OPCB

Integrated Optical and Electronic Interconnect PCB Manufacturing (OPCB)

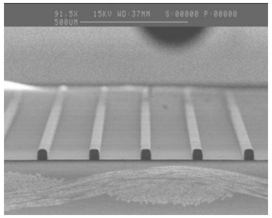
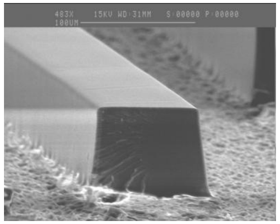
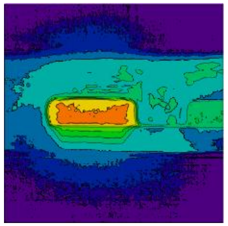
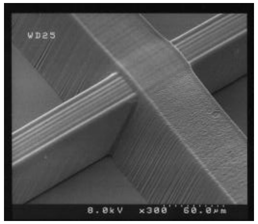
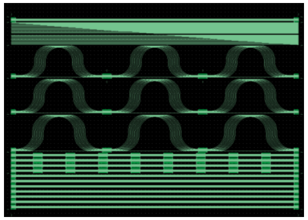
IeMRC Flagship Project

Innovative electronics Manufacturing Research Centre

IeMRC Annual Conference
Loughborough

4th July 2008

Project Objectives

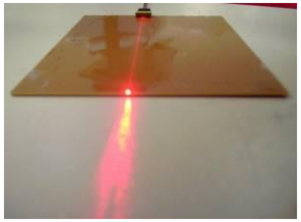
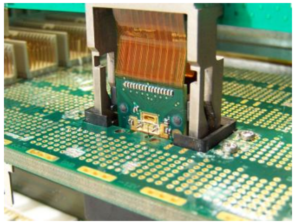






1. Enhance fabrication techniques for optical waveguides

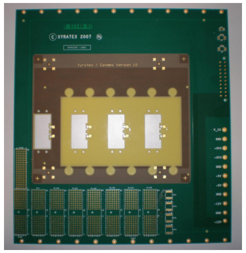
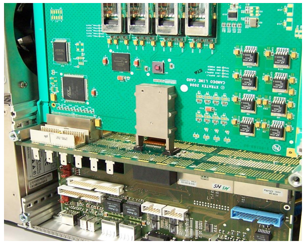
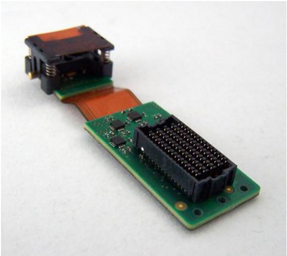
2. Integrate optical layers into Printed Circuit Boards (PCBs)

3. Develop technology enablers: Connectors, CAD, Design Rules

4. Deploy Electro-Optical PCBs into end-user applications

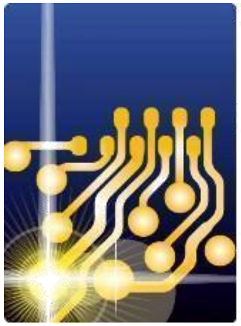



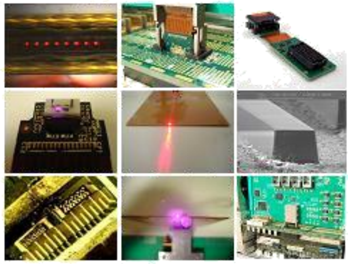


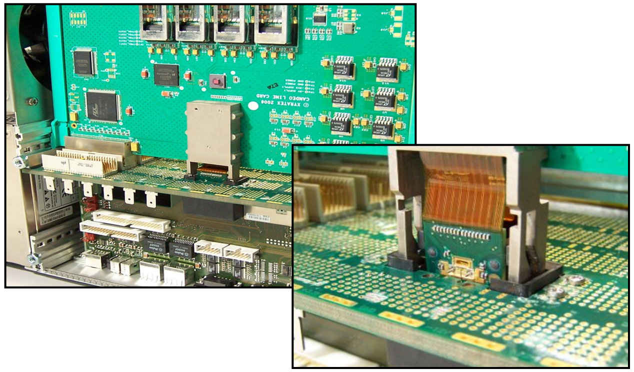




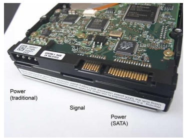
Research Objectives

- Investigate optical PCB technology
- Identify technology challenges
- Develop optical PCB and connector technology
- Integrate OPCB backplanes into storage systems
- Aid commercial proliferation





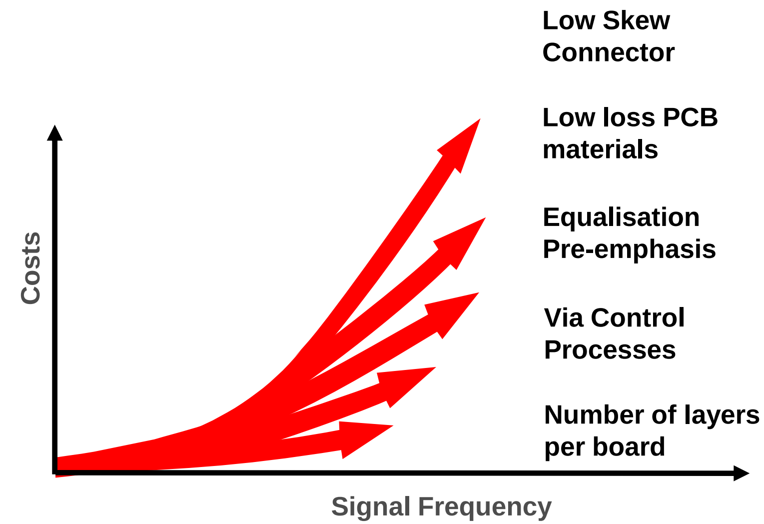


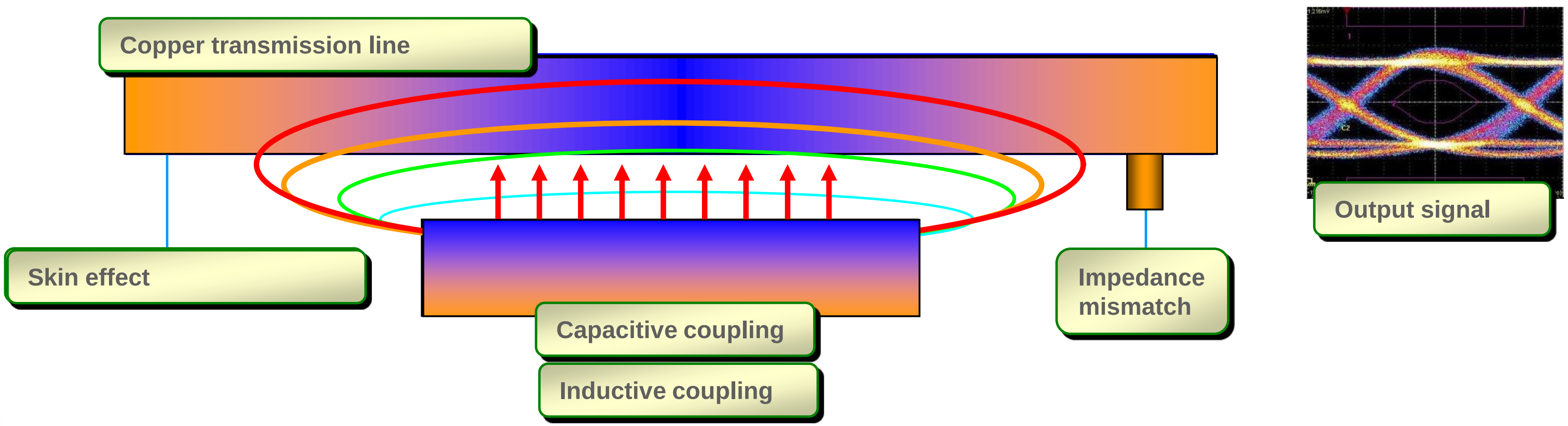


Cost Implications of High Speed Copper

High frequency copper issues

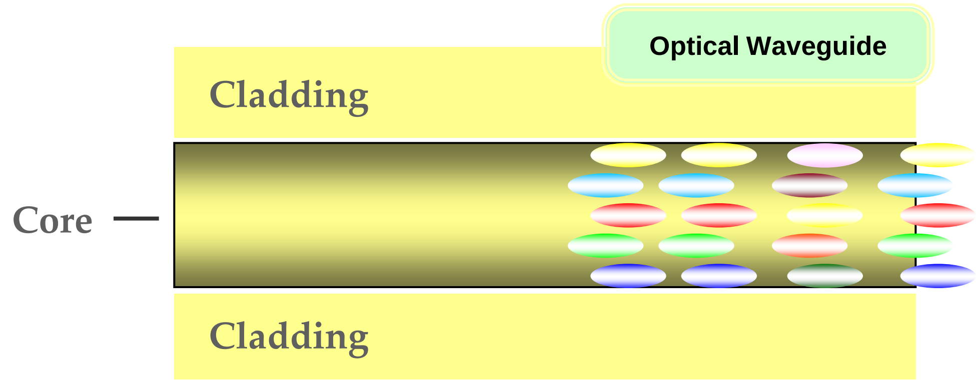
- Crosstalk
- Reflections
- Electromagnetic Interference (EMI)
- Dielectric Loss / Skin effect
- Skew

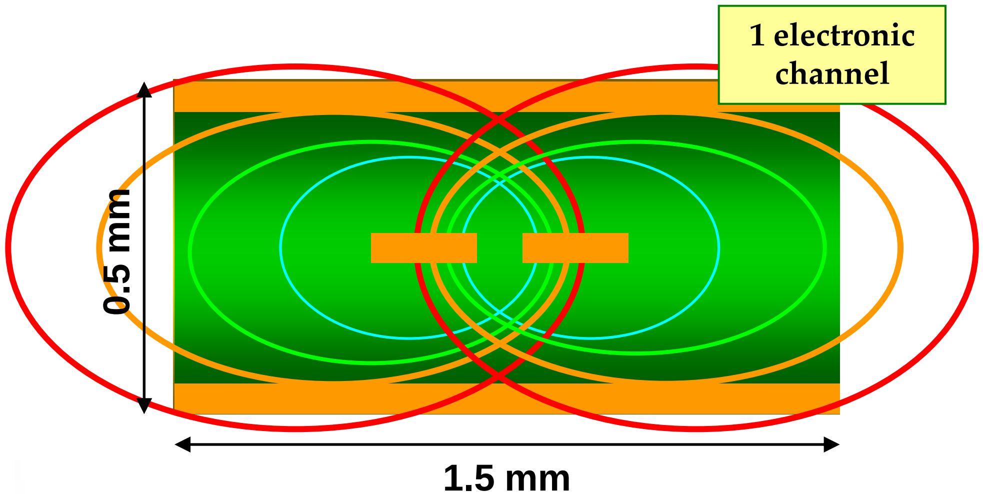


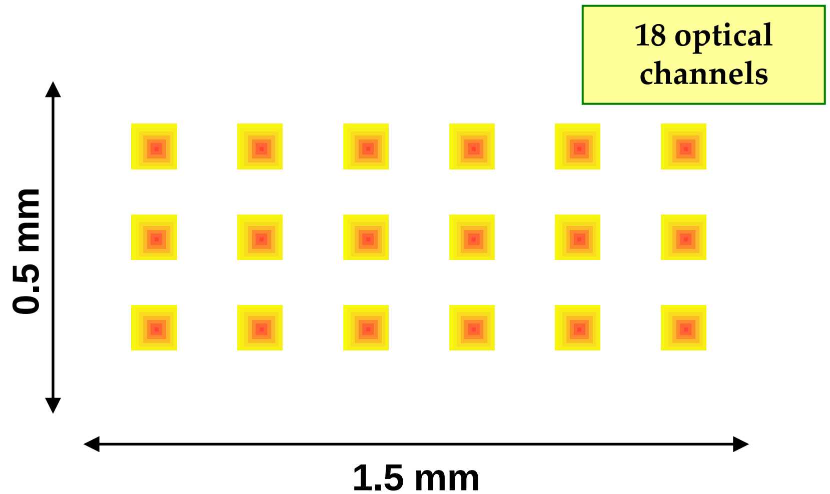


The Light Alternative

- Optical signal pipelines possible
- Send optical data further
- Fit more optical channels
- Send data faster
- No EMI outside the waveguide
- Send multiple signals (WDM)







Storage System Trends

Data storage systems increasing in complexity, density and speed

Storage demand increasing

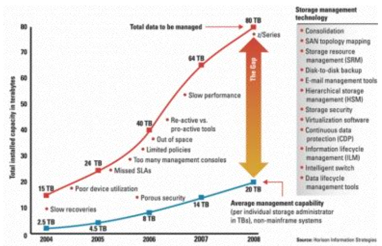
- ❑ Manage more storage
- ❑ Increased complexity

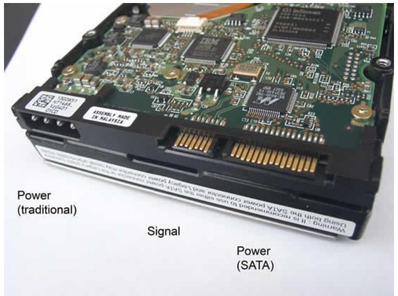
Disk sizes decreasing

- ❑ Increased system density

Data rates increasing

- ❑ Data access speeds:
  - ❑ *3 Gb/s SAS -> 6 Gb/s SAS*
  - ❑ *10 Gb/s Gigabit Ethernet*
  - ❑ *12 Gb/s SAS*





Material Supply and Development

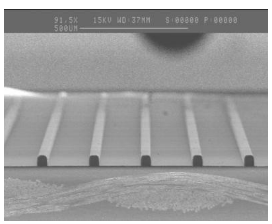
Two different classes of optical polymer evaluated and compared for waveguide production

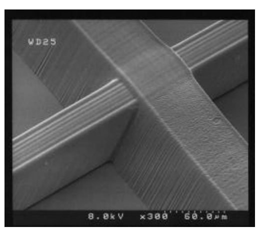
Polyacrylates

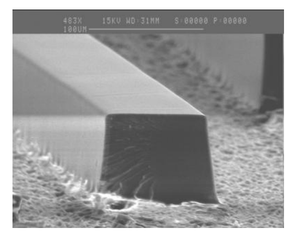
- ❑ Truemode® polymer - Exxelis
- ❑ New polymer formulations - Heriot Watt U

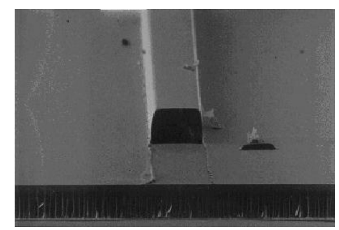
Polysiloxane

- ❑ Polysiloxane formulations – Dow Corning









HERIOT WATT UNIVERSITY

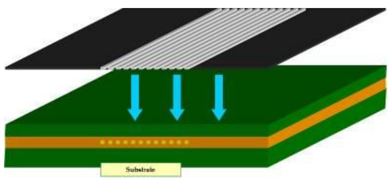
EXXELIS

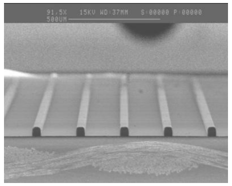
DOW CORNING

Optical Waveguide Fabrication

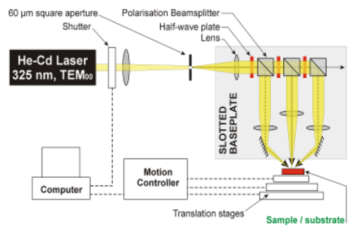
Four techniques for fabricating optical waveguides investigated and characterised

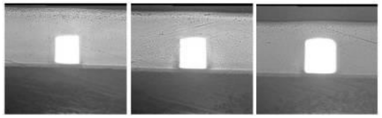
Photolithography



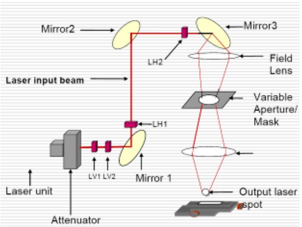


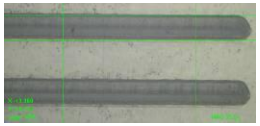
Laser Writing



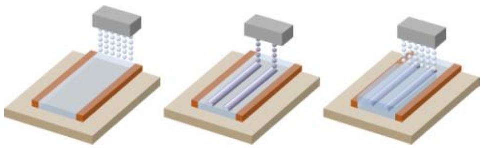


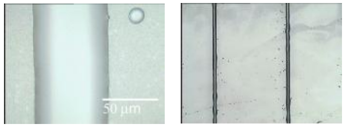
Laser Ablation





Ink Jet Printing





STEVENAGE CIRCUITS
TAKING TECHNOLOGY FURTHER

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IeMRC Innovative electronics Manufacturing Research Centre

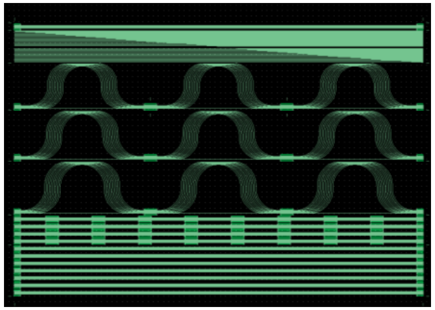
Design services for optical waveguide layout developed

