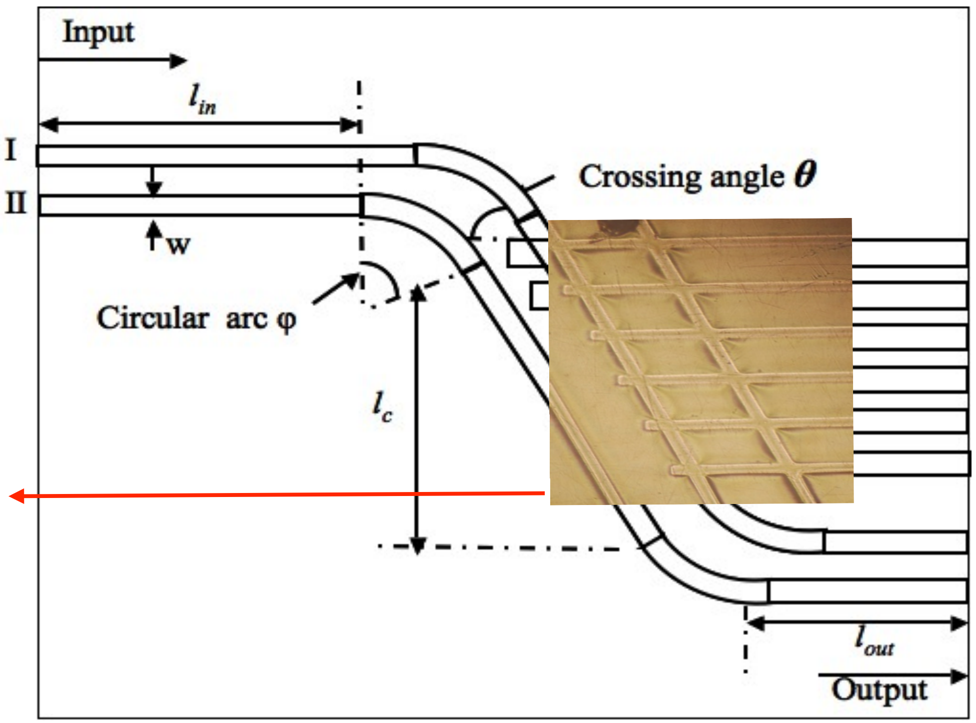
Design Rules for Inter-waveguide Cross Talk



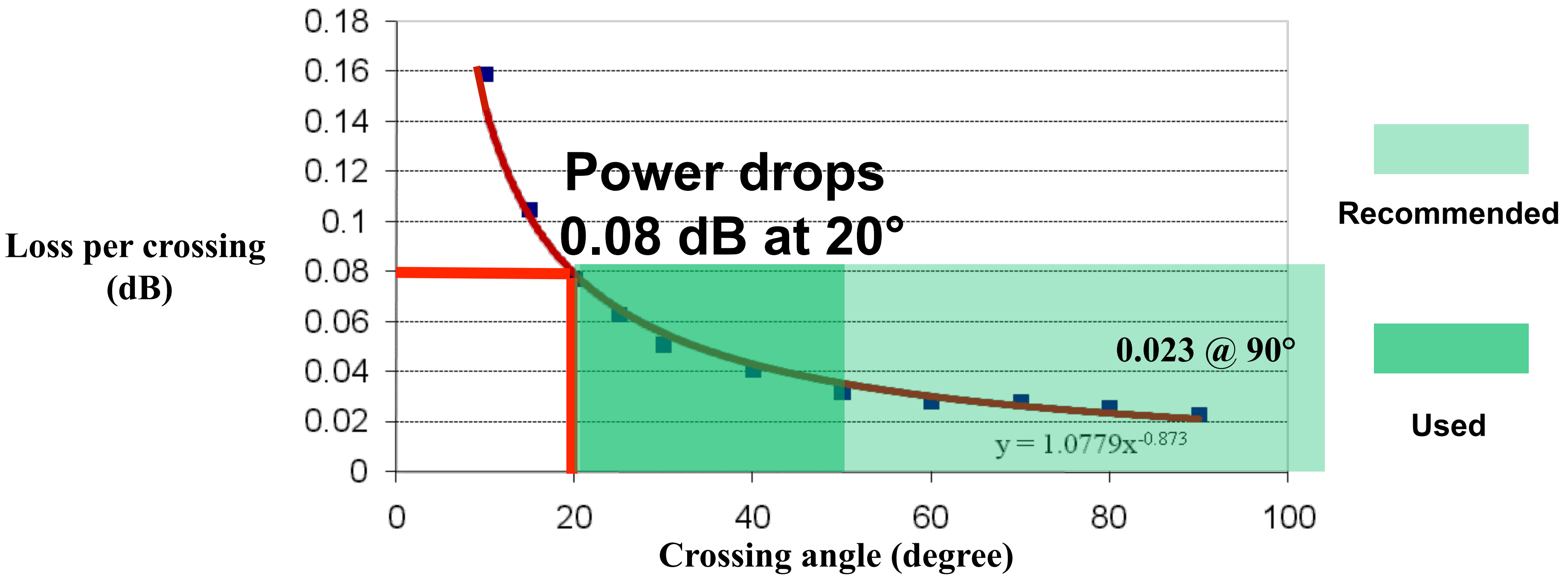
- 70 µm × 70 µm waveguide cross sections and 10 cm long
- In the cladding power drops linearly at a rate of 0.011 dB/μm
- Crosstalk reduced to -30 dB for waveguides 1 mm apart