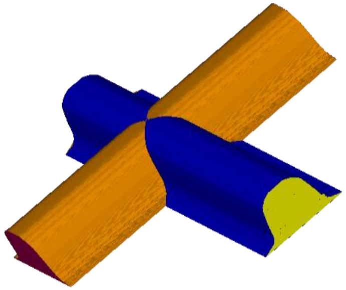
Design Rules and Characterisation

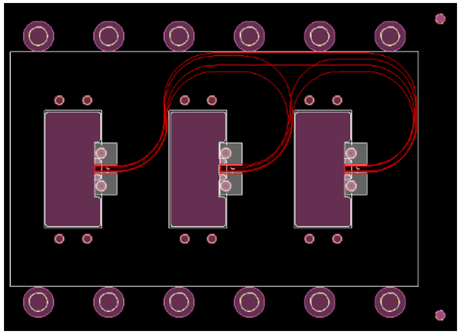
- ❑ PCB layout constraints for waveguides:
  - ❑ *Minimum bend radius*
  - ❑ *Separation*
  - ❑ *Crossing angle*

OPCB CAD Design

- ❑ Cadence software adapted to layout optical tracks
- ❑ Software used to design optical backplane



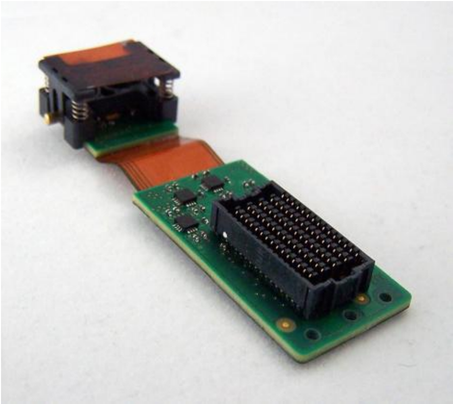


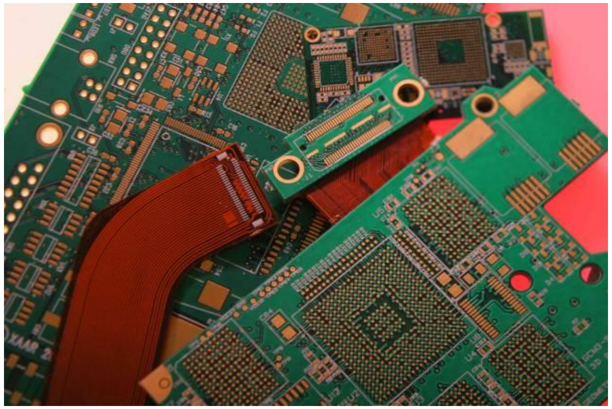


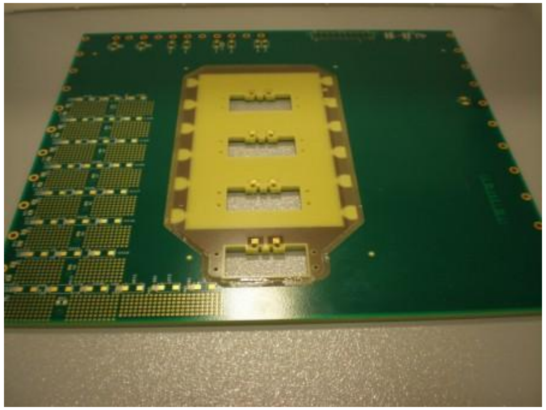
UCL

Electro-Optical PCB Manufacture

PCB Manufacturer to adapt fabrication techniques toward commercial production of electro-optical PCBs







STEVENAGE CIRCUITS

TAKING TECHNOLOGY FURTHER

End User Requirements

Deployment by end-users of OPCB technology into various applications

Data Storage / processing

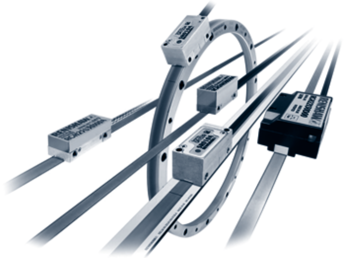
❑ High density, fast communication within storage backplanes

xyratex

Sensors

❑ Flexible optical sensors for biomedical applications

RENISHAW apply innovation™

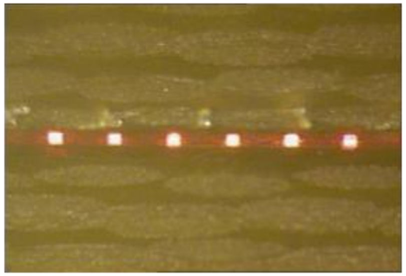


Military

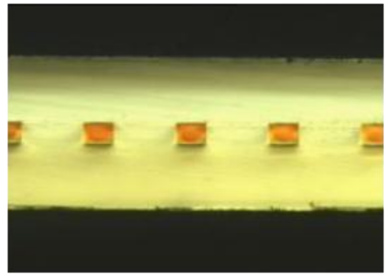
❑ Robust, low EMI, high speed communication within military vehicles

BAE SYSTEMS

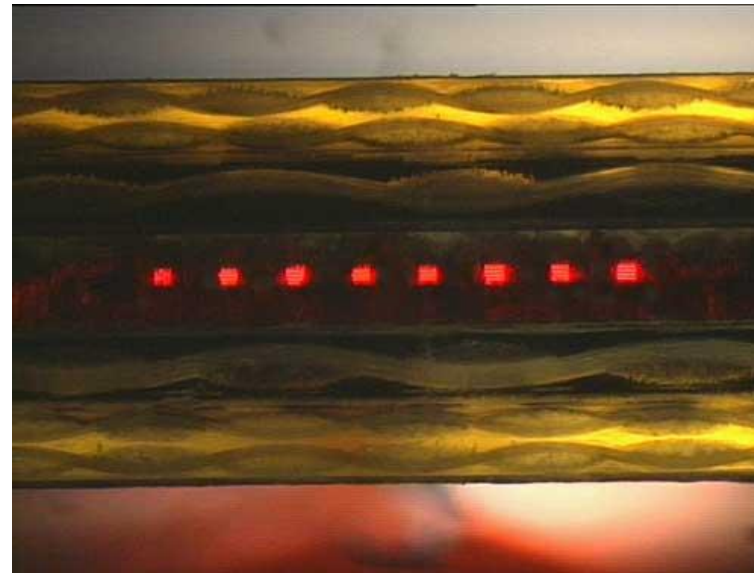
Polymer Waveguide Technology Exists



Source: Exxelis Ltd

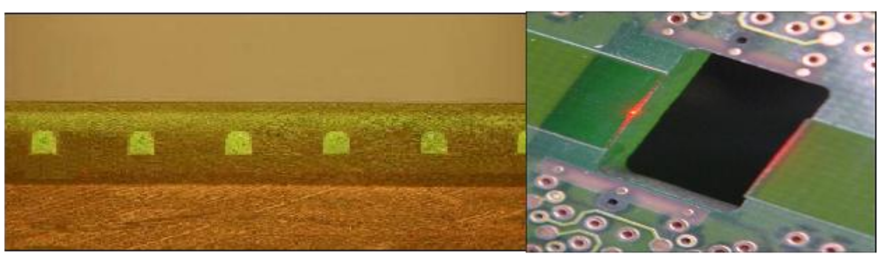


Source: Fraunhofer IZM

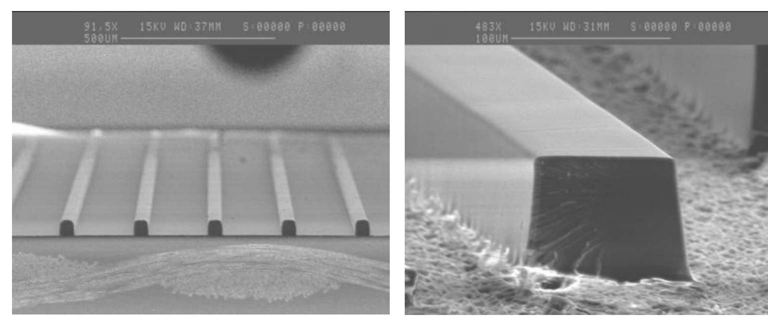


Source: Fraunhofer Institute

Source: Varioprint AG



Source: IBM Zürich

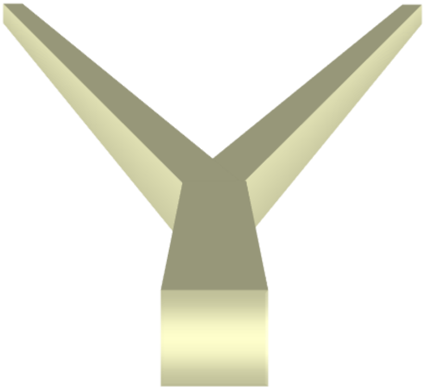


Source: Exxelis

Optical Layout Advantages

Splitters

- 1 – many power splitters possible
- Depends on loss budget



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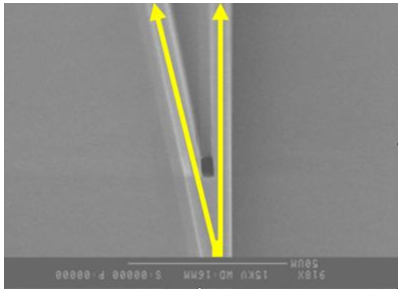
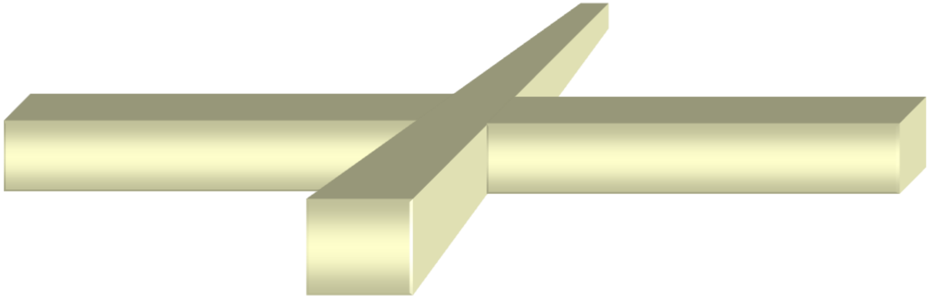
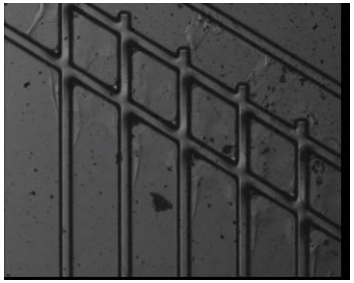


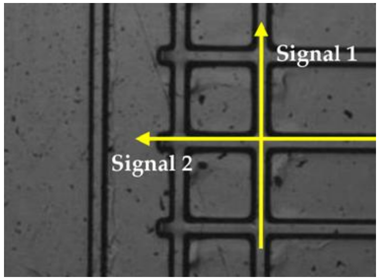
Source: Exxelis

Crossovers

- Signal crossovers on same layer without shorts





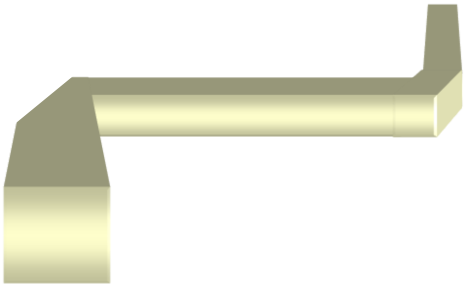


Source: Exxelis

Optical Layout Advantages

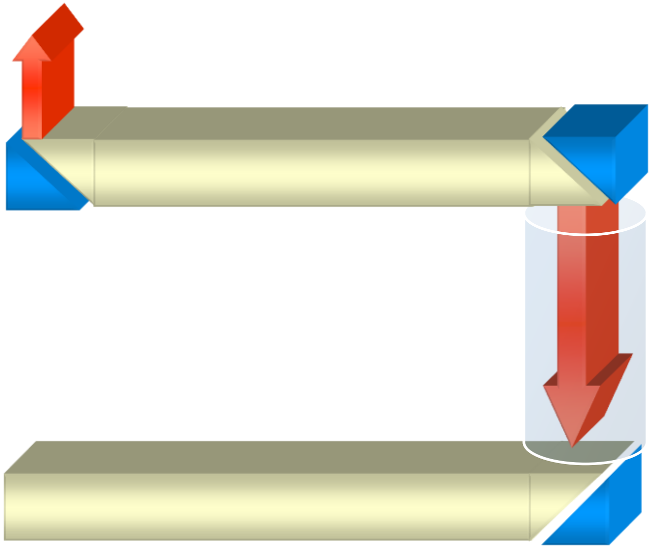
Right Angled Bends (In-plane)

- Overcomes bend radius restrictions
- Allows higher density routing



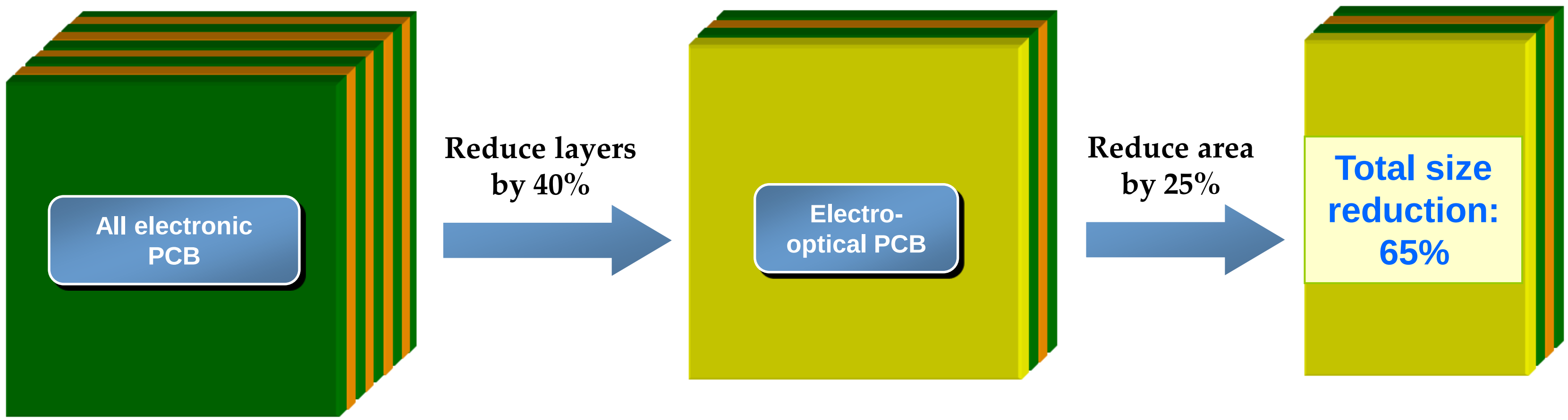
Right Angled Bends (Out-of-plane)

- Eases optical signal insertion
- Basis for optical vias

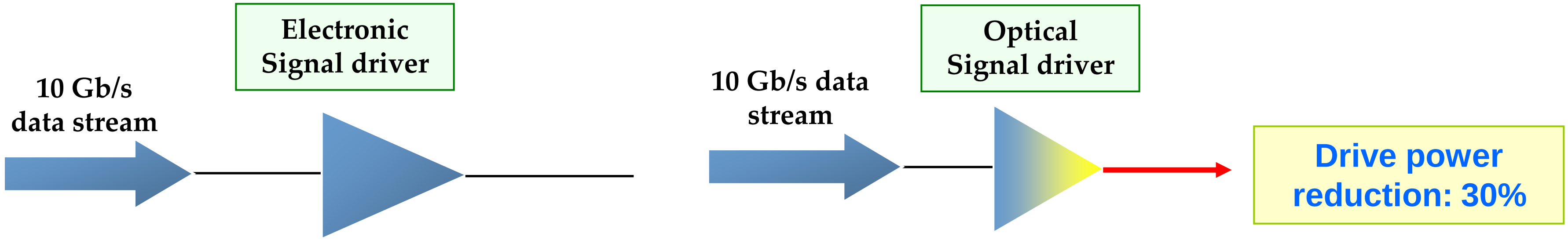


Environmental Benefits

Reduction in PCB Waste Material

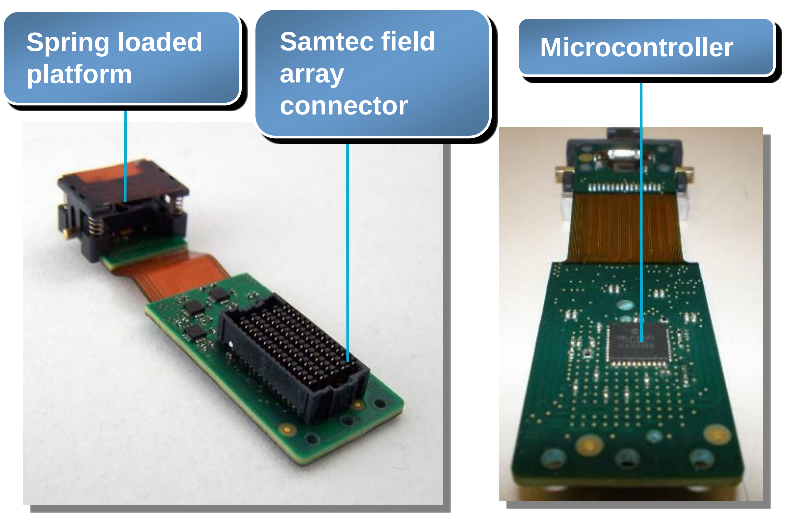


Reduced Power Consumption



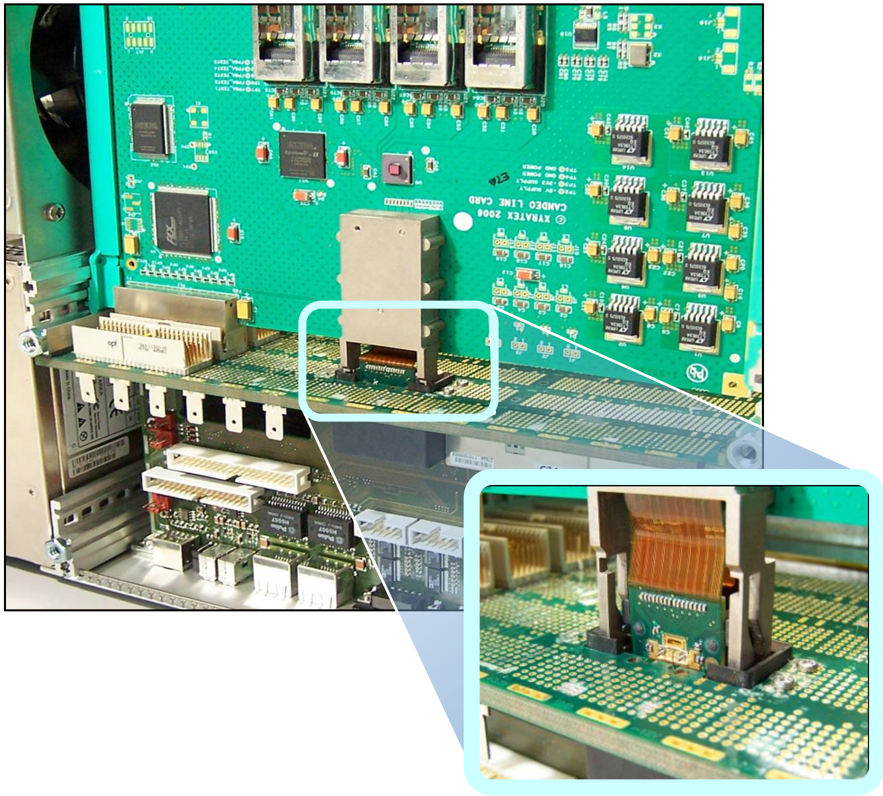
Parallel Optical Transceiver

- Small form factor
- 10 Gb/s per channel
- Microcontroller with I^{2}C interface