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



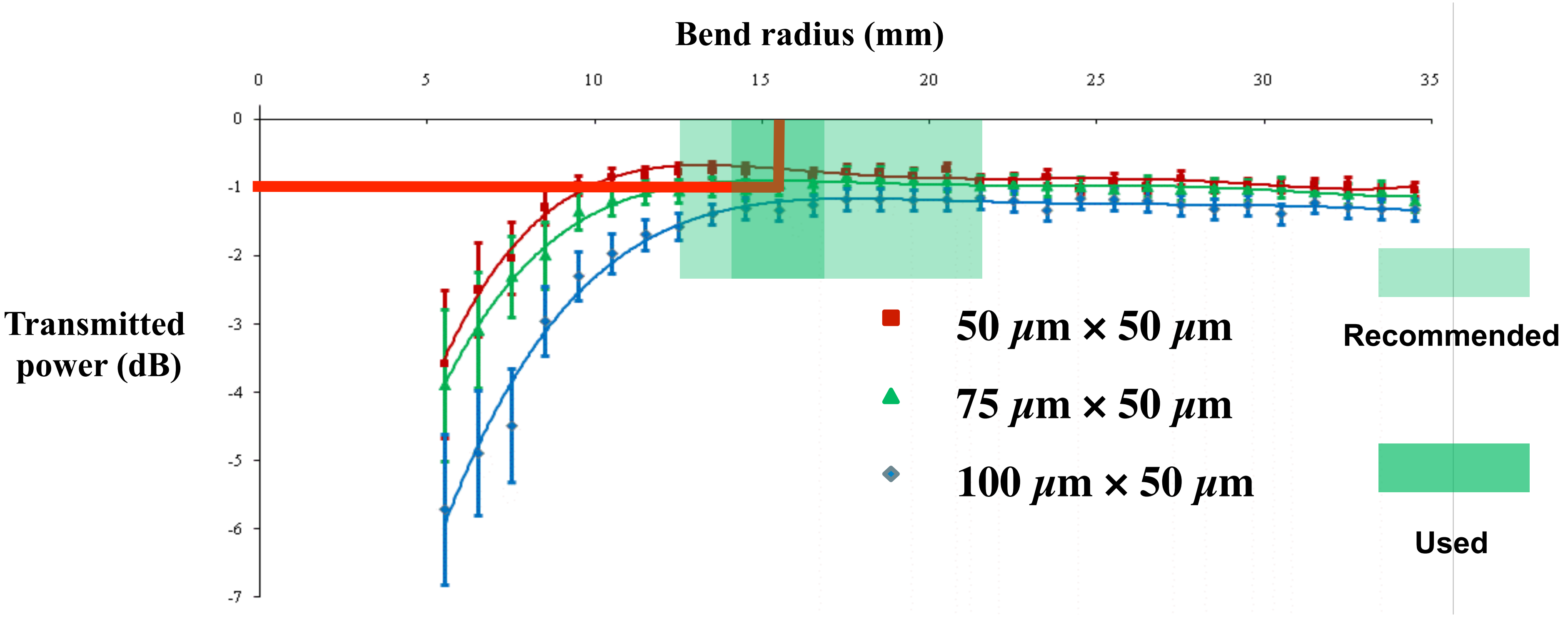


Design Rules for Arbitrary Angle Crossings



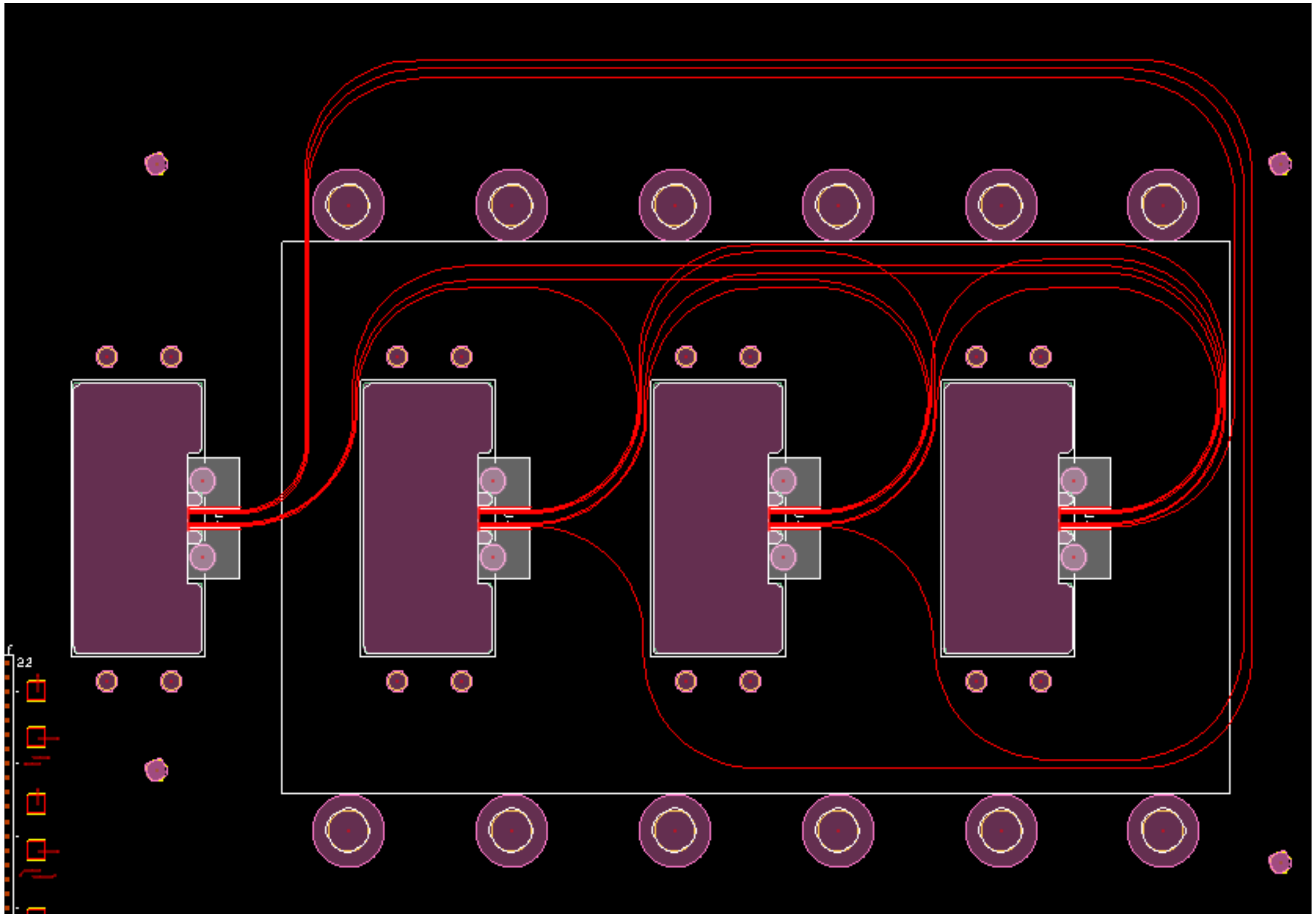
- Loss of 0.023 dB per 90° crossing consistent with other reports
- The output power dropped by 0.5% at each 90° crossing
- The loss per crossing (L_c) depends on crossing angle (θ), $L_c = 1.0779 \cdot \theta^{-0.8727}$

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



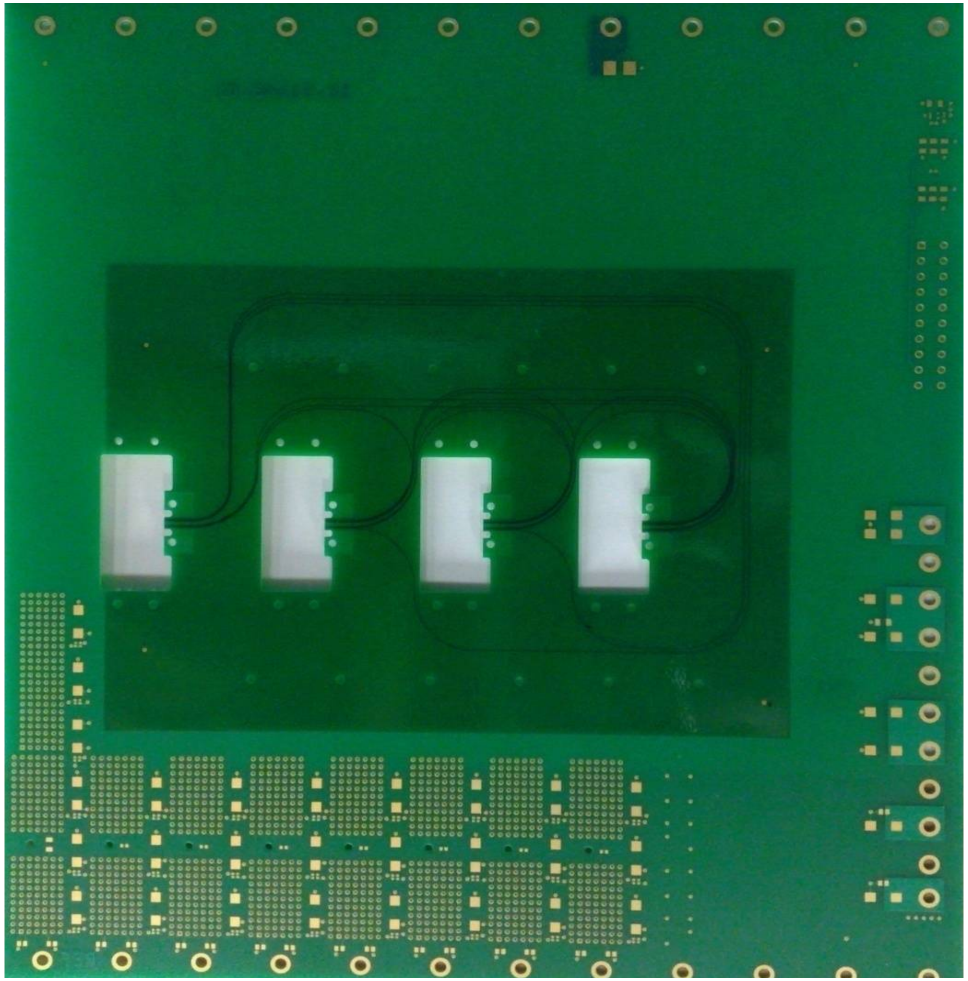
Fully connected waveguide layout using design rules

Power Budget

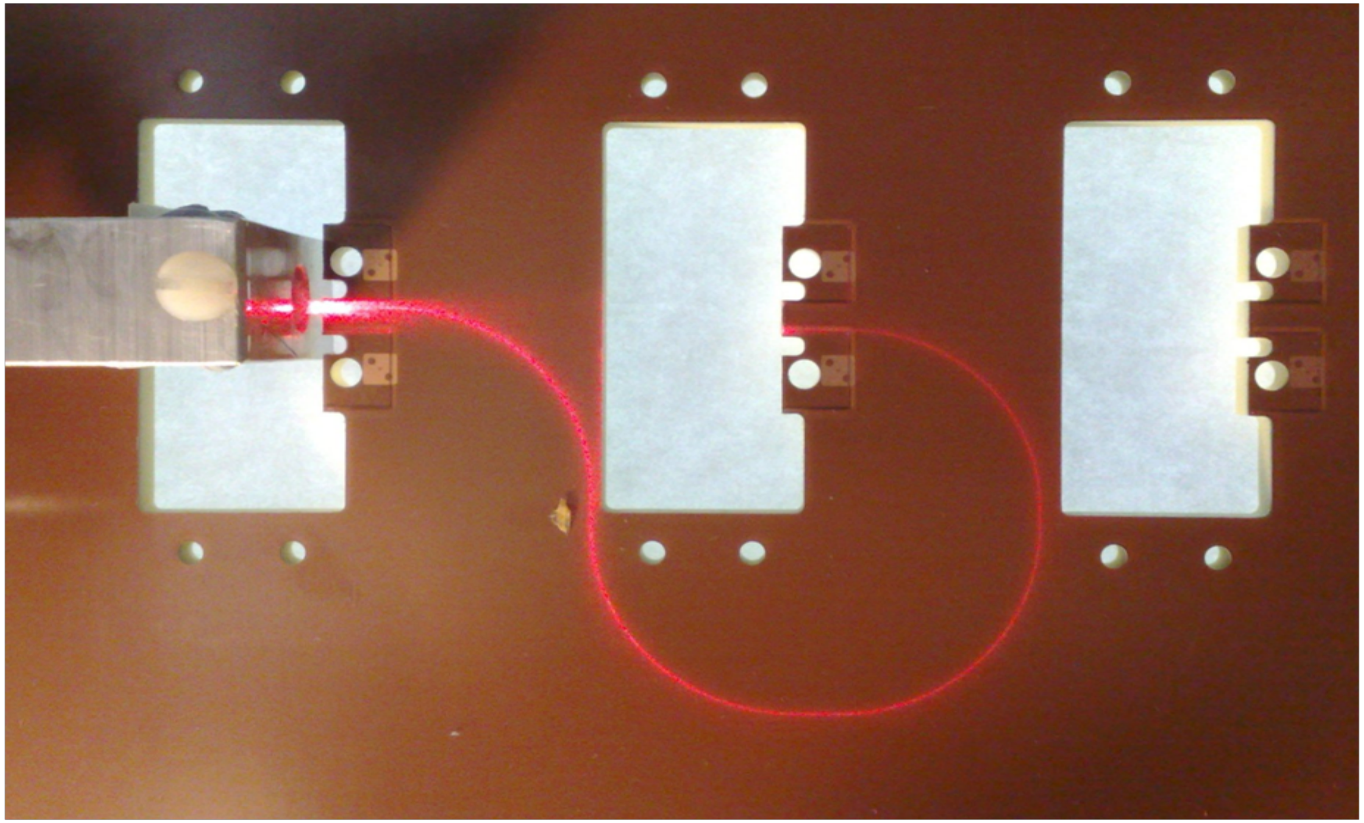
<table>
<tr><td>Input power (dBm/mW)</td><td colspan="6">-2.07 / 0.62</td></tr>
<tr><td></td><td colspan="6">Bend 90°</td></tr>
<tr><td>Radii (mm)</td><td>15.000</td><td>15.250</td><td>15.500</td><td>15.725</td><td>16.000</td><td>16.250</td></tr>
<tr><td>Loss per bend (dB)</td><td>0.94</td><td>0.91</td><td>0.94</td><td>0.94</td><td>0.95</td><td>0.95</td></tr>
<tr><td></td><td colspan="6">Crossings</td></tr>
</table>