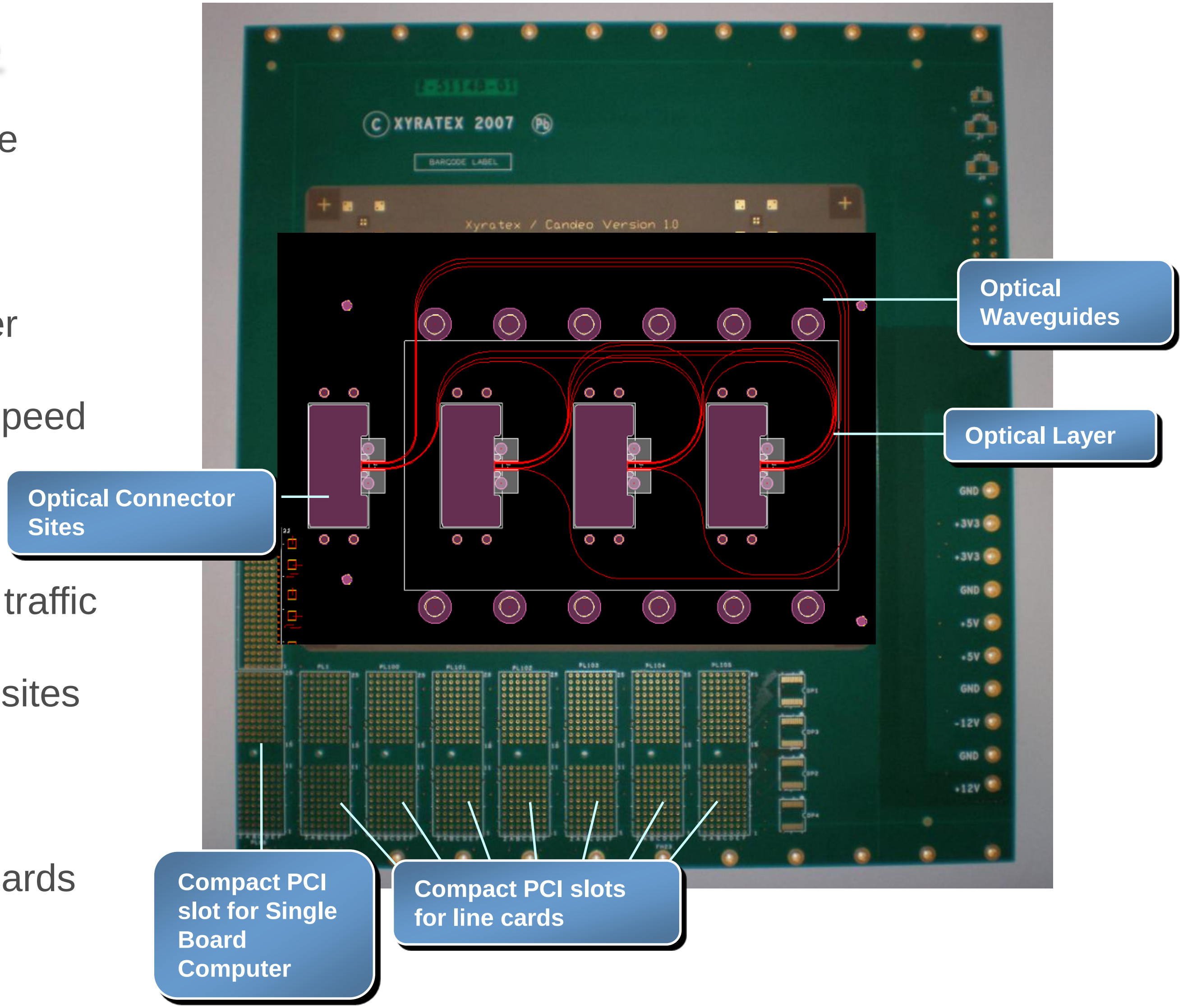
Backplane Connector Module

- Automated connector mechanism
- High precision alignment

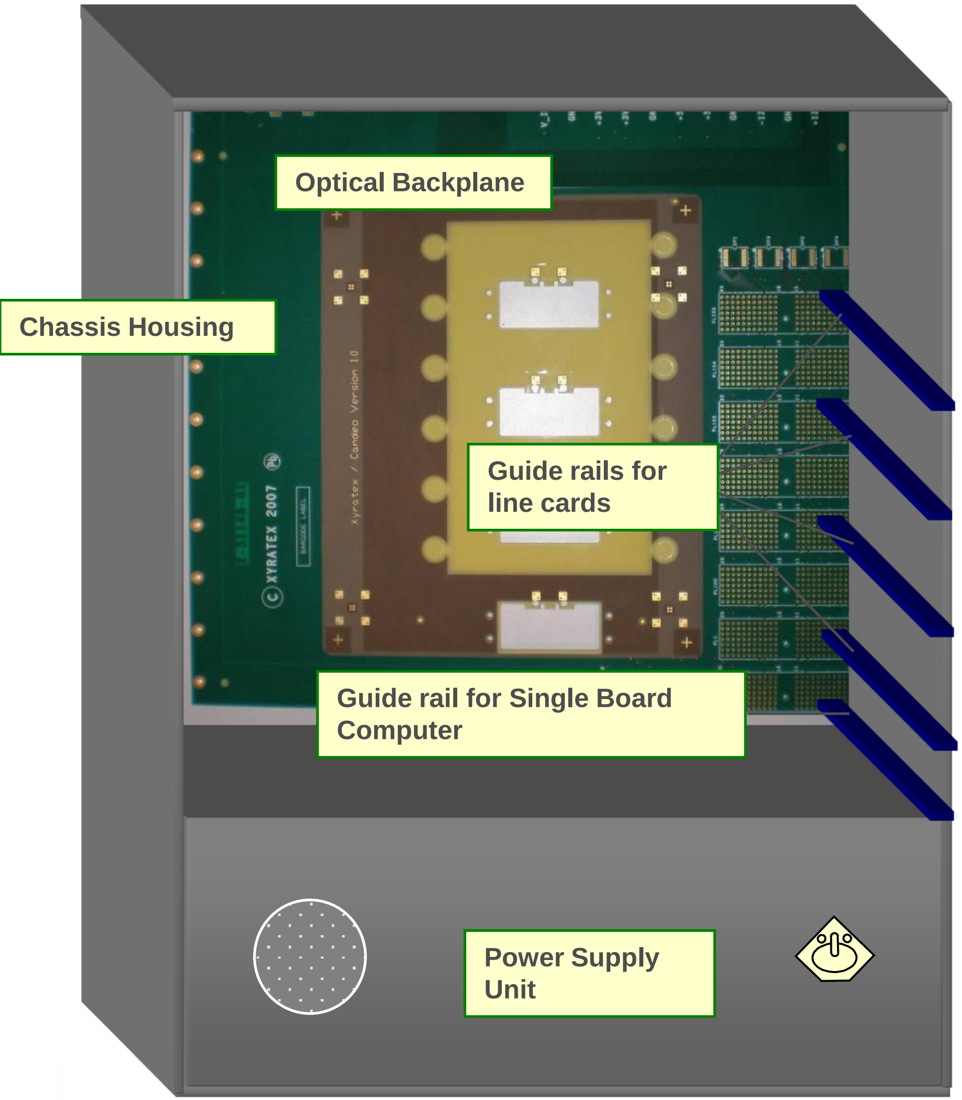


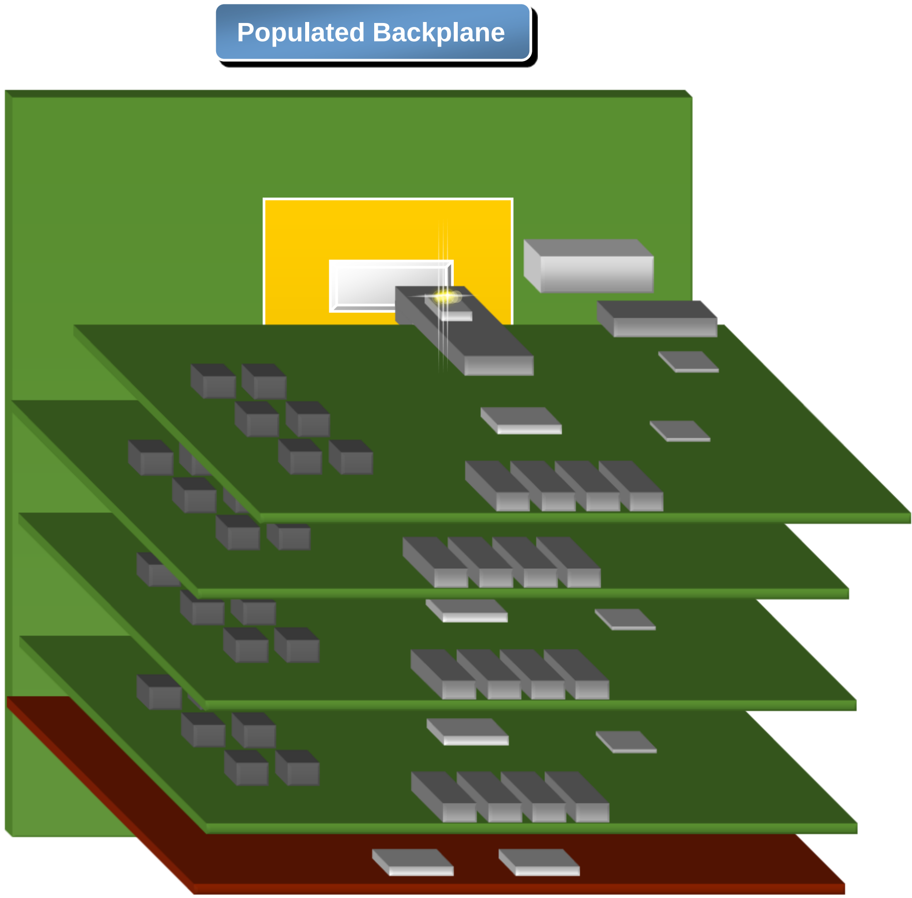
Electro-Optical Backplane

- ❑ Compact PCI architecture
- ❑ Electrical layers for power
- ❑ Electrical layers for low speed
- ❑ Optical layer for 10 Gb/s traffic
- ❑ 4 optical PCB connector sites
- ❑ Connector slots for line cards