<table>
<tr><td>Crossing angles (°)</td><td>22.27</td><td>29.45</td><td>36.23</td><td>42.10</td><td>47.36</td></tr>
<tr><td>Loss per crossing (dB)</td><td>0.078</td><td>0.056</td><td>0.047</td><td>0.041</td><td>0.037</td></tr>
<tr><td>Min. detectable power (dBm)</td><td colspan="5">-15 / 0.03</td></tr>
<tr><td>Min. power no bit error rate</td><td colspan="5">-12 / 0.06</td></tr>
</table>

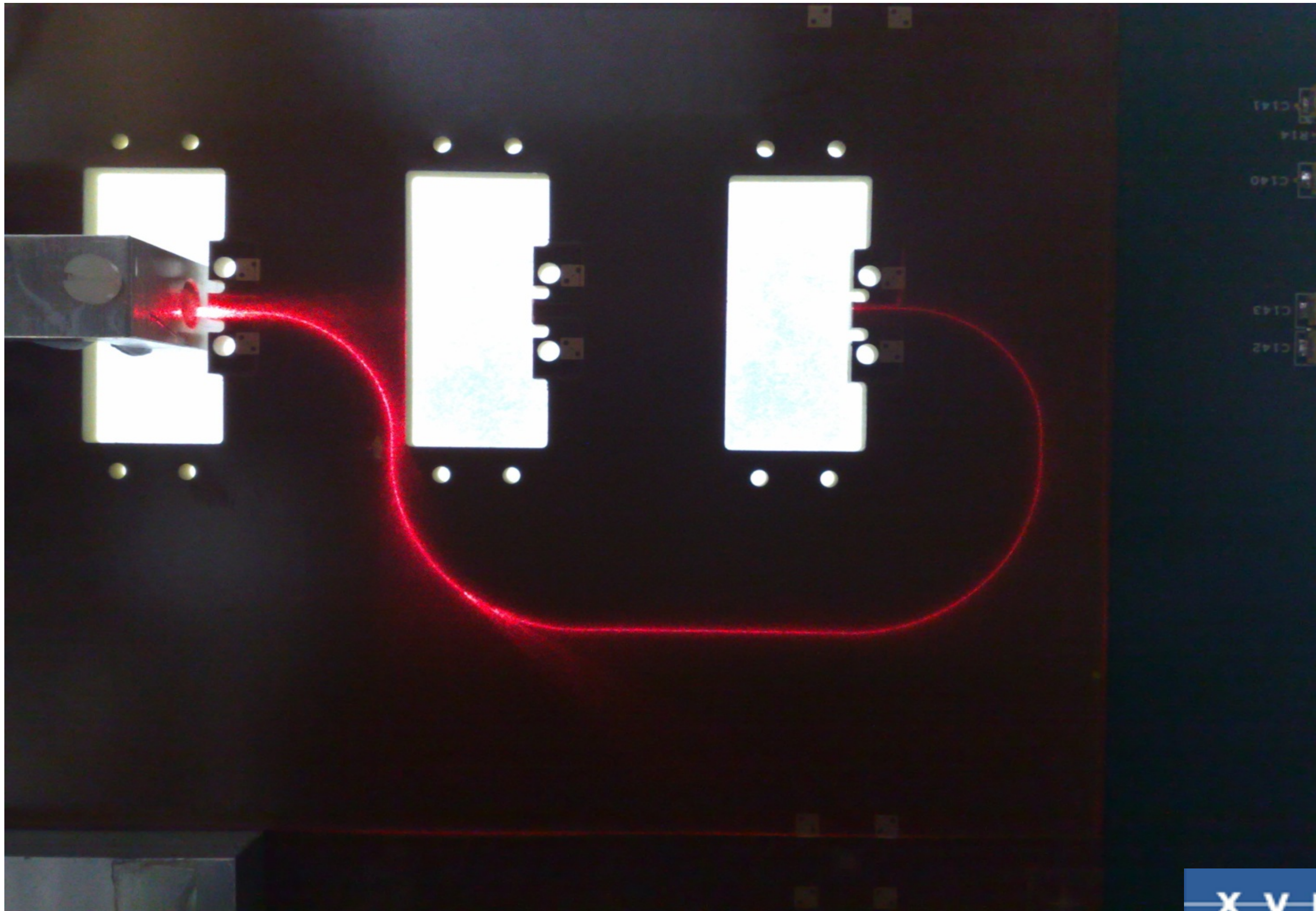
Demonstrator Dummy Board



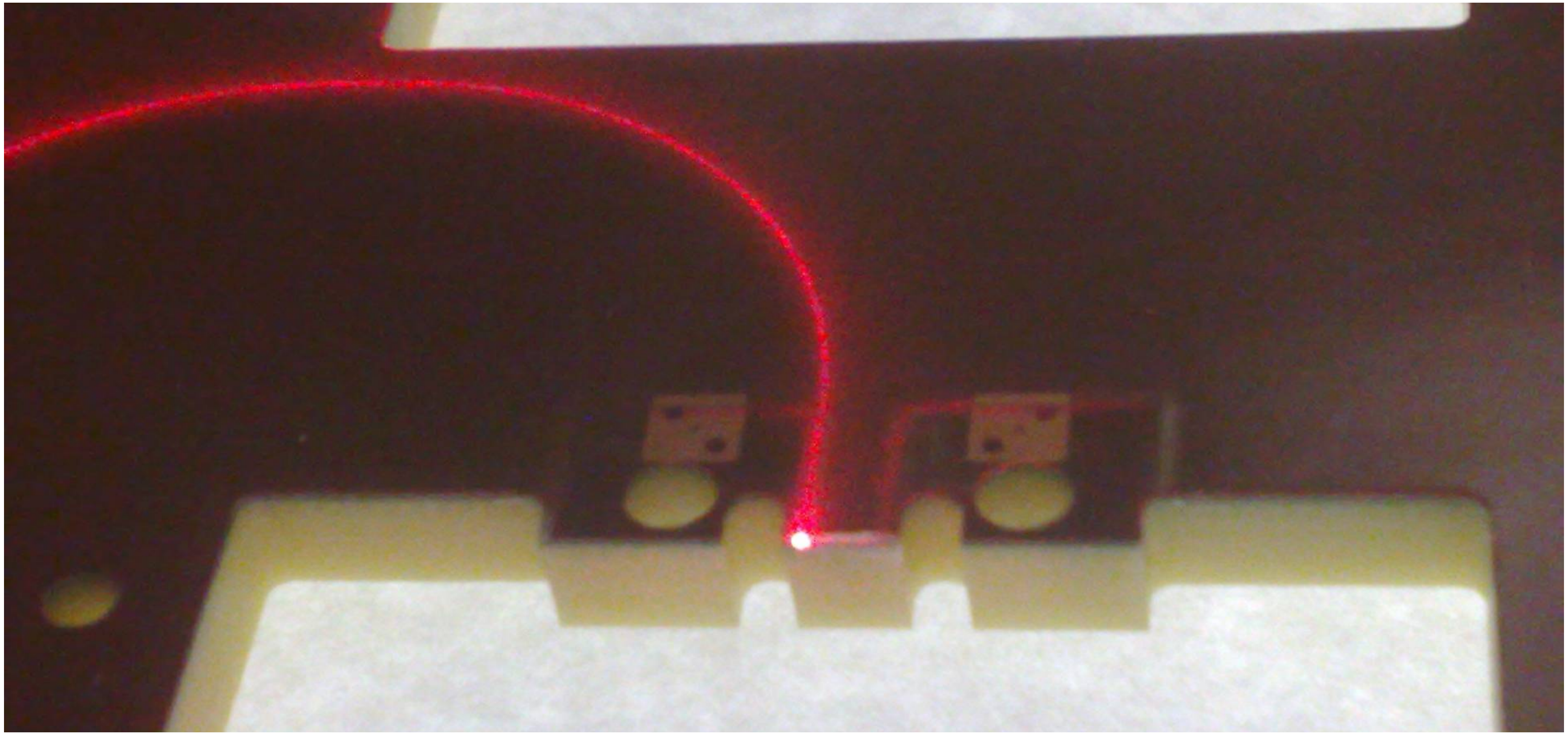
The Shortest Waveguide Illuminated by Red Laser