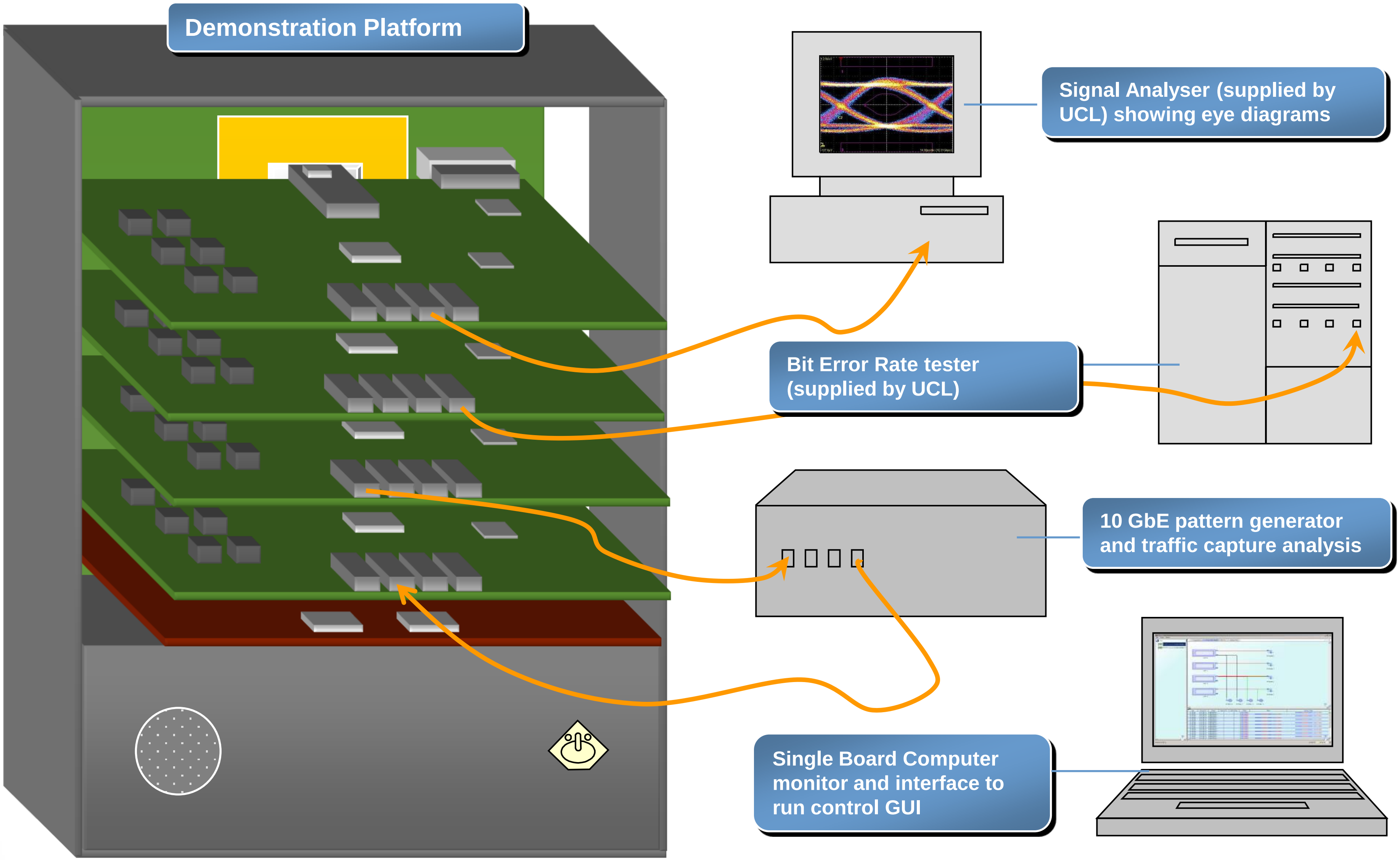


Demonstration Platform for ECOC 2008





Demonstration Platform for ECOC 2008

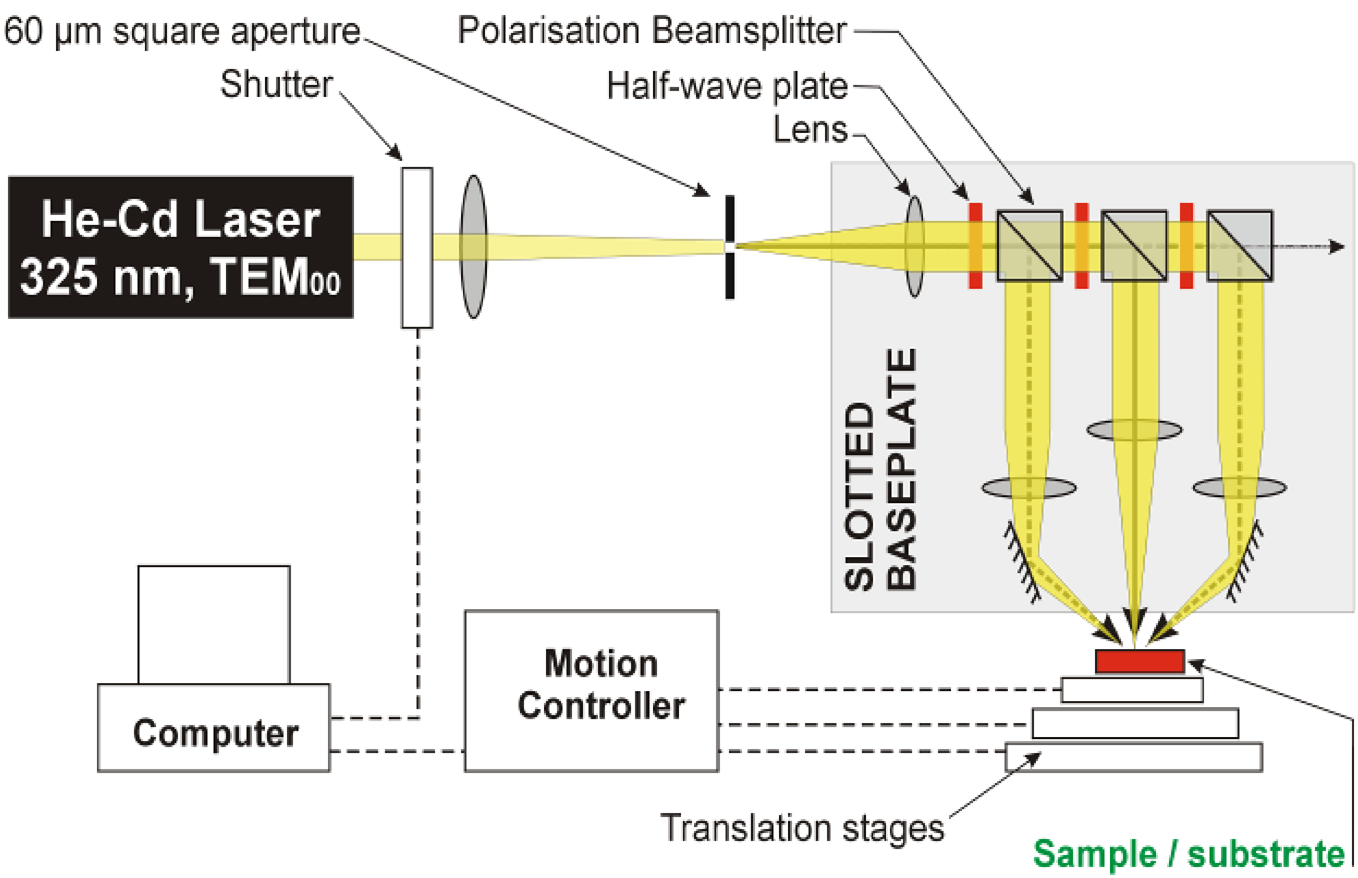


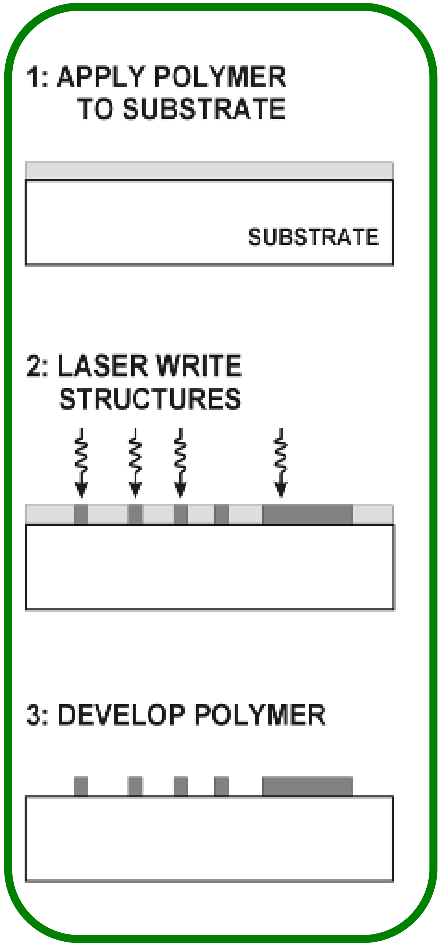
HWU Contribution to OPCB Project

Andy Walker, Aongus McCarthy, Himanshu Suyal

- **Direct Laser-writing of waveguides**
  - Increase writing speeds and manufacturability
- **Photo-polymer Formulation**
  - Optimise for faster writing; alternative polymer systems; possible dry formulation
- **Writing over a large areas** (400 – 500 mm long)
  - Stationary “writing head” with board moved on long translation stage
- **Connectors**
  - Possible use of 45-deg out-of-plane mirrors
- **Advanced Optoelectronic Integration**

Direct Laser-Writing Setup: Schematic

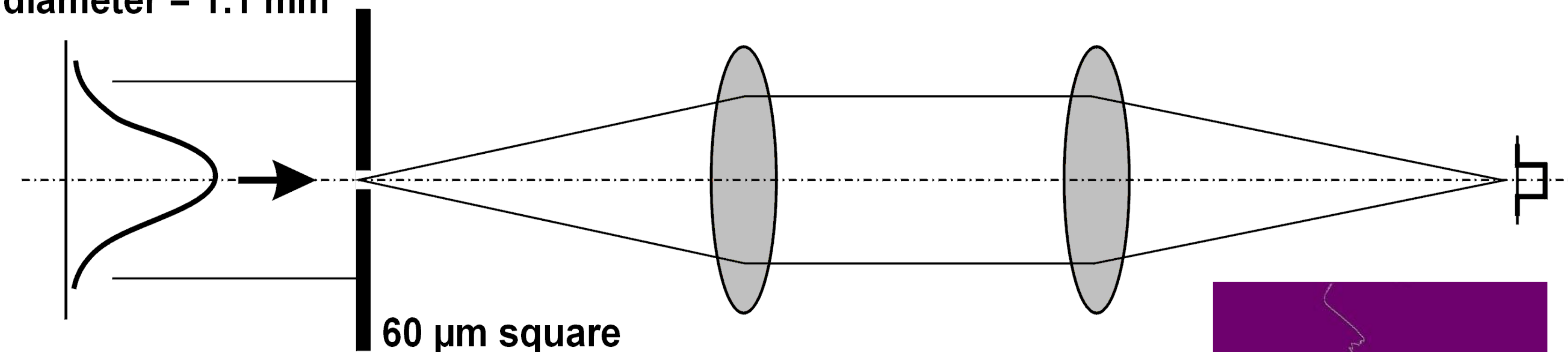


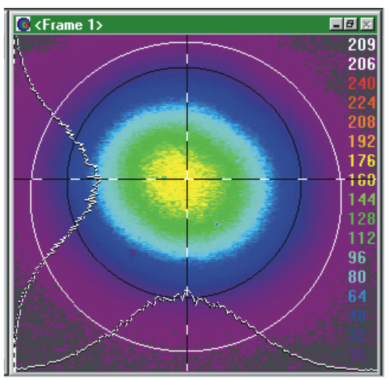


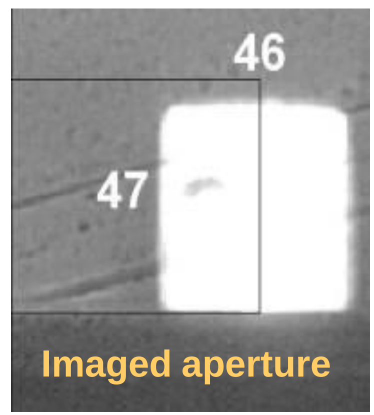
- **Slotted baseplate** mounted vertically over translation, rotation & vertical stages; components held in place with magnets
- By using two opposing 45º beams we minimise the amount of substrate rotation needed

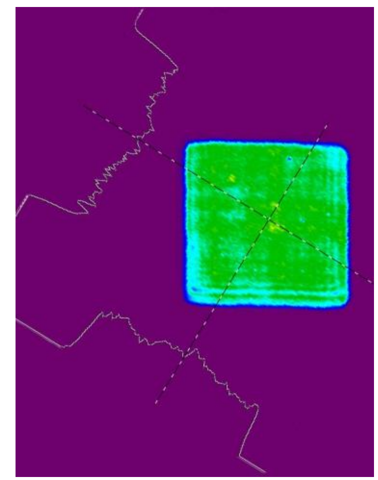
Writing Sharply Defined Features

– flat-top, rectangular laser spot







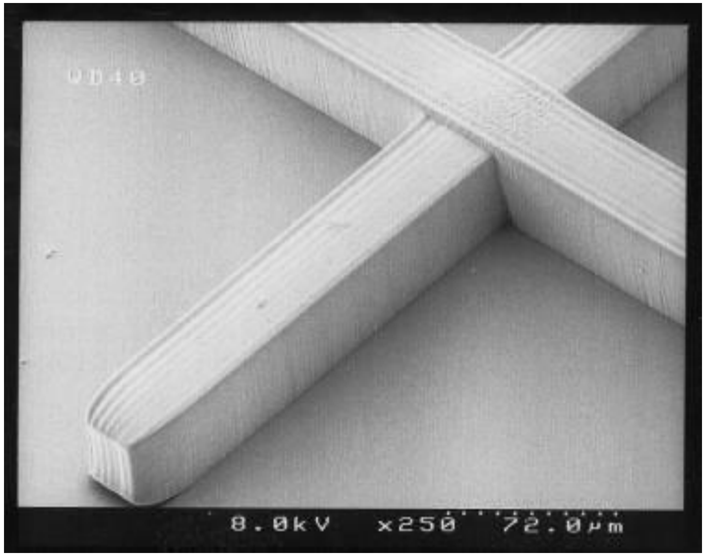


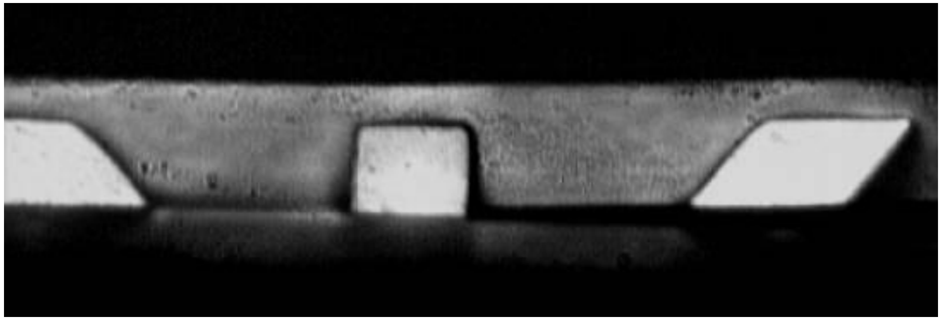
Images of the resulting waveguide core cross-sections

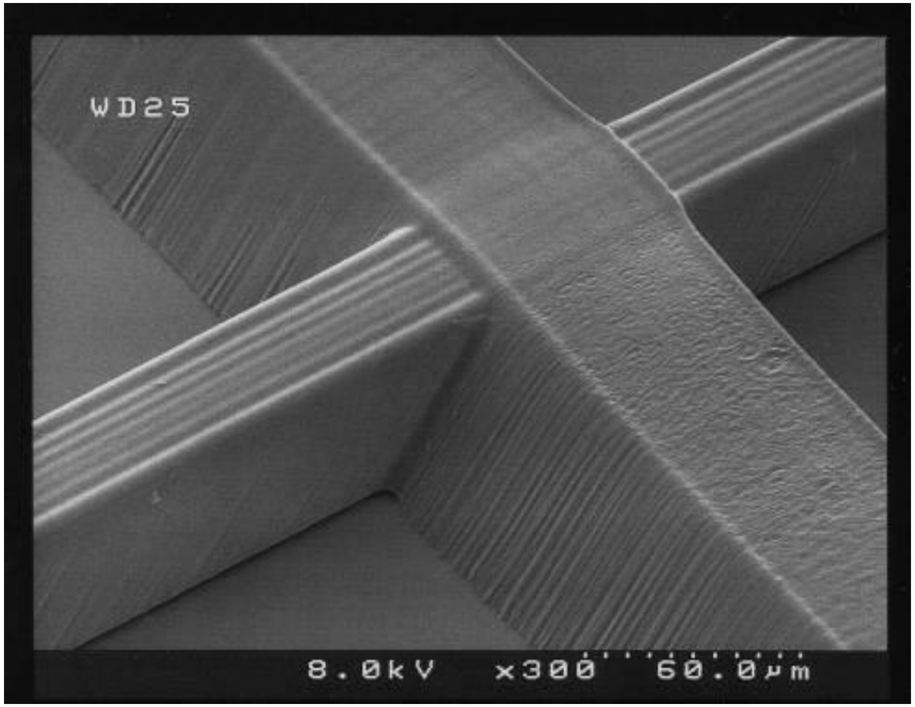
Laser Written Polymer Structures

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



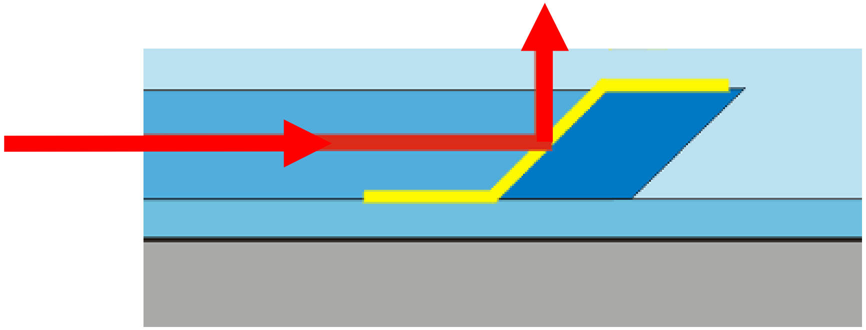




Optical microscope image showing end on view of the 45º surfaces

Waveguide Terminated with 45°Mirror

Out-of-plane coupling,
using 45-deg mirror (silver)



Microscope image looking
down on mirror
coupling light towards camera

OPTICAL INPUT

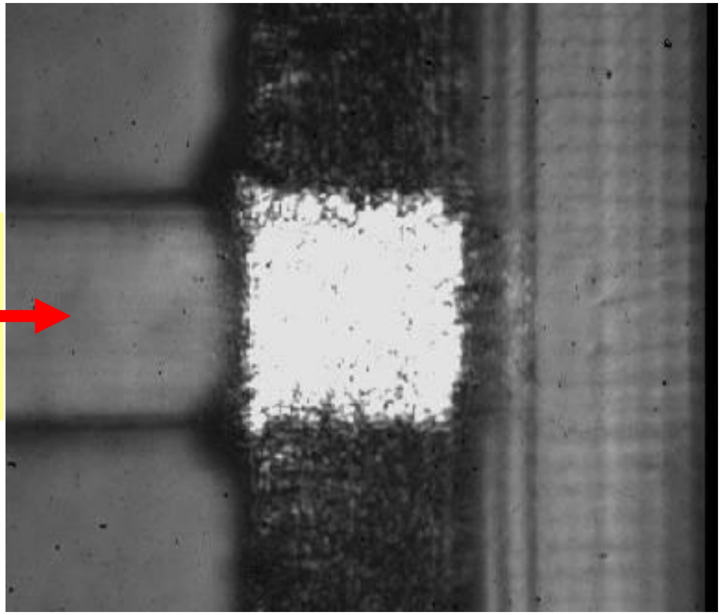


Photo-Polymer & Processing

- Polymer Types: Acrylate (HWU custom & Exxelis) & polysiloxane systems (Dow Corning)
- Tuning of refractive index and viscosity is possible
- Equivalent to negative photoresist processing
- Compatible with a wide range of substrates
- Mechanical and thermal properties compatible with PCB processing
- “Wet” format processing; Possibility of a dry film format formulation
- Low optical loss at 850 nm (>0.1 dB/cm typical)
- Polymer deposition techniques include: Spinning, doctor-blading, casting, spray coating

Laser Writing Parameters

- **Polymer system / formulation**
- **Writing speed**
  - New Aerotech stages capable of speeds of up to 2 m/s
- **Intensity profile**
  - Gaussian
  - Flat top (imaged aperture)
- **Optical power**
  - Gaussian beam: up to ~10 mW
  - Imaged aperture: up to ~1.5 mW
- **Oil immersion**
  - Permits writing of 45º surfaces
  - Excludes oxygen, which inhibits polymerisation process
- **Number of passes**
  - Exposure process is non-reciprocal
  - Can obtain better results with multiple fast passes than single slow pass

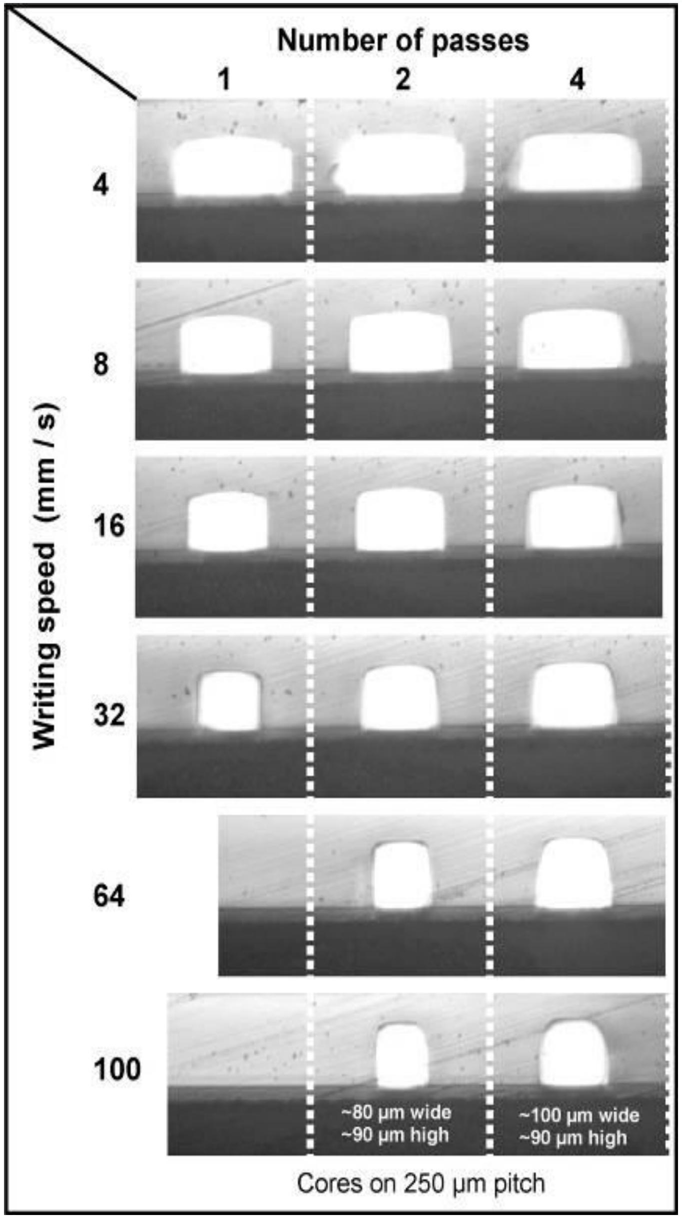
Laser-writing Parameters:

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

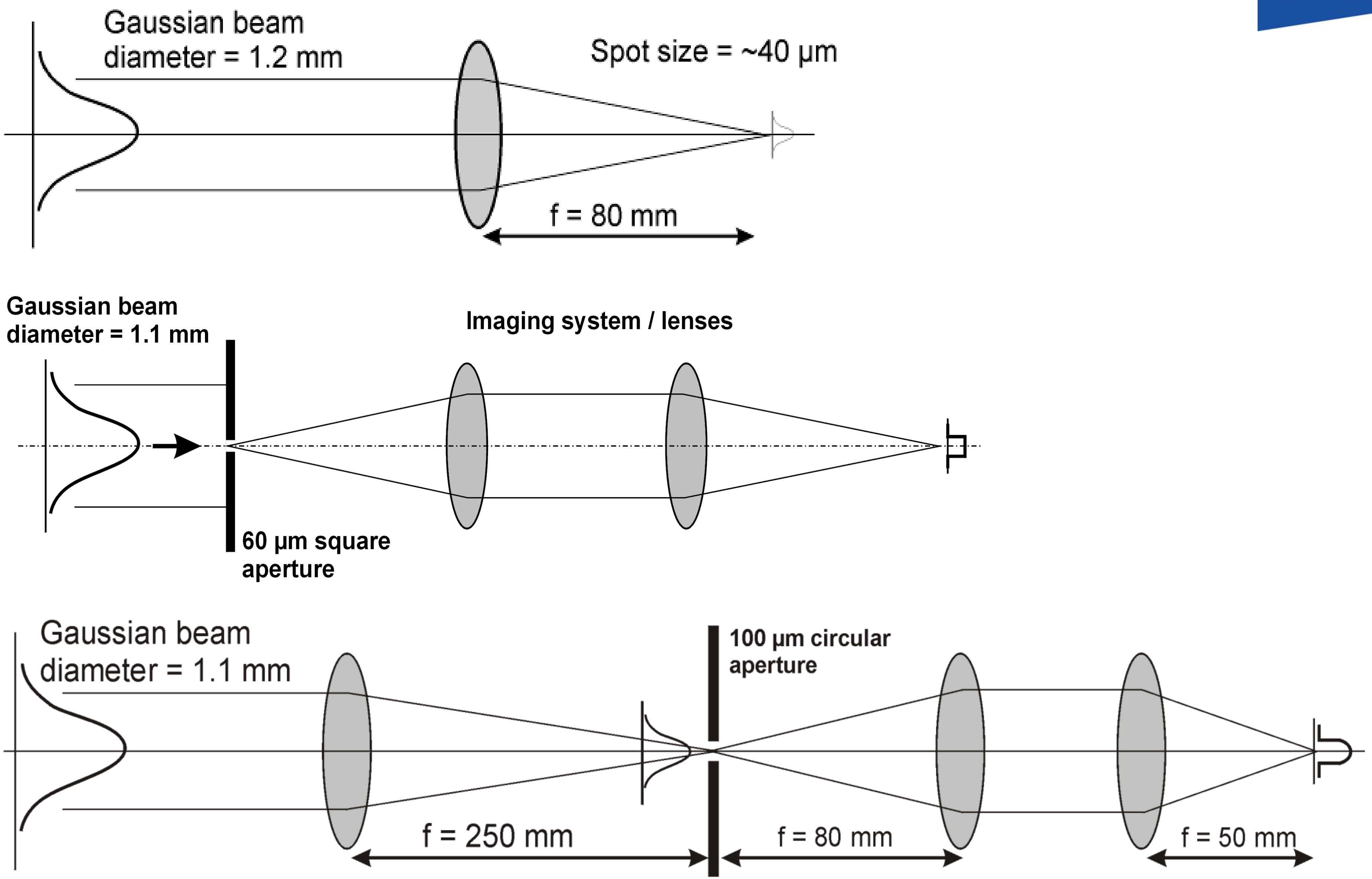
Polymer:

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

(Substrate: FR4 with polymer undercladding)

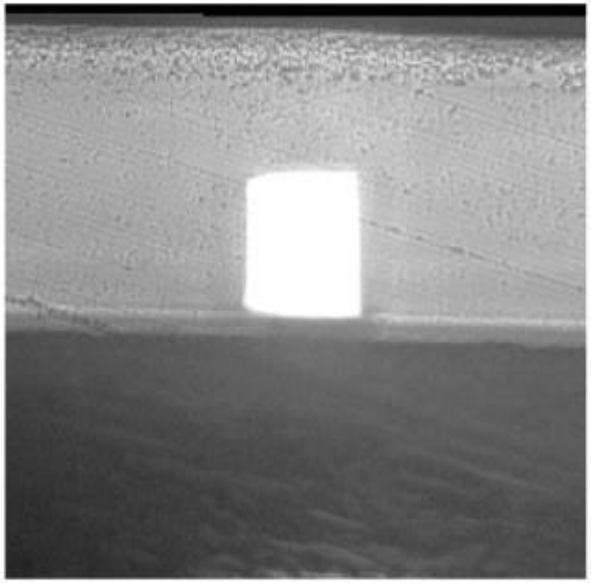


Intensity Profiles

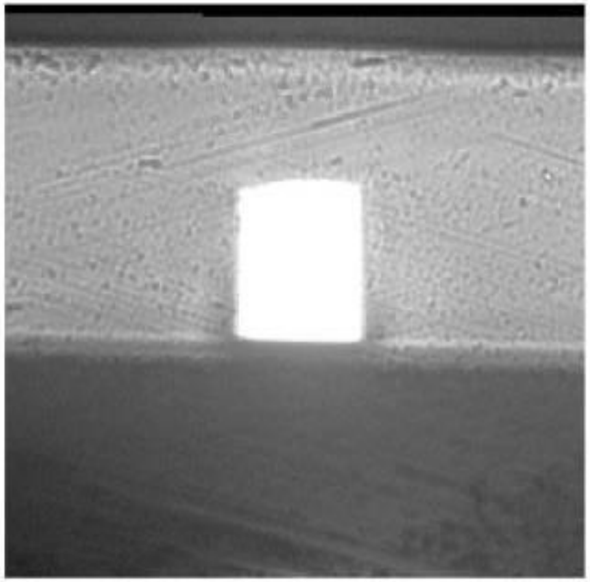


Direct Laser Written Waveguides using Imaged Circular Aperture

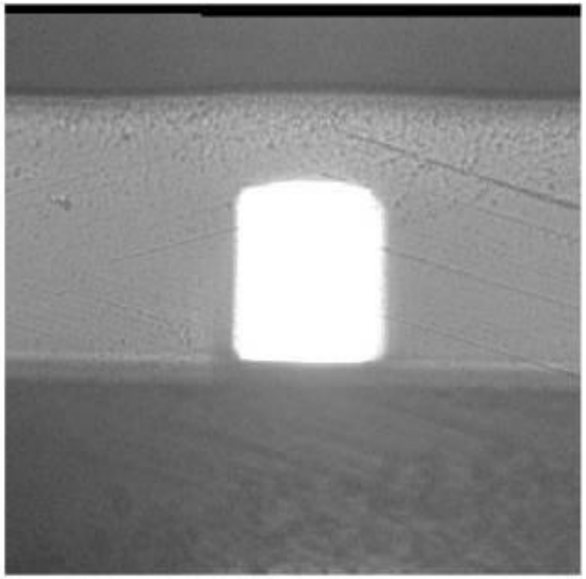
- 100 µm aperture was de-magnified
- Optical power at sample ~0.5 mW
- HWU custom photo-polymer



8 mm/s
63 x 74 µm



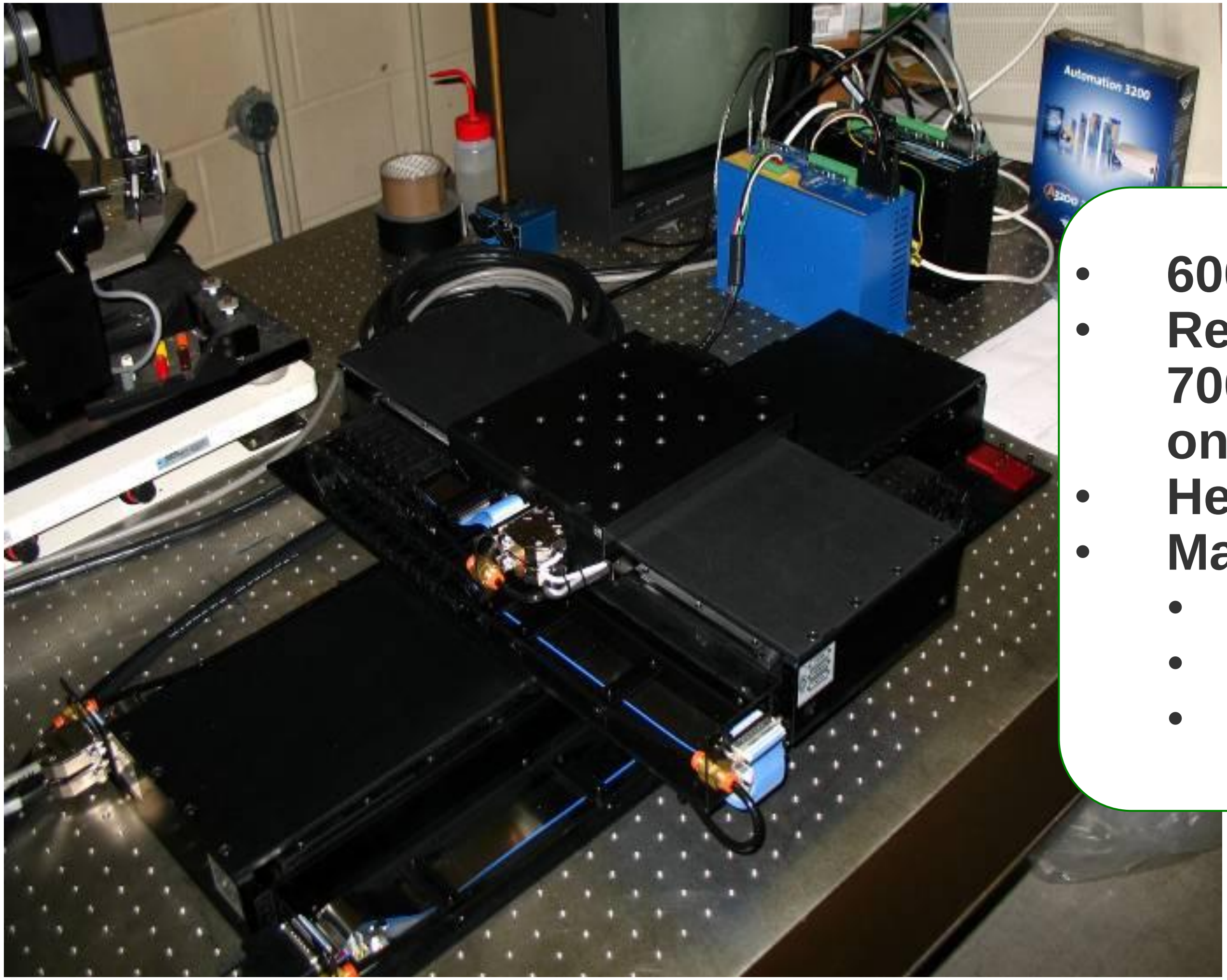
4 mm/s
69 x 78 µm



2 mm/s
76 x 84 µm

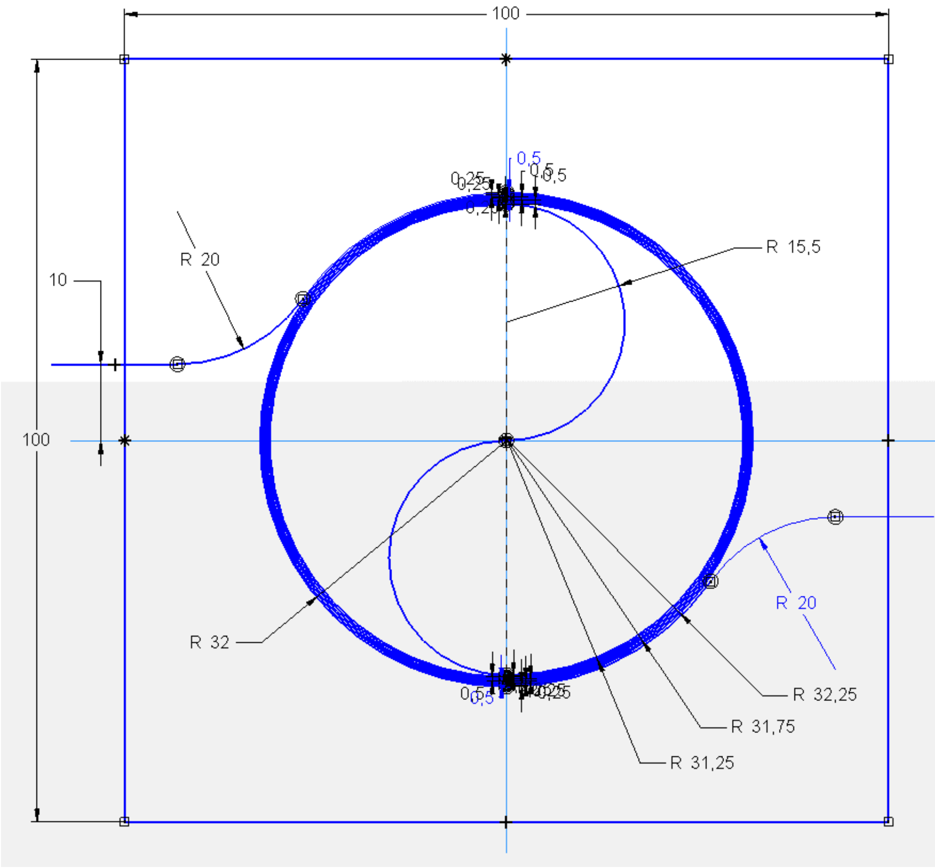
Large Board Processing: Writing

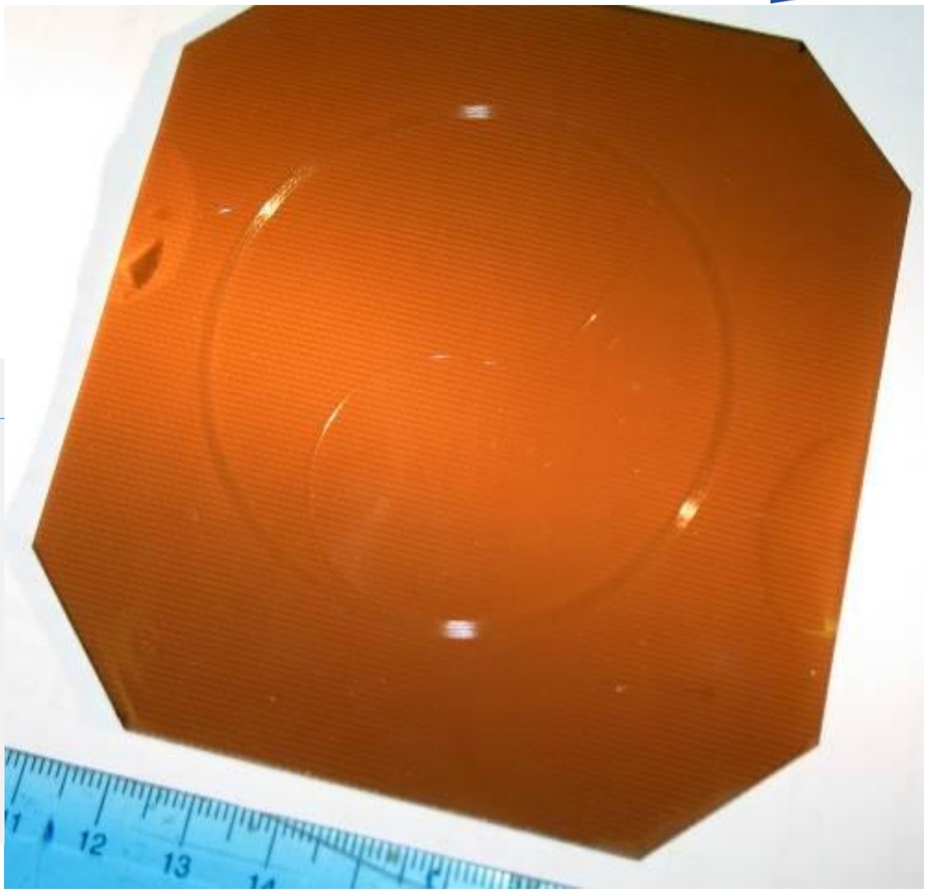
- Stationary "writing head" with board moved using Aerotech sub-µm precision stages
- Waveguide trajectories produced using CAD program



- **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.