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



Output Facet of the Waveguide Interconnection



Data storage protocol and form factor trends

Hard Disk Drive Sizes Decreasing

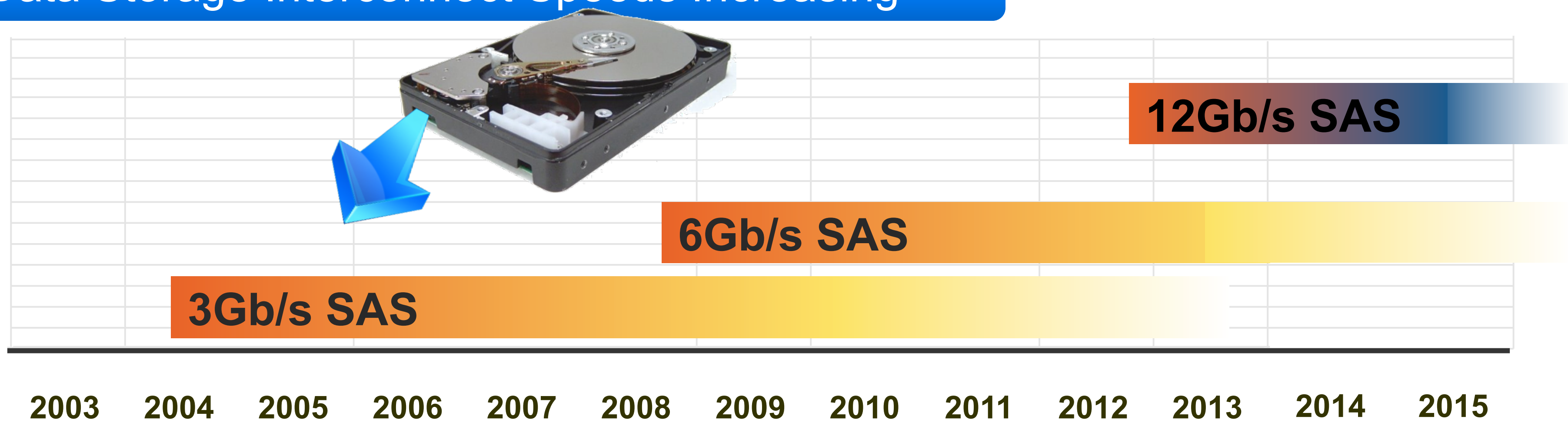
3.5" HDD

2.5" HDD

2.5" SSD

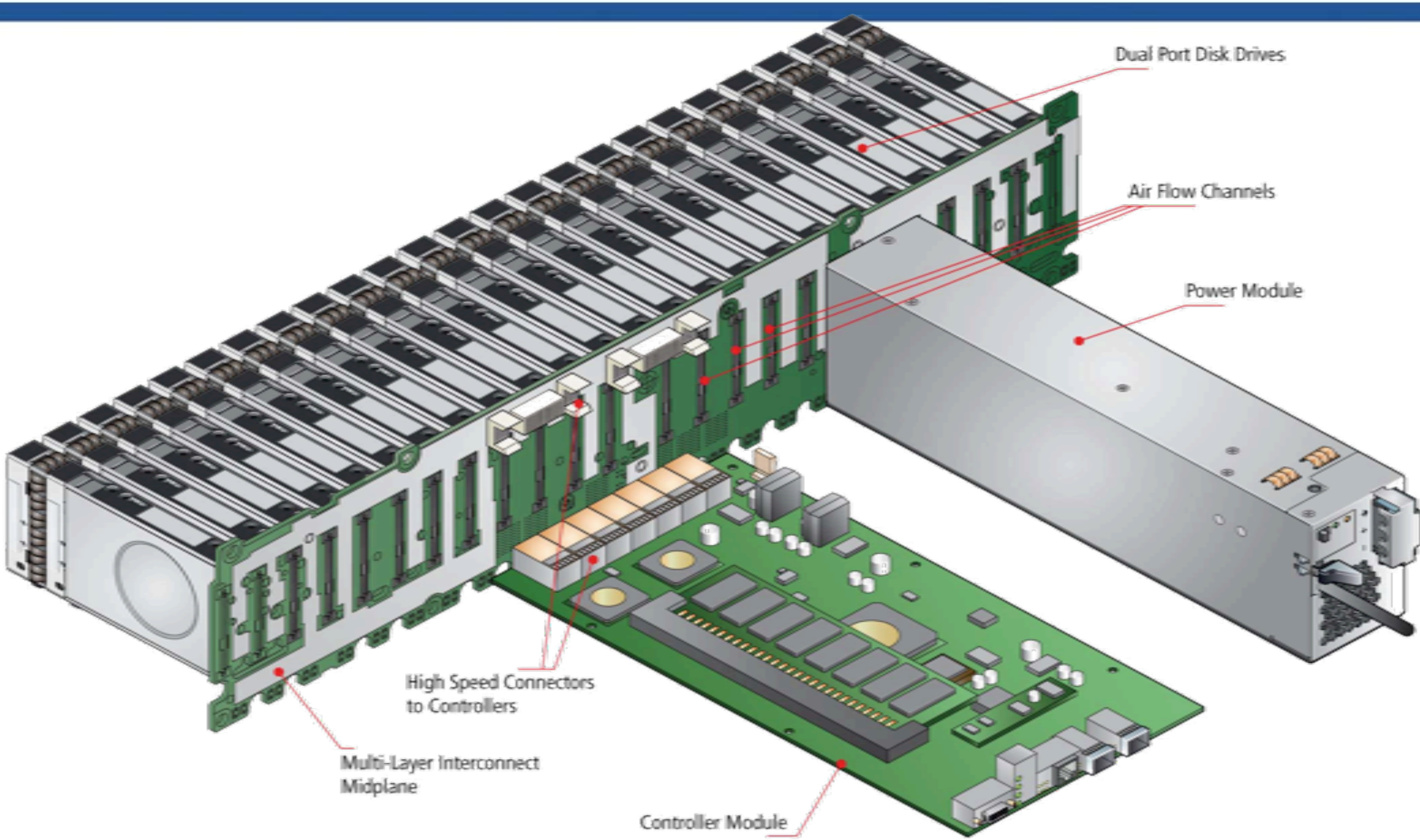
1.8" SSD

Data Storage Interconnect Speeds Increasing



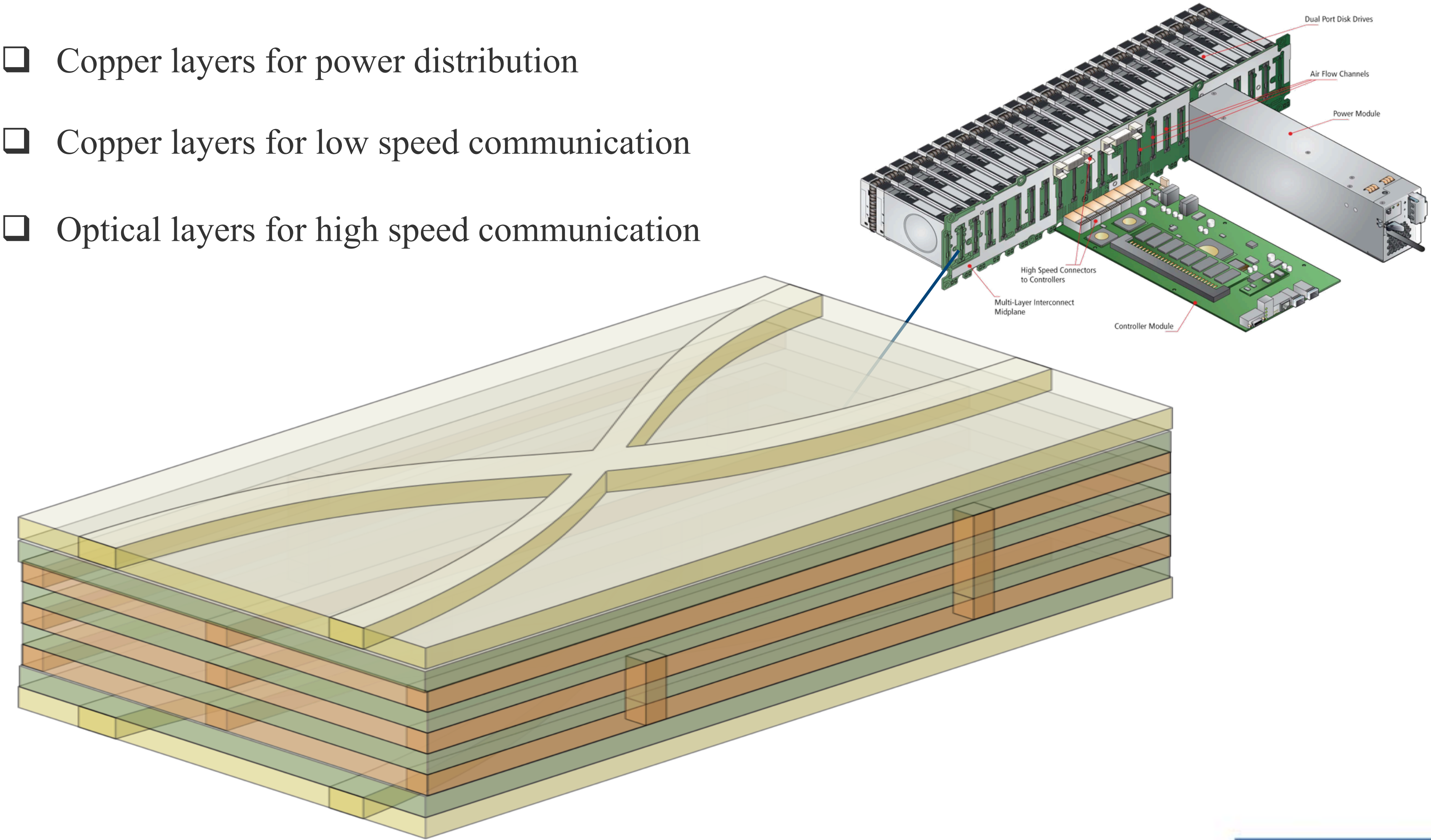
Source: SCSI Trade Association Sep 08 **www.scsita.org**