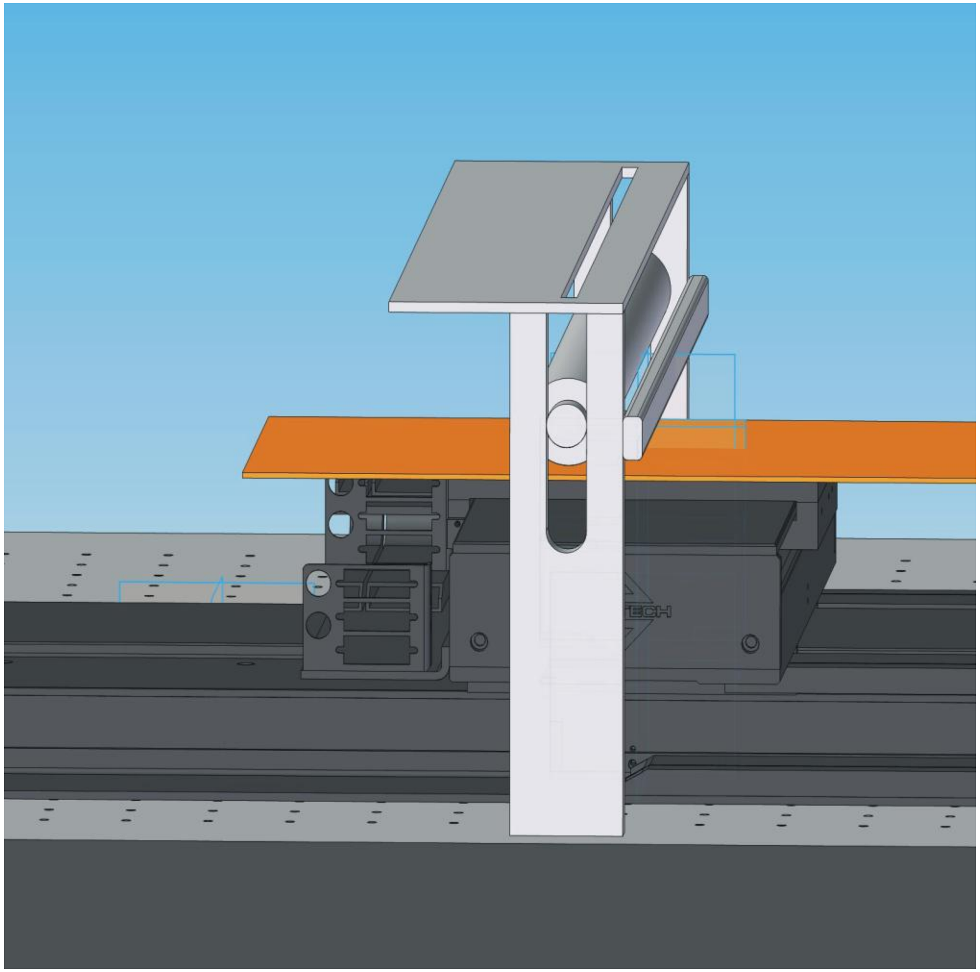
Large Board Processing: Polymer Dispensing / Developing

Key challenge: Dispensing / applying a uniform layer of liquid photo polymer over a large are FR4 boards.

We plan to experiment with a number of techniques including the use of a roller system (as shown in the CAD drawing on right)

- Shims along edge
- Mylar sheet

Board Developing: Appropriate container for developing large FR4 boards after UV exposure

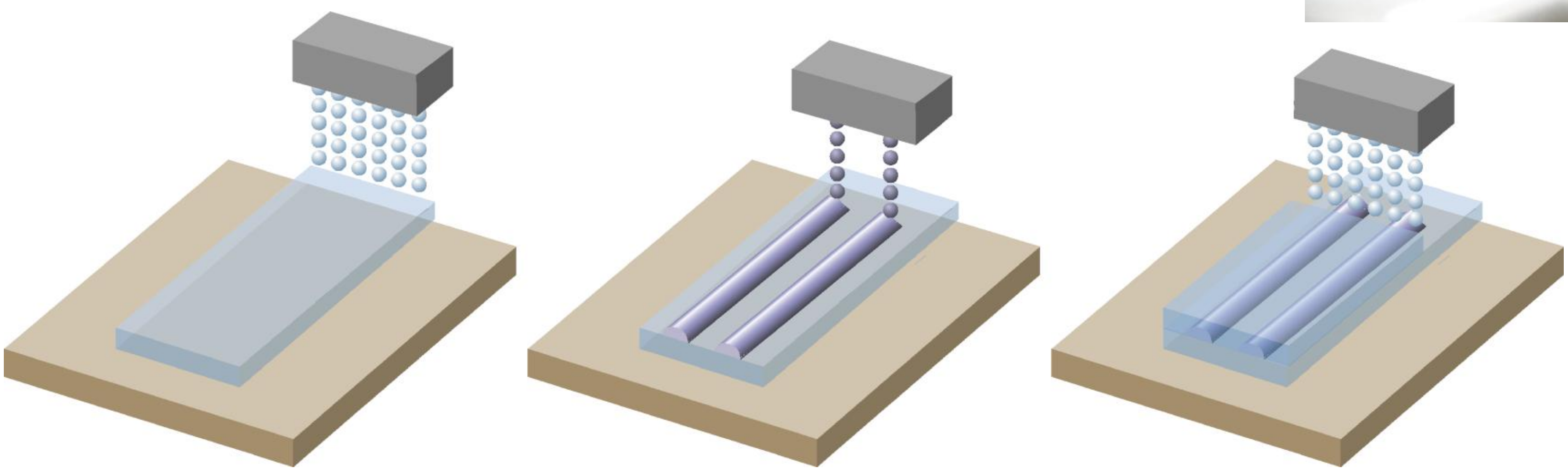


Inkjet Fabrication of Optical Waveguides
IeMRC, 4th July 2008

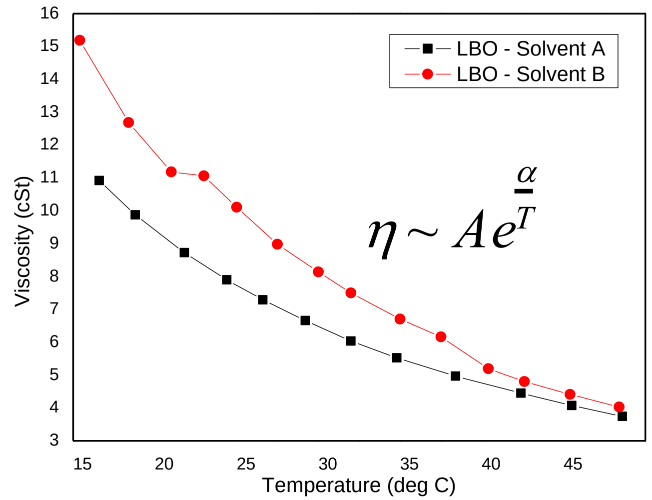
John Chappell, David Hutt

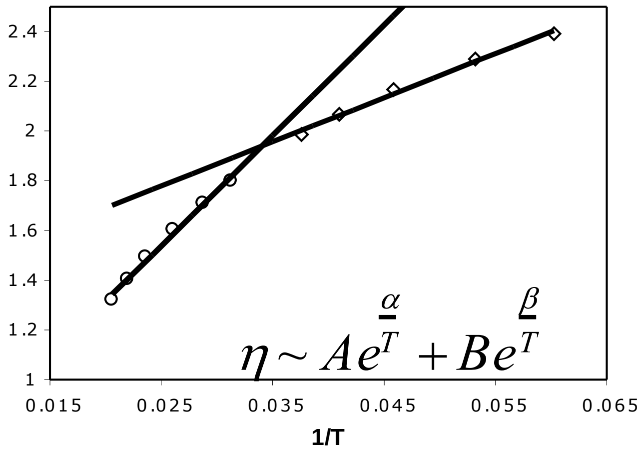
Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University

- Advantages
  - selective deposition of core and clad - less wastage: picolitre volumes
  - large area printing
  - low cost
- Target core dimensions of 50-100 microns height/width

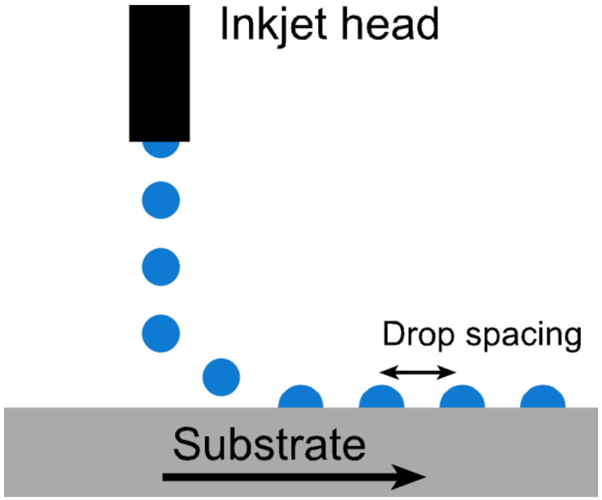


- Material properties tailored to inkjet head
- Optimising 'waveform' for each fluid - fluid dynamics
- Interaction of material with substrate: wetting, adhesion
- Control and stability of liquid structures
- Truemode (Exxelis) suitable material core/clad
- Solvent needed to tailor viscosity

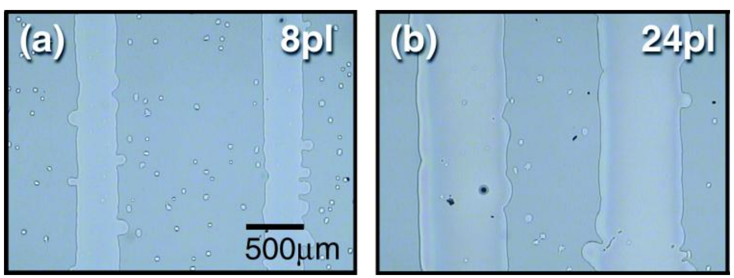




INKJETTING CORE ON CLADDING

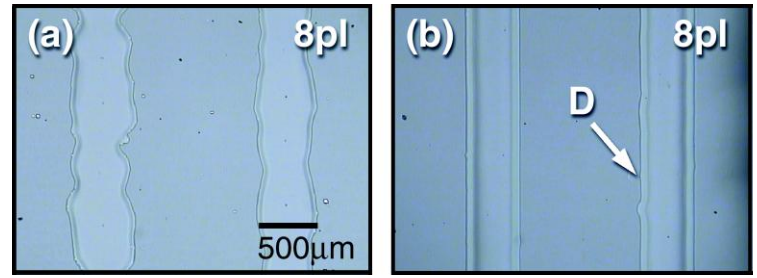


Room temperature substrate

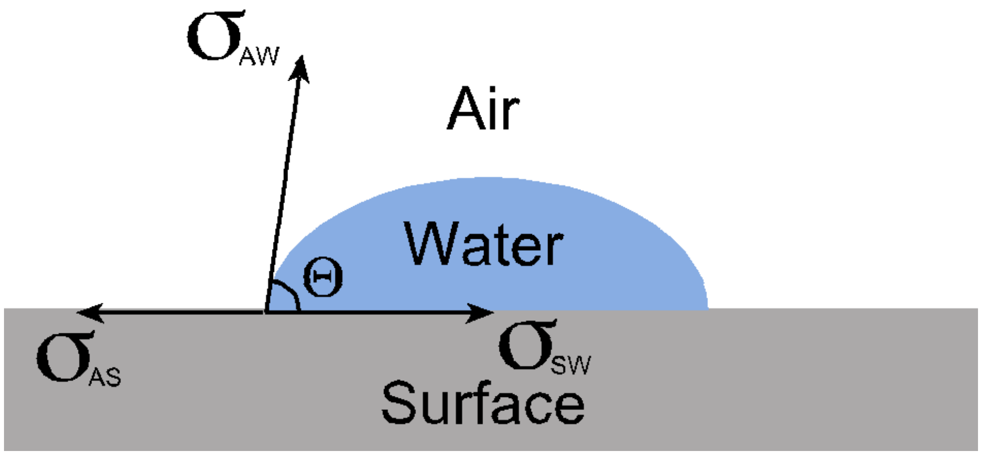


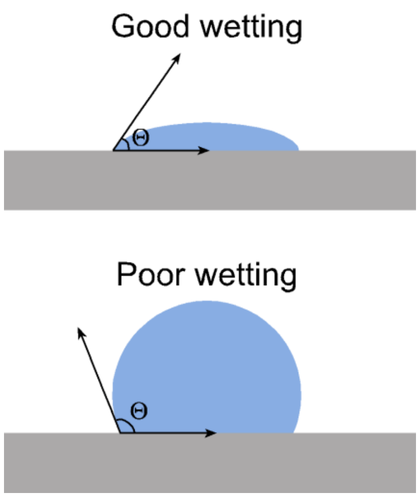
- Extensive spreading
  - drop spacing of 70 microns

Substrate temperature ~-20ºC



- Controlled spreading
  - drop spacing of 17.5 microns (4x jetting frequency)
- (a) low BP solvent
  (b) high BP solvent
  - rate of solvent evaporation affecting line shape

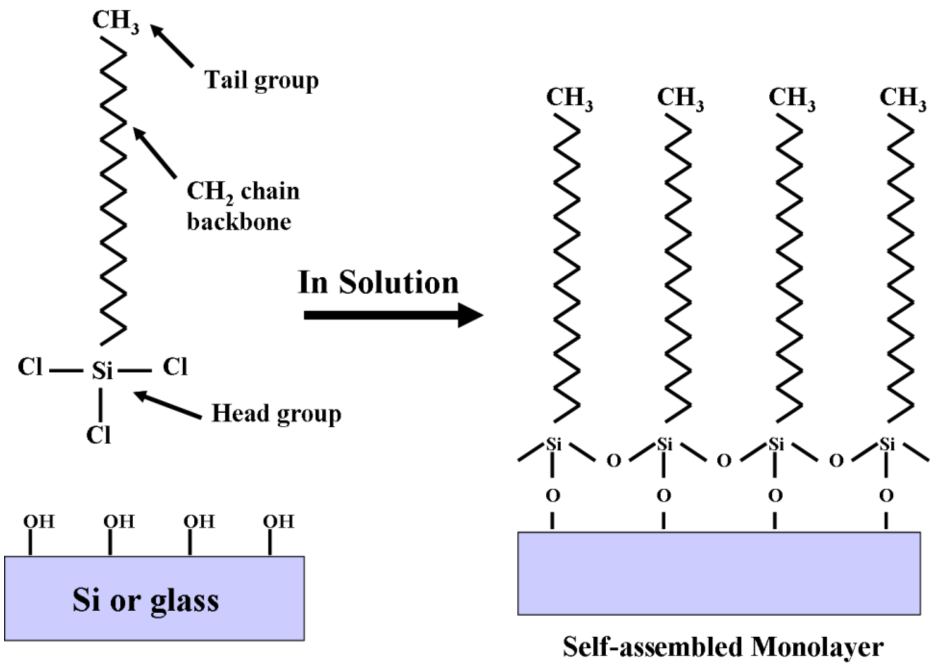




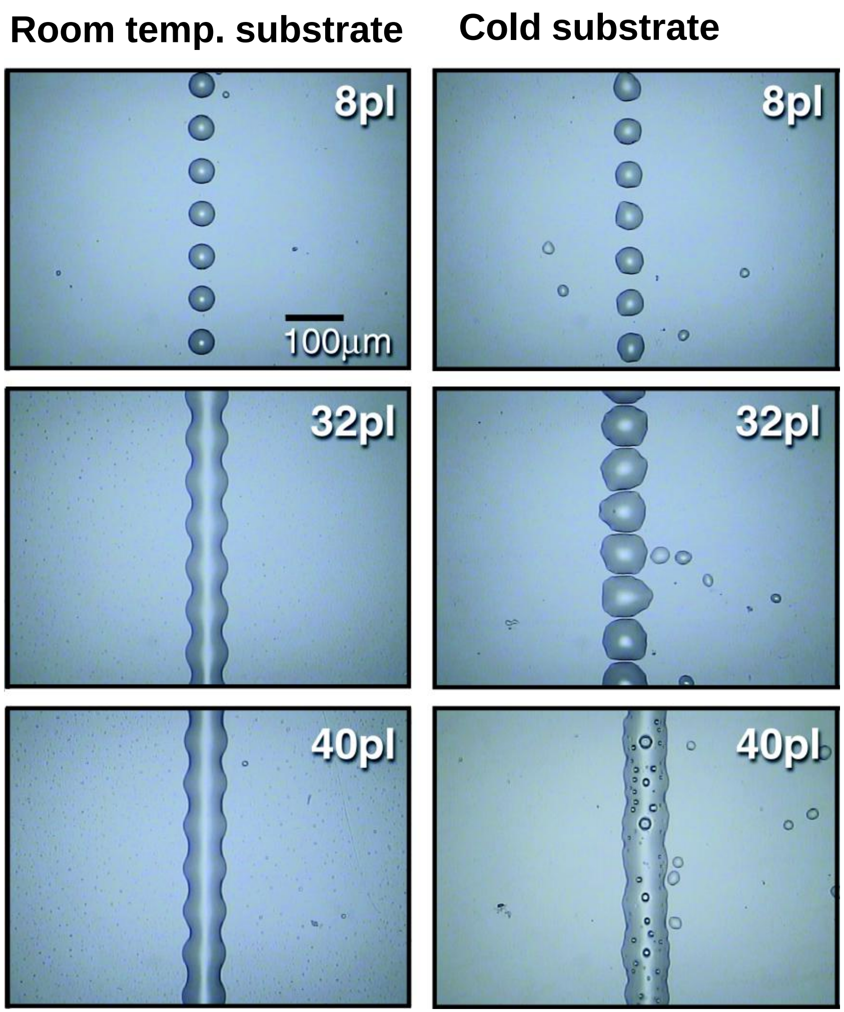
- Young's Equation $$\sigma_{AS} = \sigma_{SW} + \sigma_{AW}\cos\Theta$$
- Balance of surface tensions acting at the contact lines
- Differences in material properties will affect the contact angle of the drop with the surface
- Surface tension (and viscosity) are temperature related - lowering the temperature increases surface tension (and viscosity)