Design and performance constraints



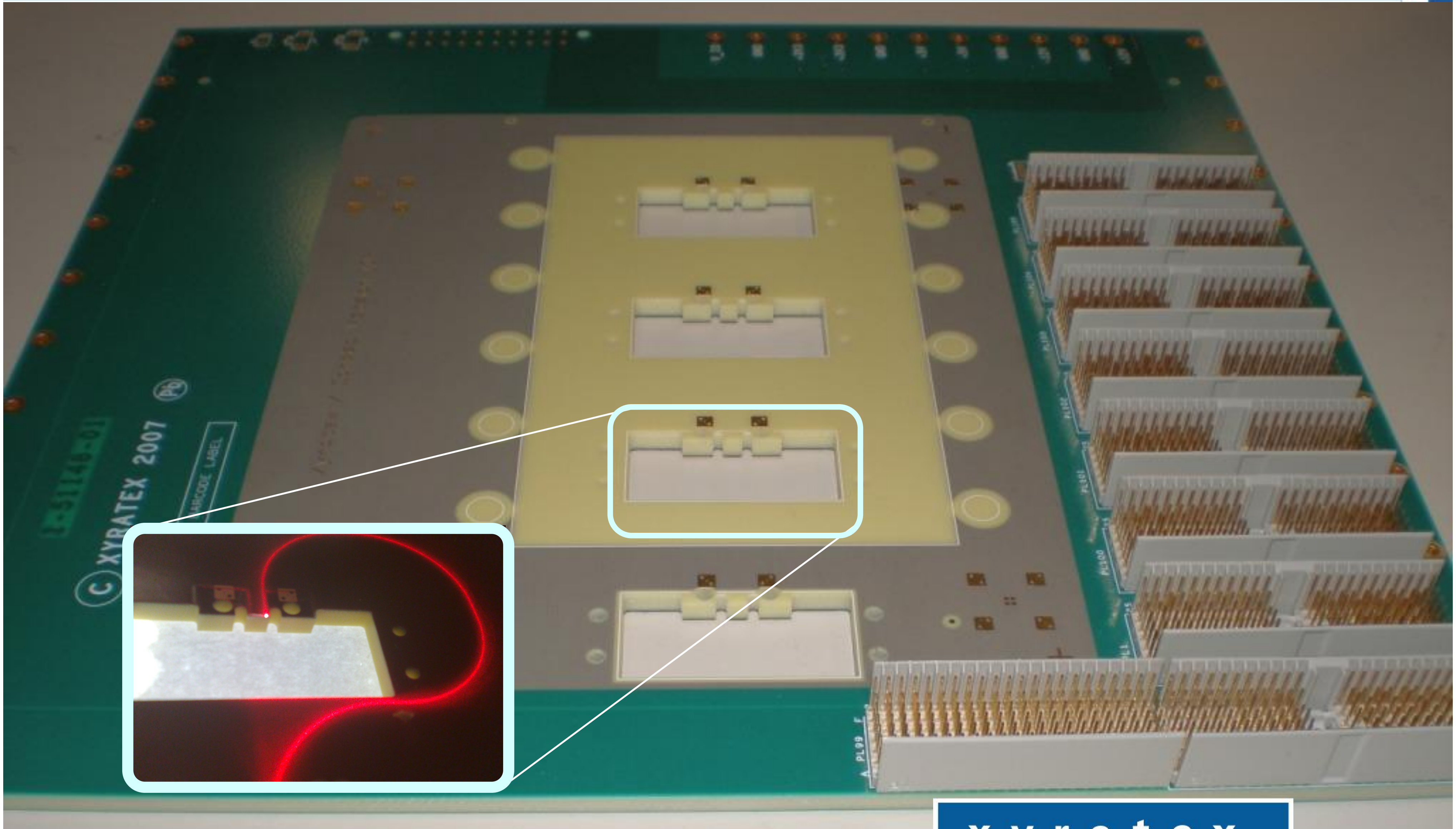
Embedded copper and optical architectures

- Copper layers for power distribution
- Copper layers for low speed communication
- Optical layers for high speed communication



xyratex

Electro-Optical Midplane



Polymer optical waveguide layer

Optical polymer

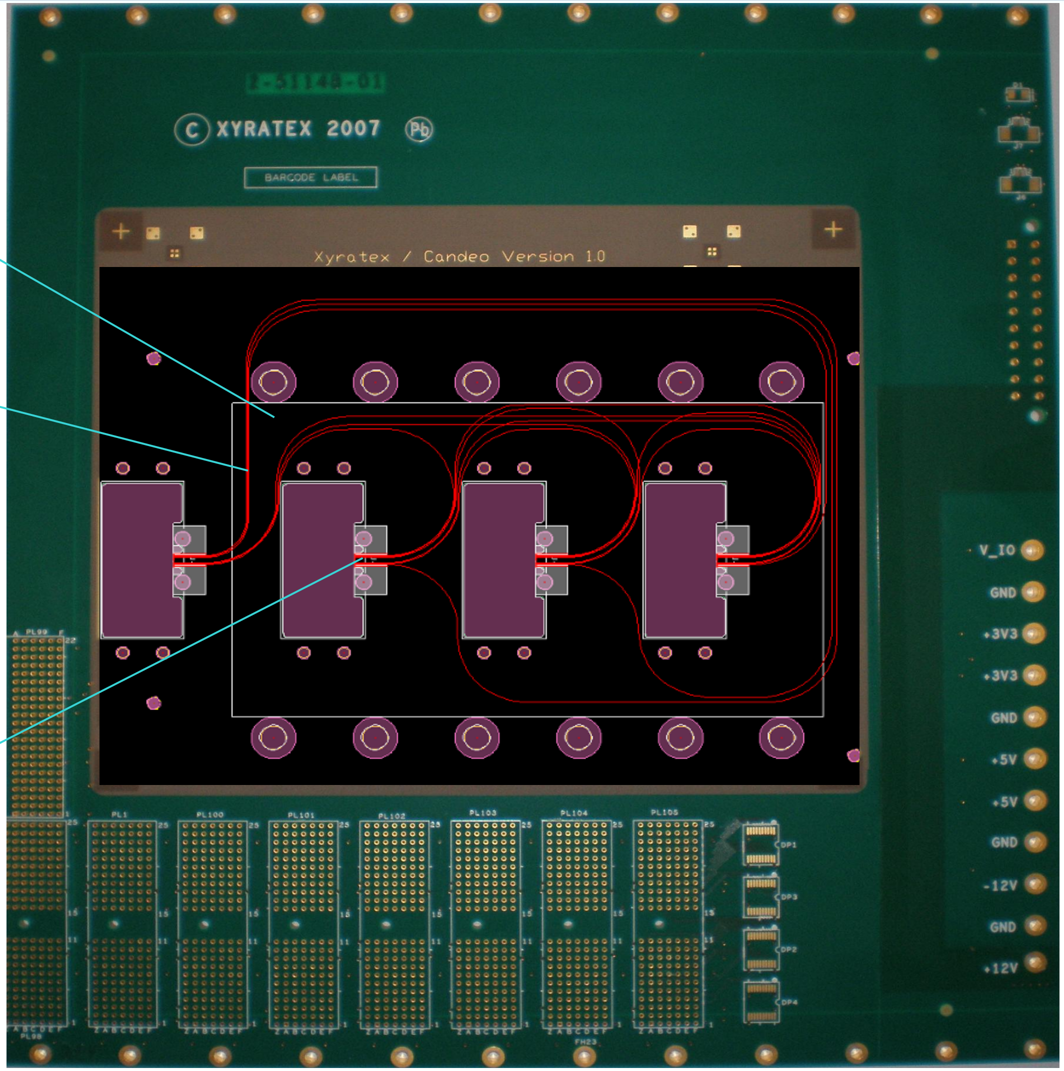
- Low loss at 850 nm

Waveguide characteristics

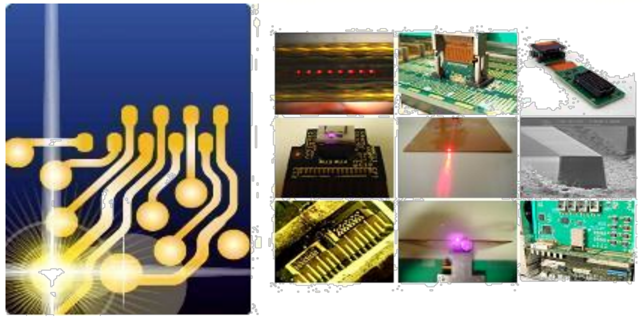
- n_{core} = 1.56
- $n_{cladding}$ = 1.524
- Δn = 2.3%
- N.A. = 0.33

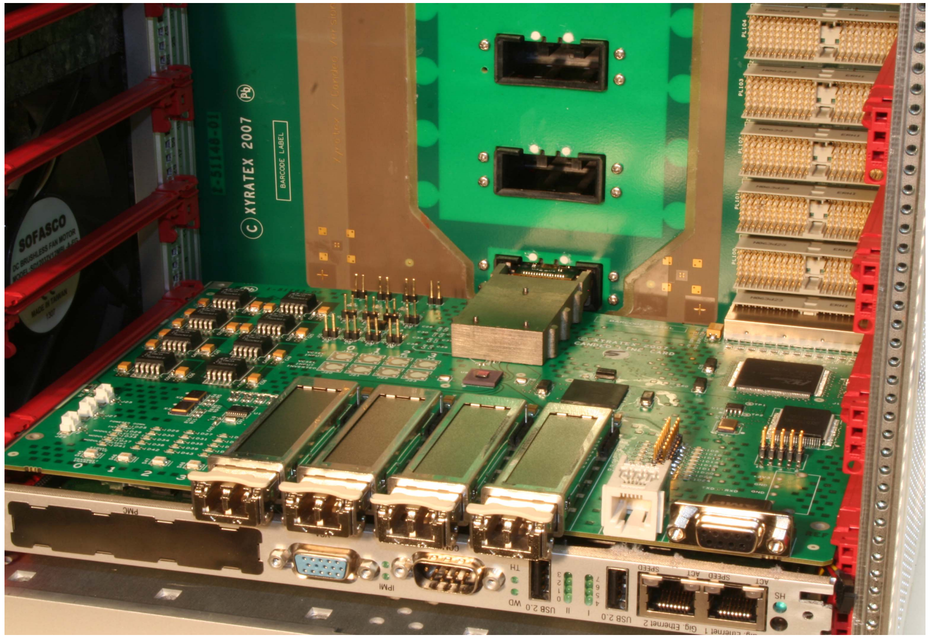
Core dimensions

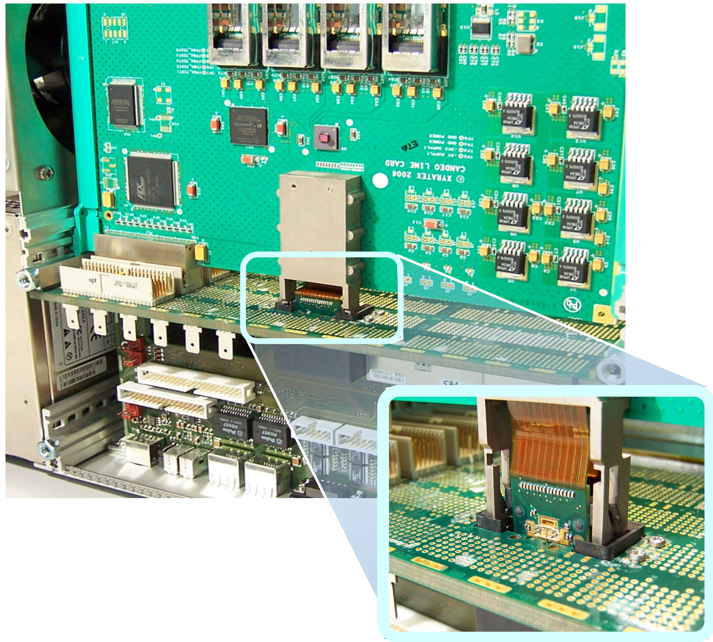
- Ø = 70 µm x 70 µm



Active optical midplane connector

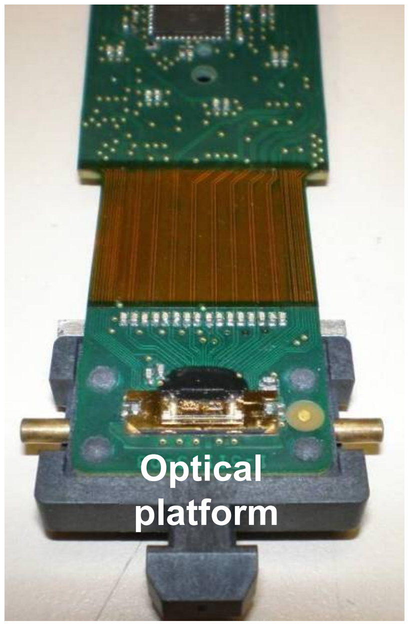


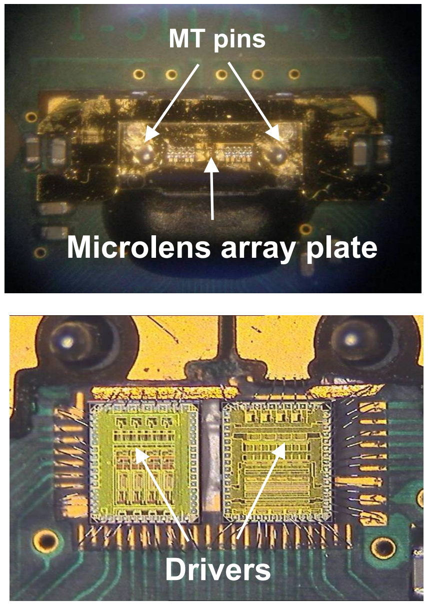


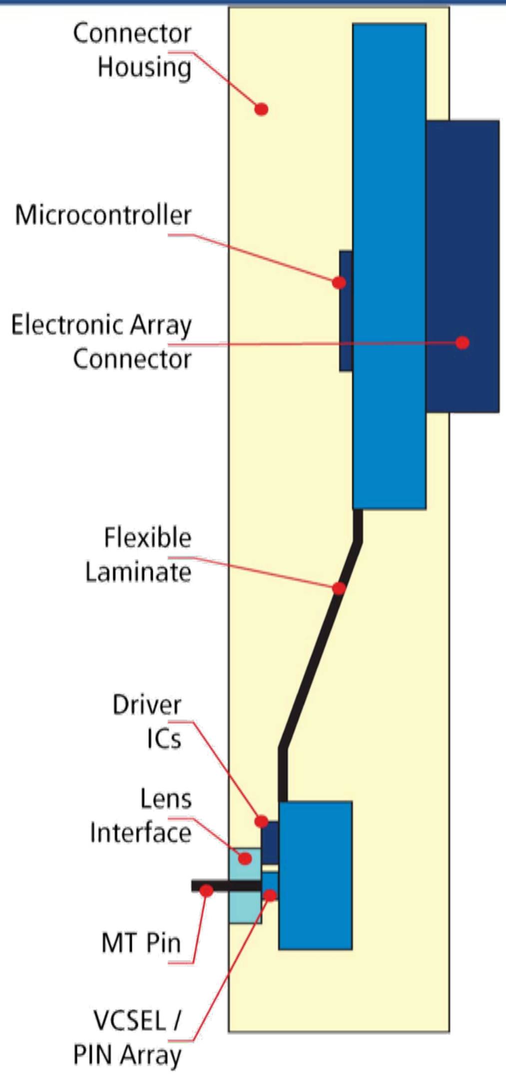


Parallel optical transceiver

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





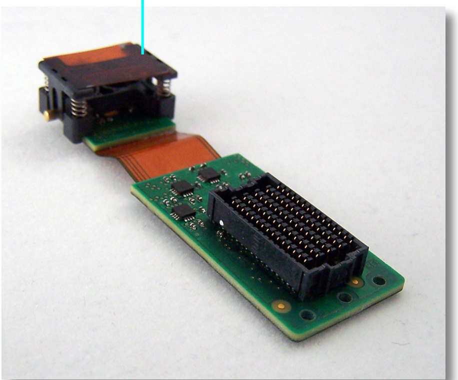


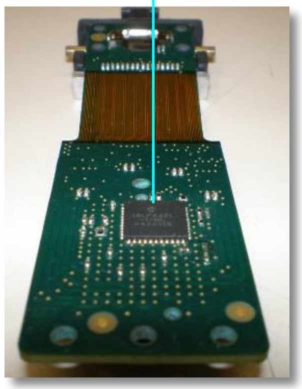
Active pluggable connector

Parallel optical transceiver