Modifying the Substrate Properties

- Increase contact angle of liquid on substrate to reduce the wetting of liquid core
- Change the surface energy
- Choose a model hydrophobic surface - octadecyltrichlorosilane (OTS) on glass
- Cladding substrate shows water contact angles of ~73^o
- Gives water droplet contact angles >100^o
- Creates adhesion problems

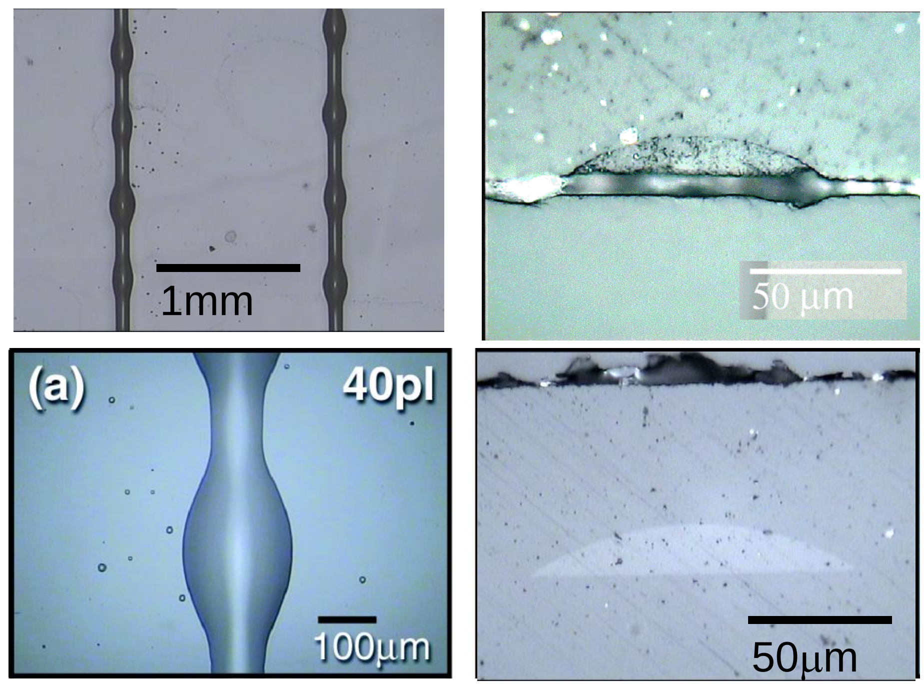


- Drop spacing of 70 microns
- Room temperature (left) and cold substrate (right)
- Discrete droplets – no splashing: material tailored well to inkjet system
- Temperature not the dominant factor in controlling feature shapes
- Possible demixing of solvent and core material at lower temperature



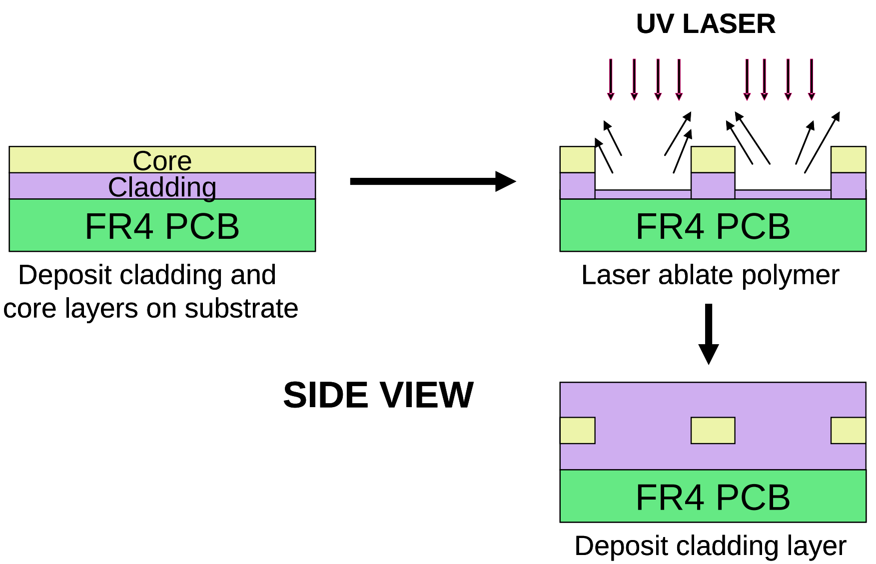
Stable Features on a Model OTS Surface

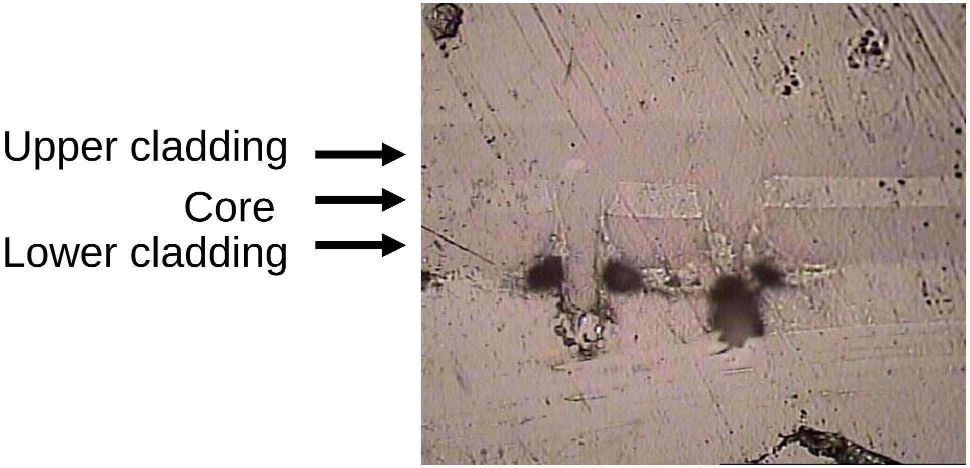
- Increasing the material deposited causes periodic features in the line shape - due to a combination of contact angles, viscosity and surface tension
- Surface roughness of ‘tracks’ is ~1nm
  - investigating optical properties of these structures
- Poor adhesion between treated glass and inkjetted material
- Aspect ratio of 5:1
  - aiming towards 1:1



Laser Ablation for Waveguide Fabrication

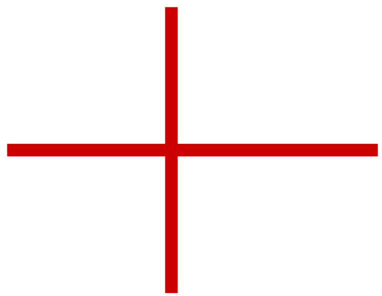
- Ablation to leave waveguides
- Excimer laser – Loughborough
- Nd:YAG – Stevenage Circuits
- Ablation process characterised
- Investigating machining of curved mirrors

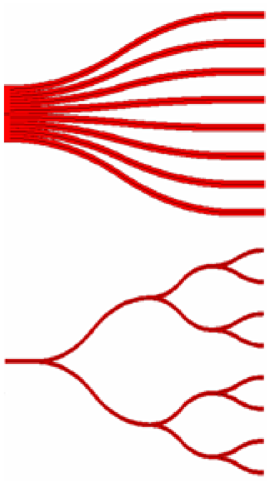


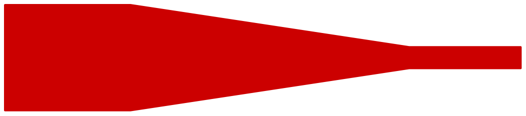


Waveguide Components And Measurements

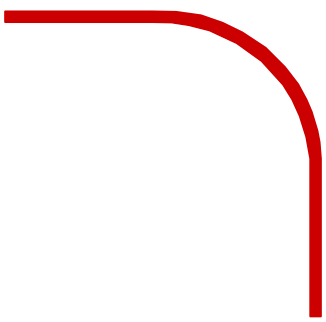
- Straight waveguides 480 mm x 70 µm x 70 µm
- Bends with a range of radii
- Crossings
- Splitters
- Spiral waveguides
- Tapered waveguides
- Bent tapered waveguides

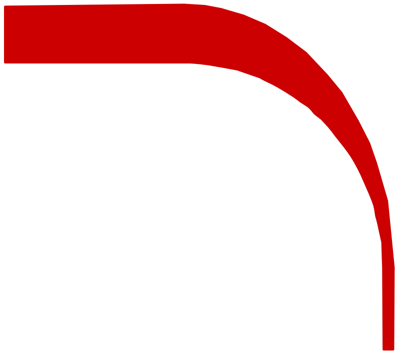




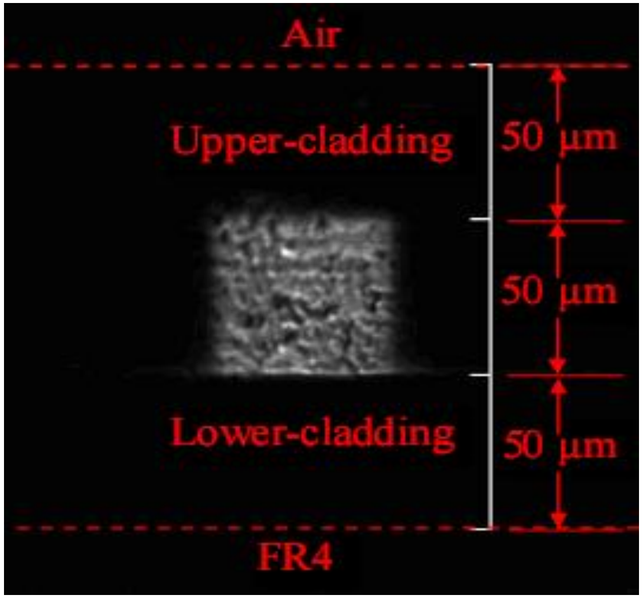


- Surface Roughness
- Loss
- Crosstalk
- Misalignment tolerance
- Bit Error Rate, Eye Diagram

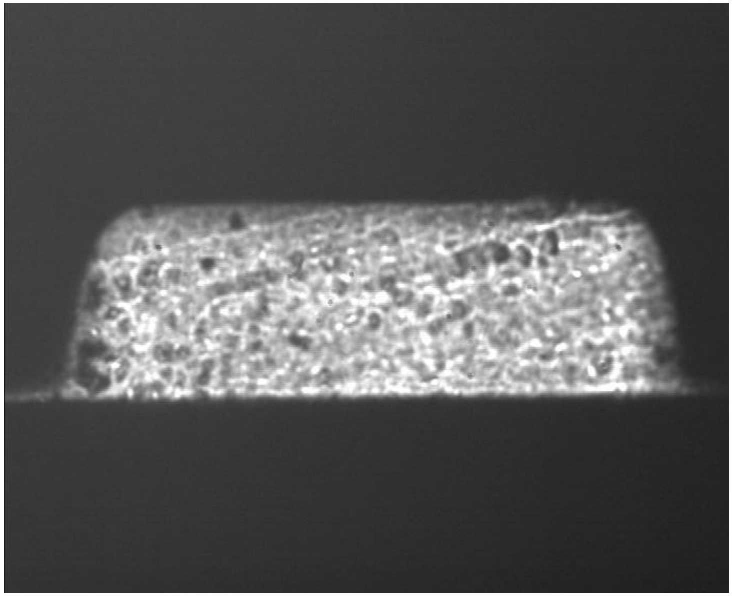




Waveguide Output face Photographs



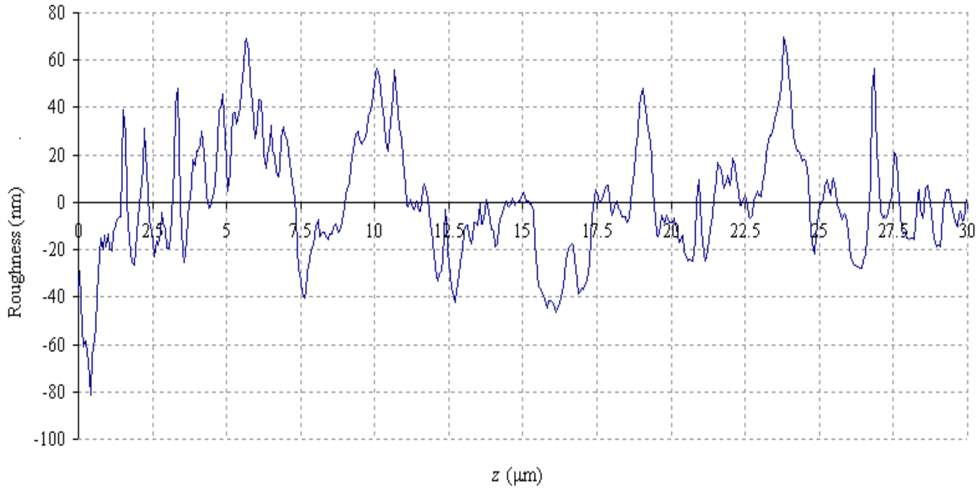
50 µm × 50 µm waveguide



50 µm × 140 µm waveguide

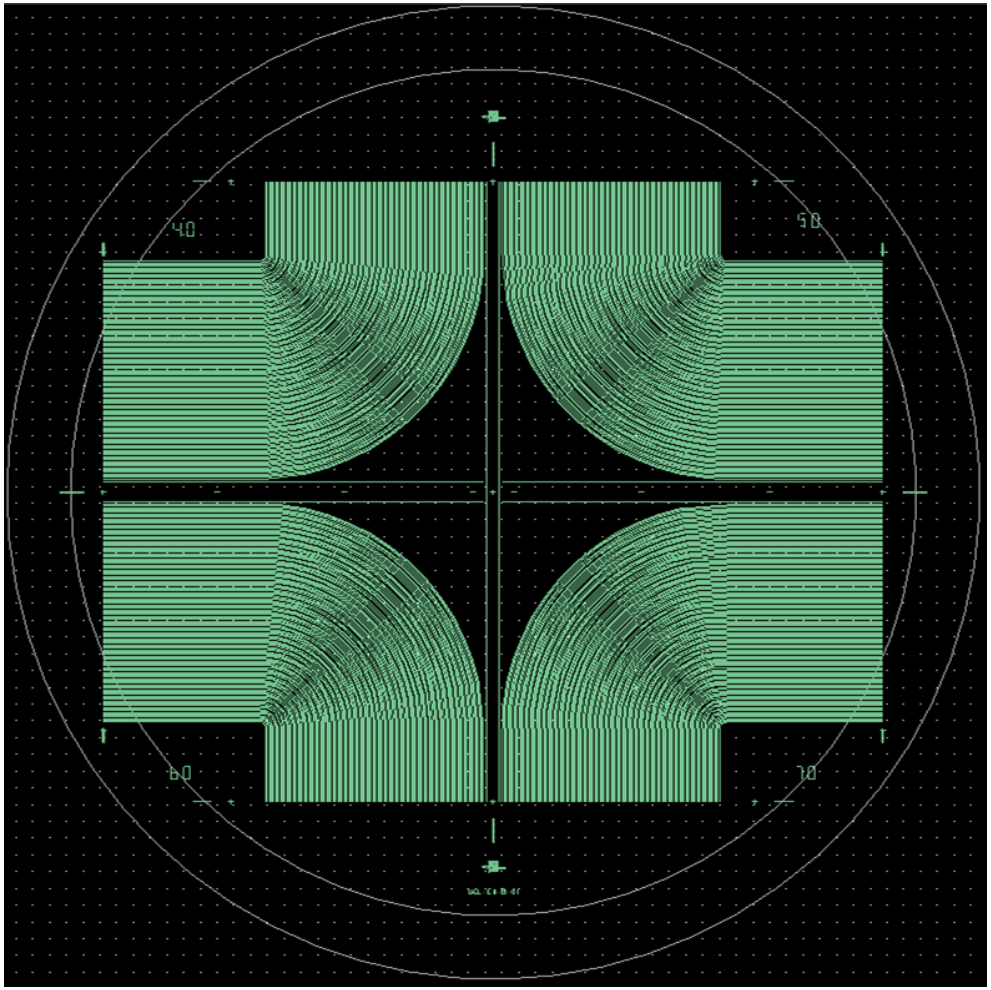
- Photolithographicly fabricated by Exxelis
- Cut with a dicing saw, unpolished
- VCSEL illuminated