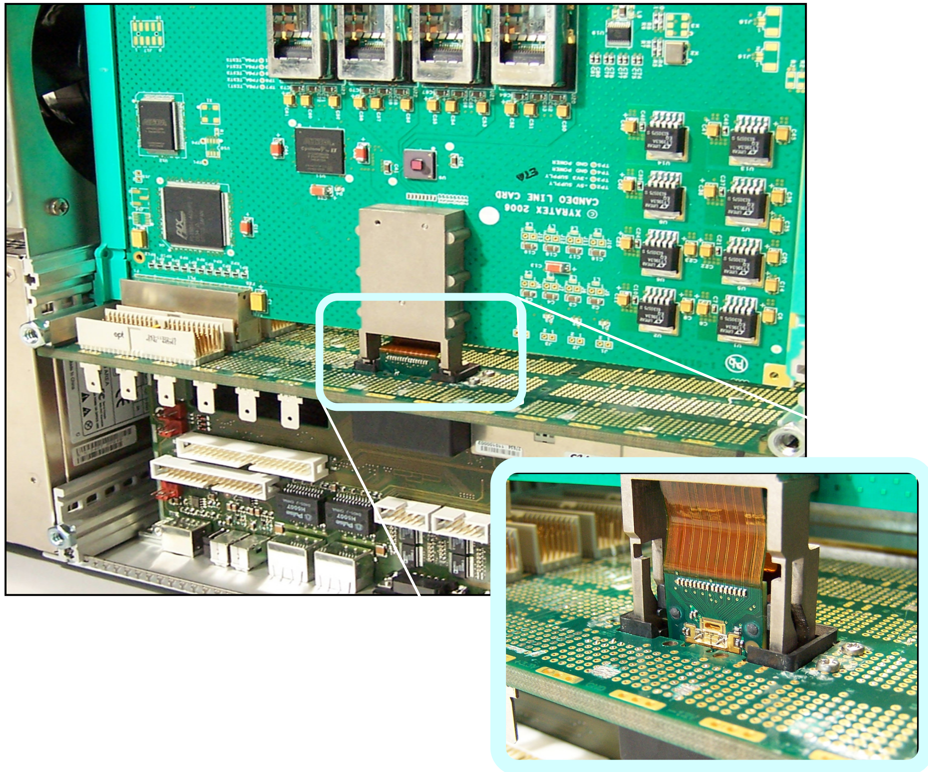
Spring loaded platform

Microcontroller



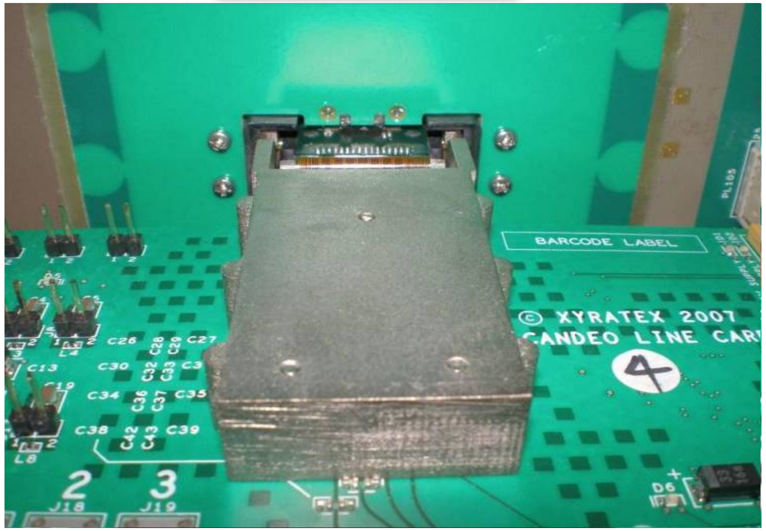


Connector module

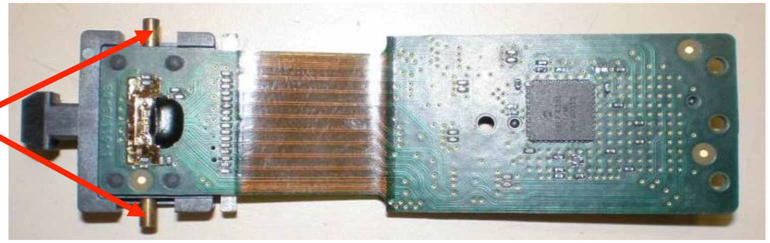


Connector engagement mechanism

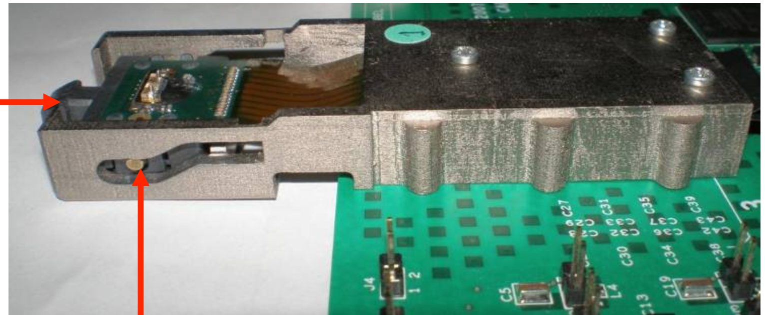
Docked



Cam followers



Ramped plug



Cam track

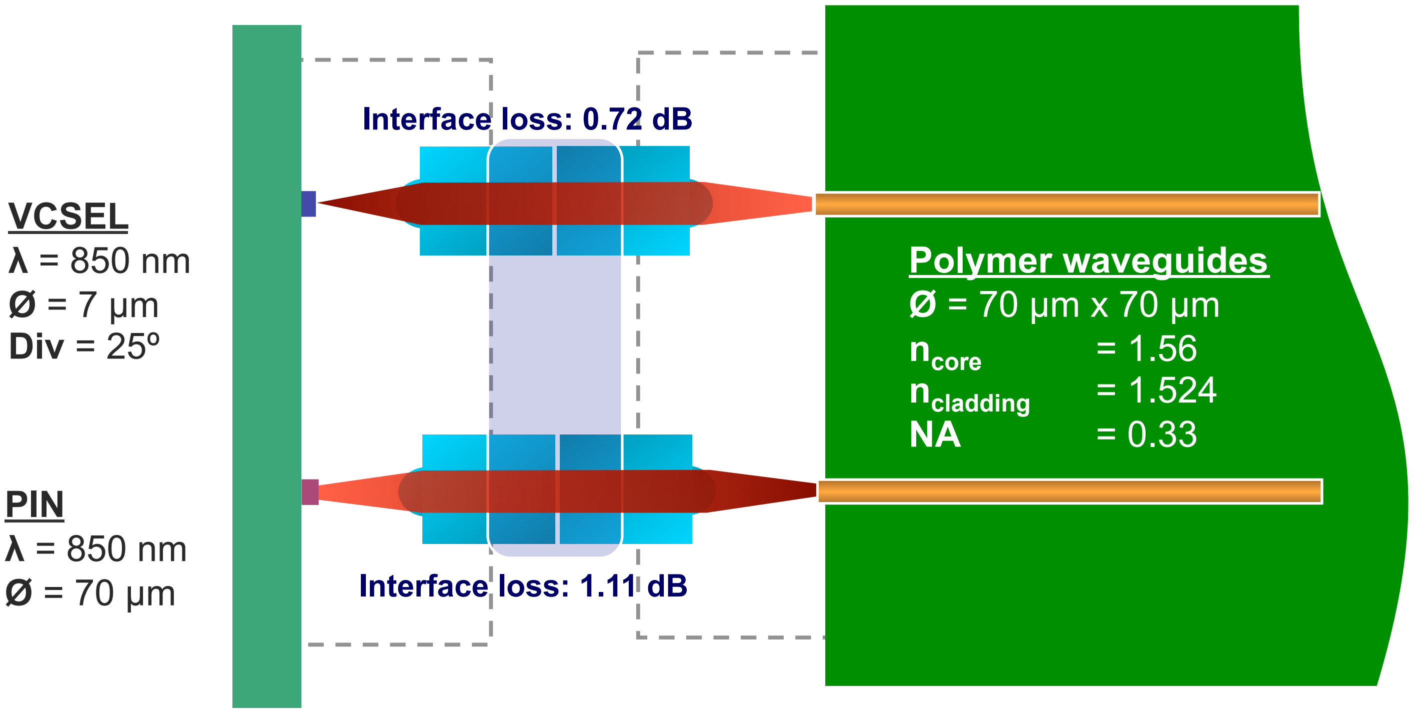
Dual lens coupling interface

Free space coupling

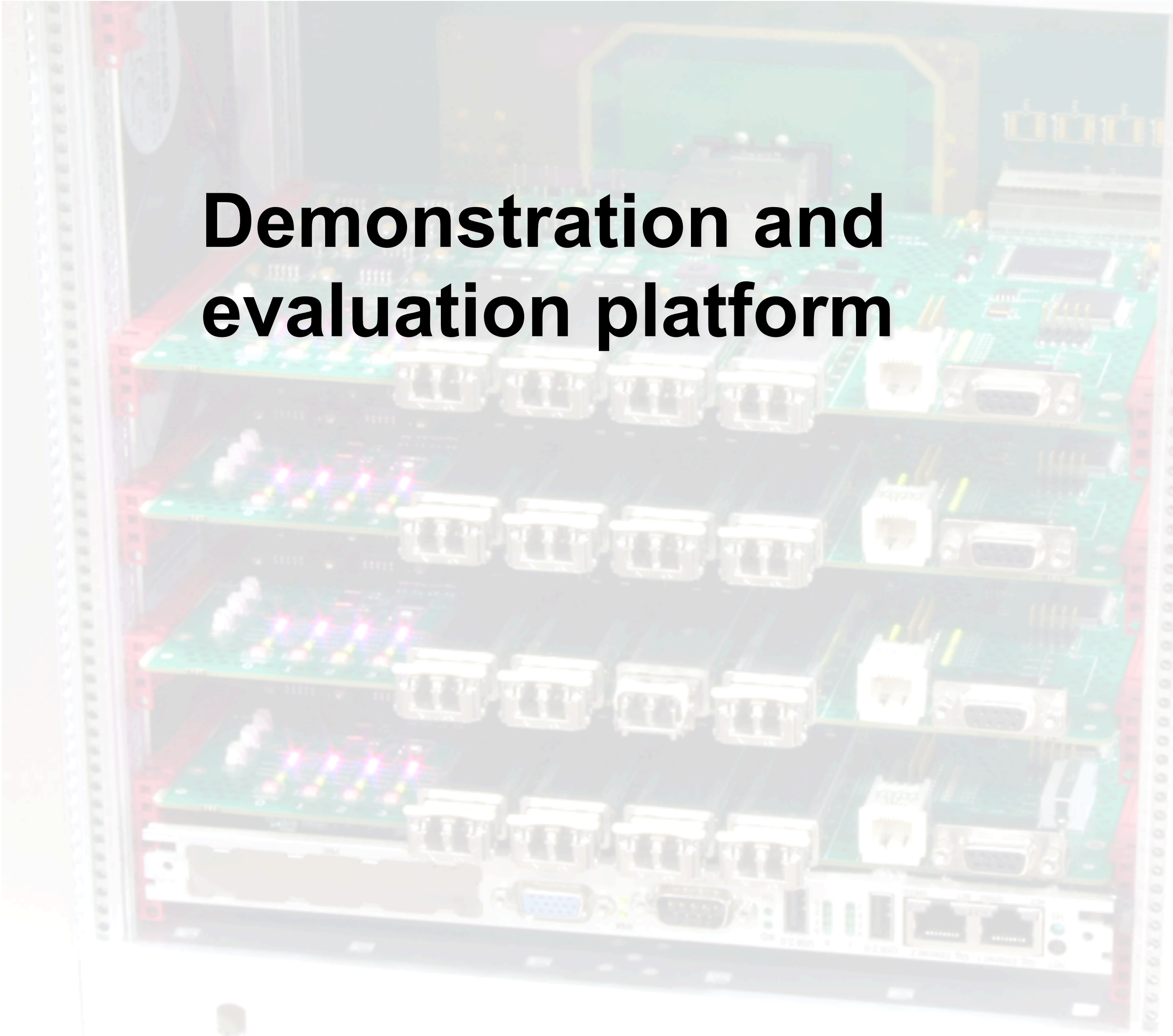
- ❑ Optimised for loss minimisation
- ❑ Maximum beam expansion

Dual lens coupling solution

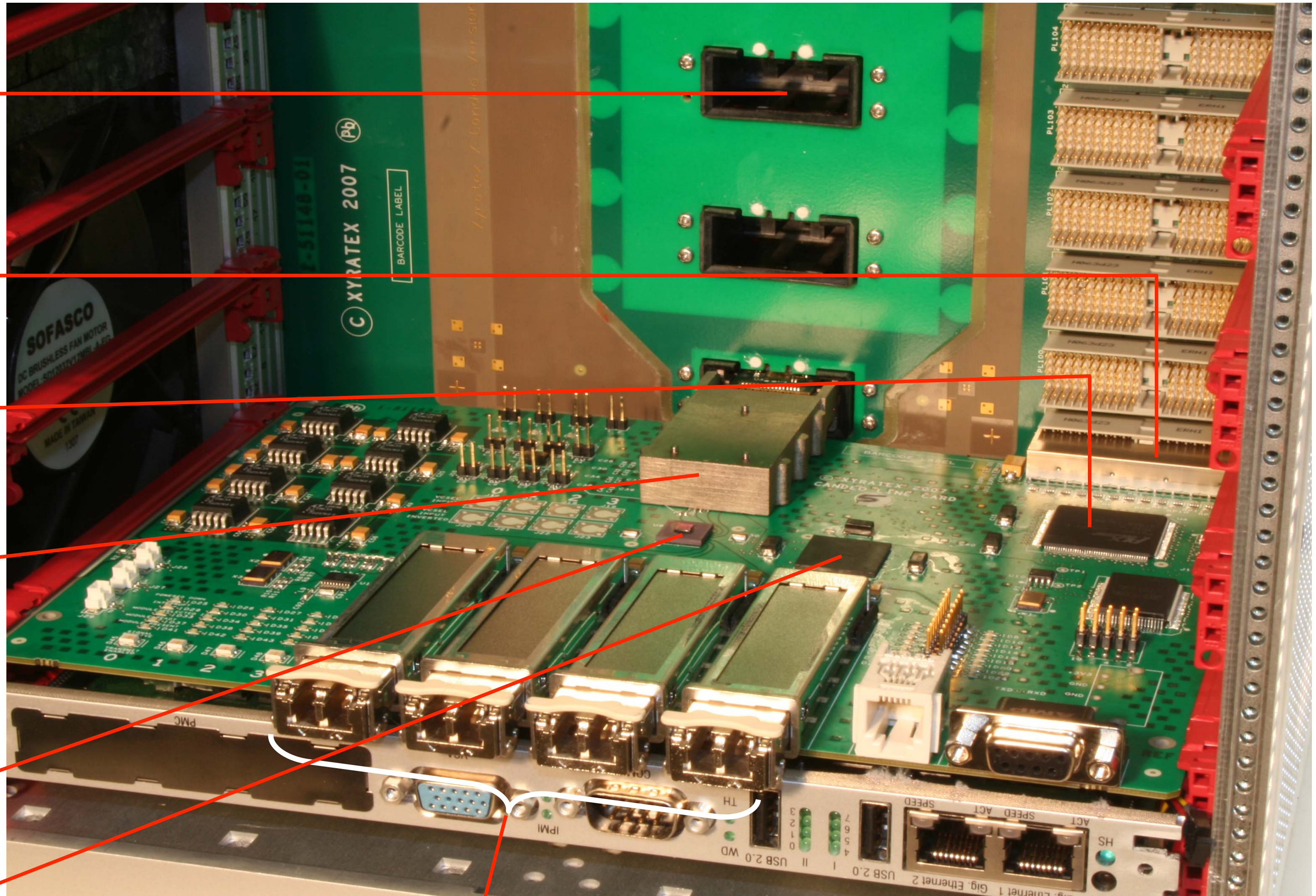
- ❑ Beam expansion at coupling interface
- ❑ Reduces susceptibility to contamination



Demonstration and evaluation platform



Peripheral test cards



Demonstration platform

Compact PCI chassis

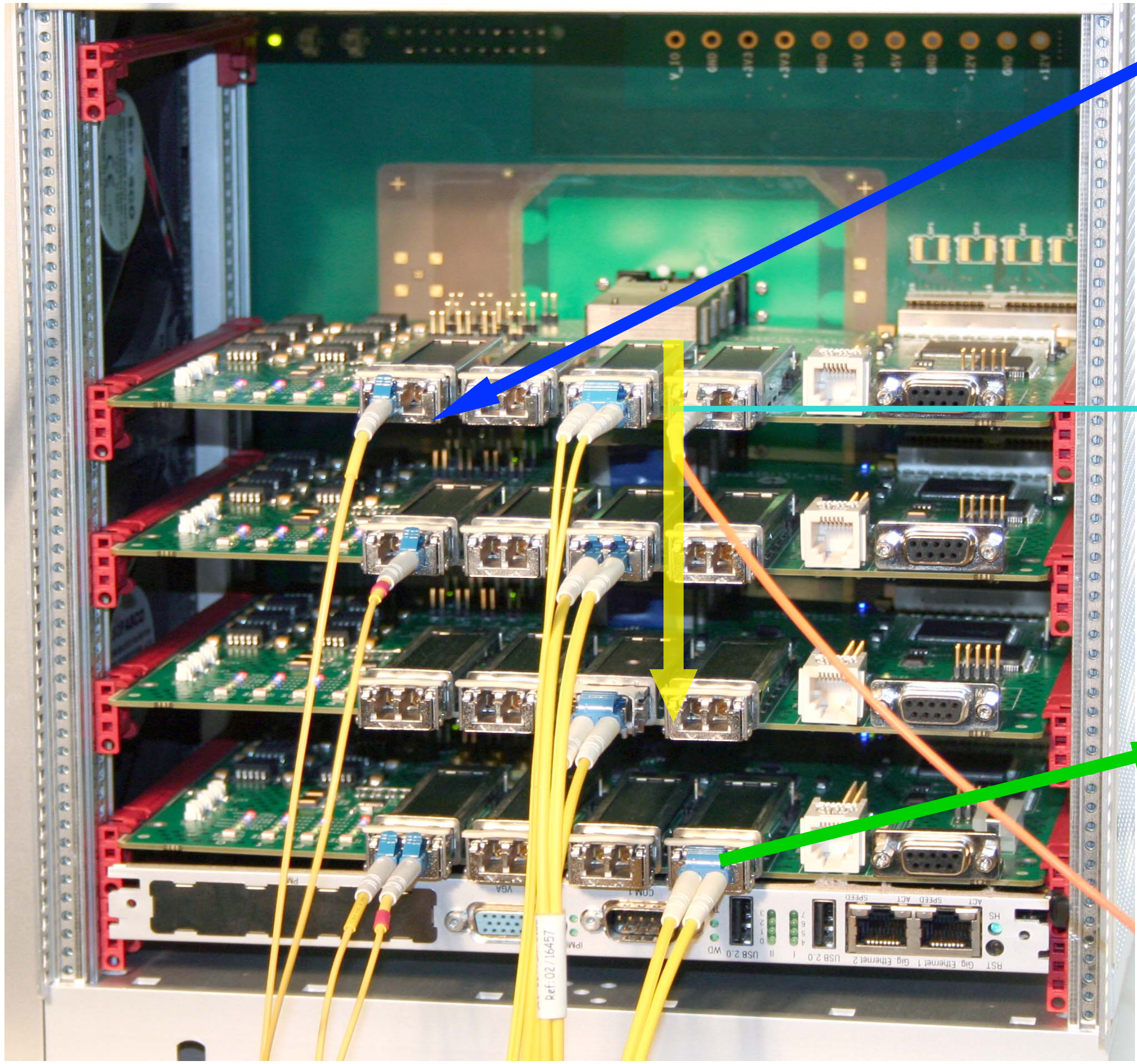
Electro-optical midplane

Pluggable optical connector

Peripheral test card

Single board computer

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

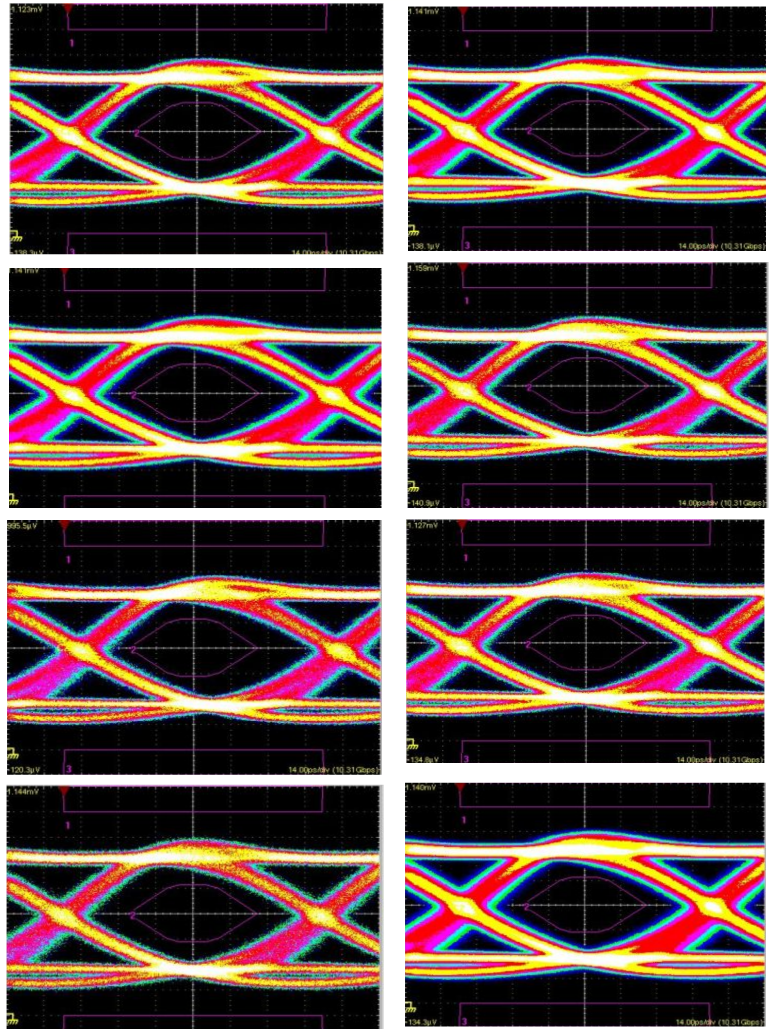
High speed data transmission measurements

Test data captured on 8 waveguides

- Data rate: 10.3 Gb/s
- Typical Pk to Pk jitter: 26 ps

BERT on waveguides

- Measured by UCL and Xyratex on all waveguides
- BER less than 10^{-12} measured



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  - Kai Wang, Hadi Baghsiahi, F. Aníbal Fernández, Ioannis Papakonstantinou
- **Loughborough University, UK**
  - David A. Hutt, Paul P. Conway, John Chappell, Shefiu S. Zakariyah
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  - **Dave Milward, Ken Hopkins, Malcolm Muggeridge**
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  - Henry White
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