Surface Roughness

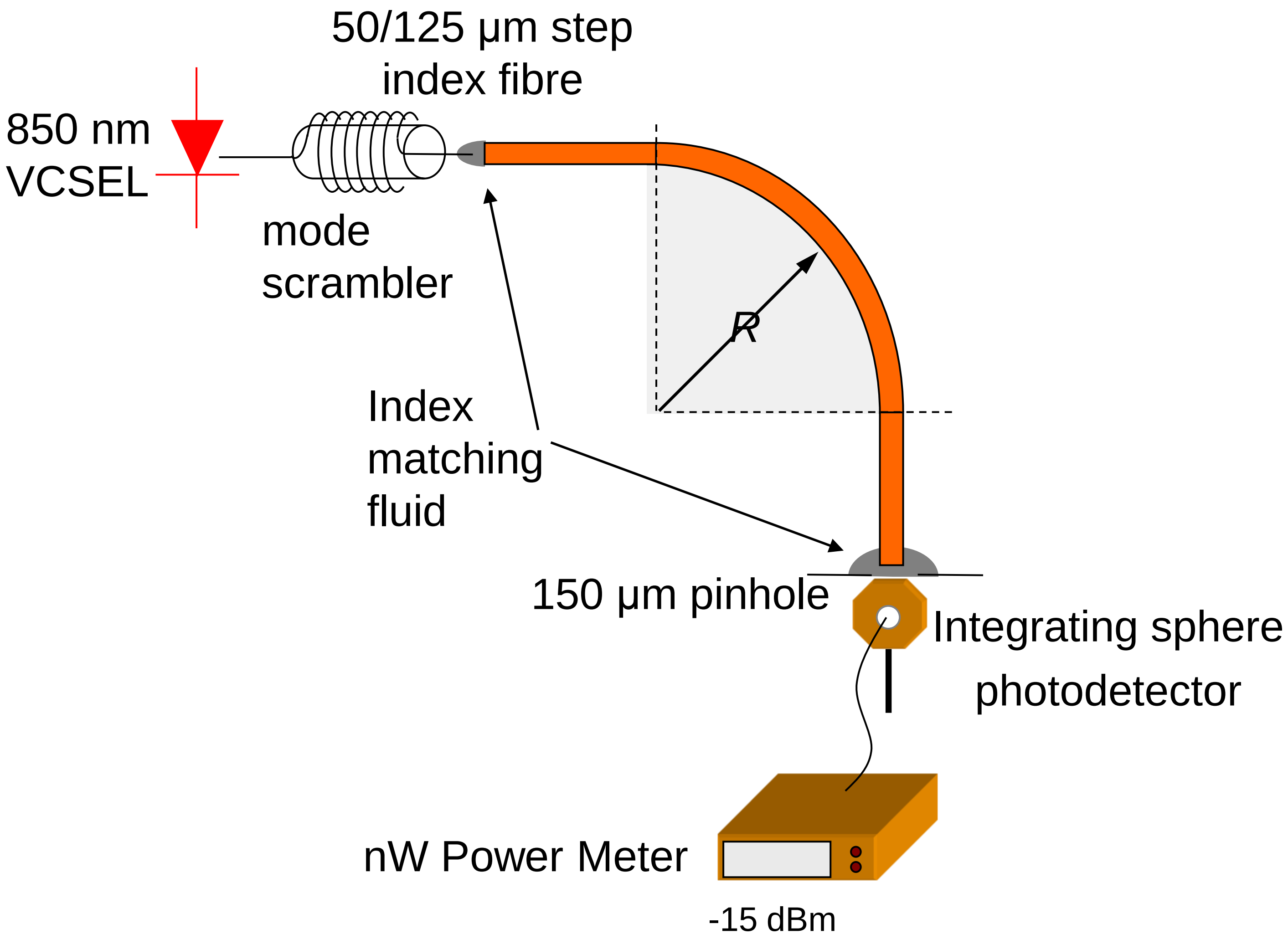


- RMS side wall roughness: 9 nm to 74 nm
- RMS polished end surface roughness: 26 nm to 192 nm.

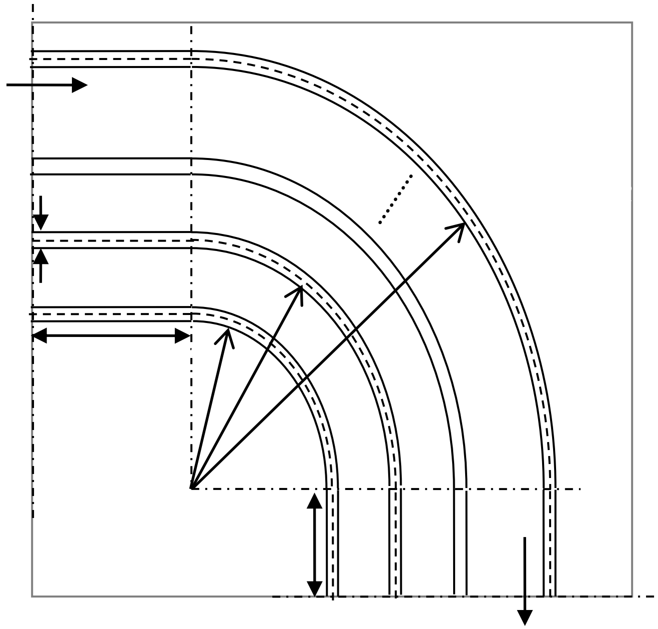
Waveguide 90 Bend Test Pattern



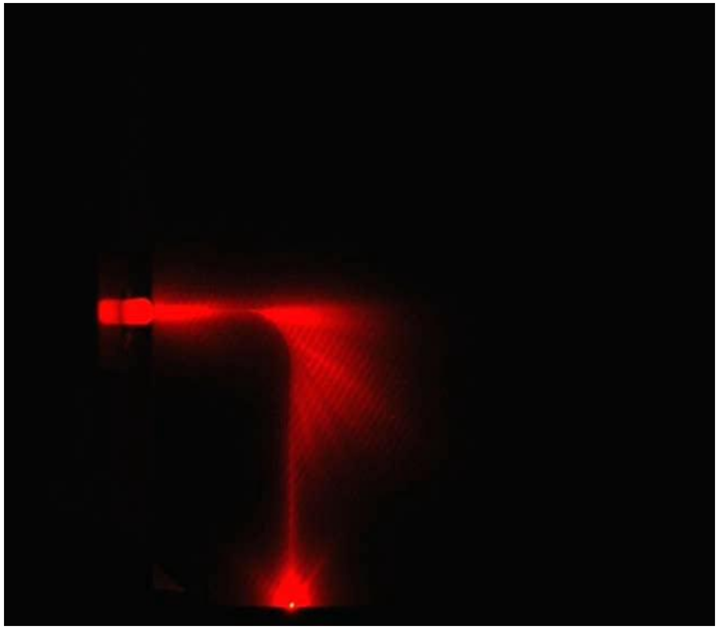
Optical loss Measurement



Optical Power Loss In 90 Waveguide Bends



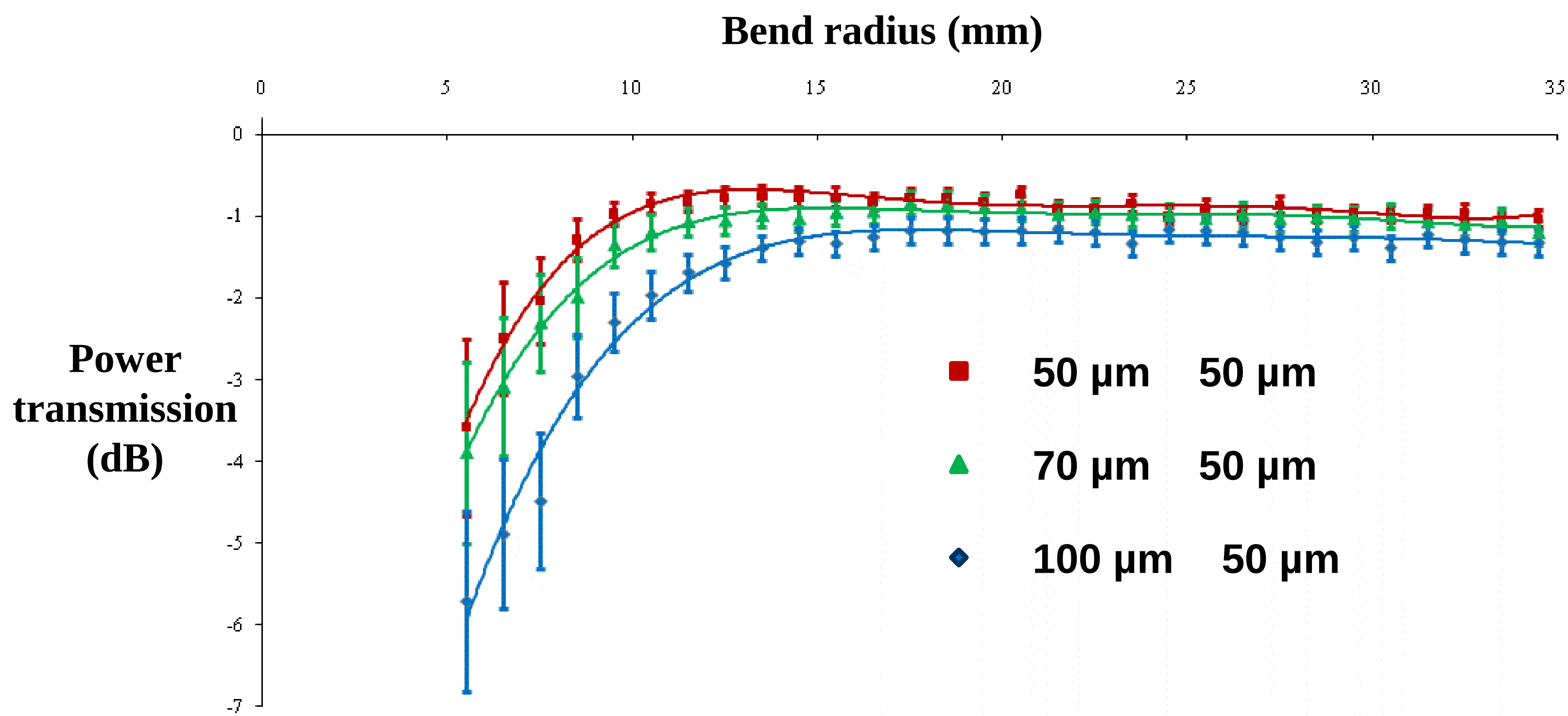
Schematic diagram of one set of curved waveguides.



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

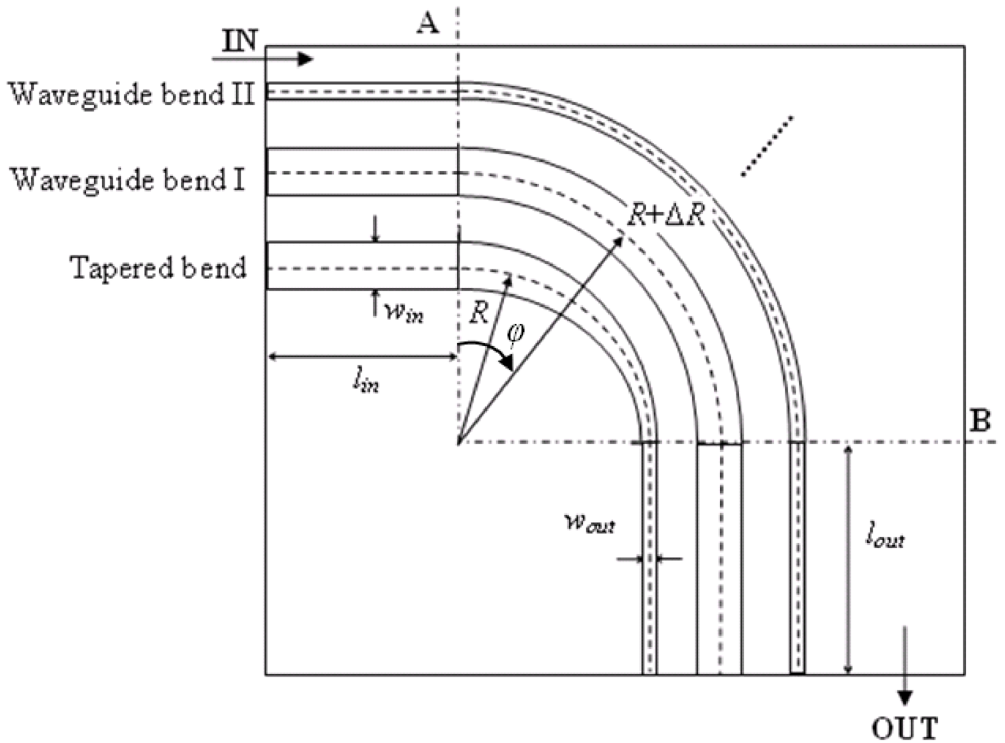
- Radius *R*, varied between 5.5 mm < *R* < 35 mm, *ΔR* = 1 mm
- Light lost due to scattering, transition loss, bend loss, reflection and back-scattering
- Illuminated by a MM fiber with a red-laser.

Loss Of Waveguide Bends



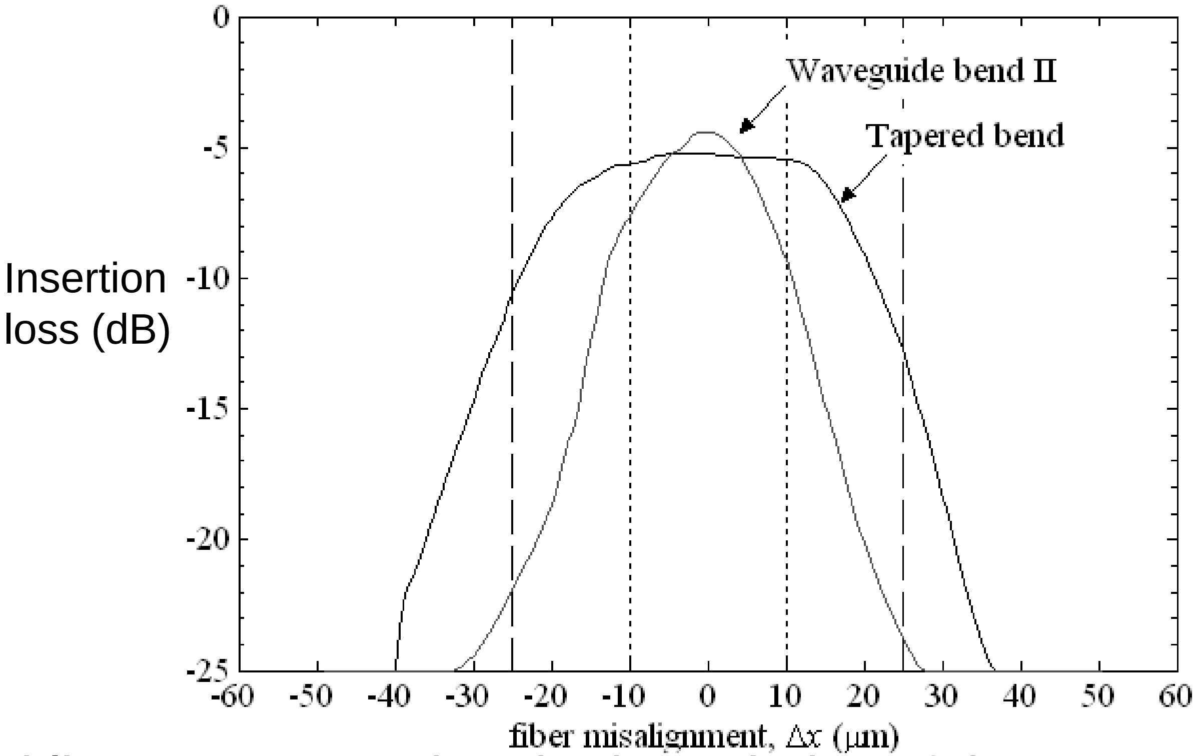
Width (µm)	Minimum Radius (mm)	Minimum Loss (dB)
50	13.5	0.74
75	15.3	0.91
100	17.7	1.18

Design Rules For Tapered Bends



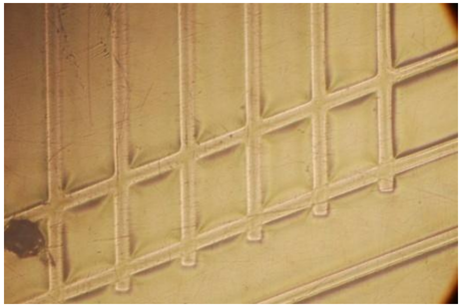
- The input section w_{in} = 50 μm, and its length l_{in} = 11.5 mm
- The tapered bend transforms the waveguide width from w_{in}, to w_{out}
- The width of the tapered bends varies linearly along its length
- Output straight waveguide length l_{out} = 24.5 mm.
- Output widths w_{out} = 10 μm, 20 μm, 25 μm, 30 μm and 40 μm

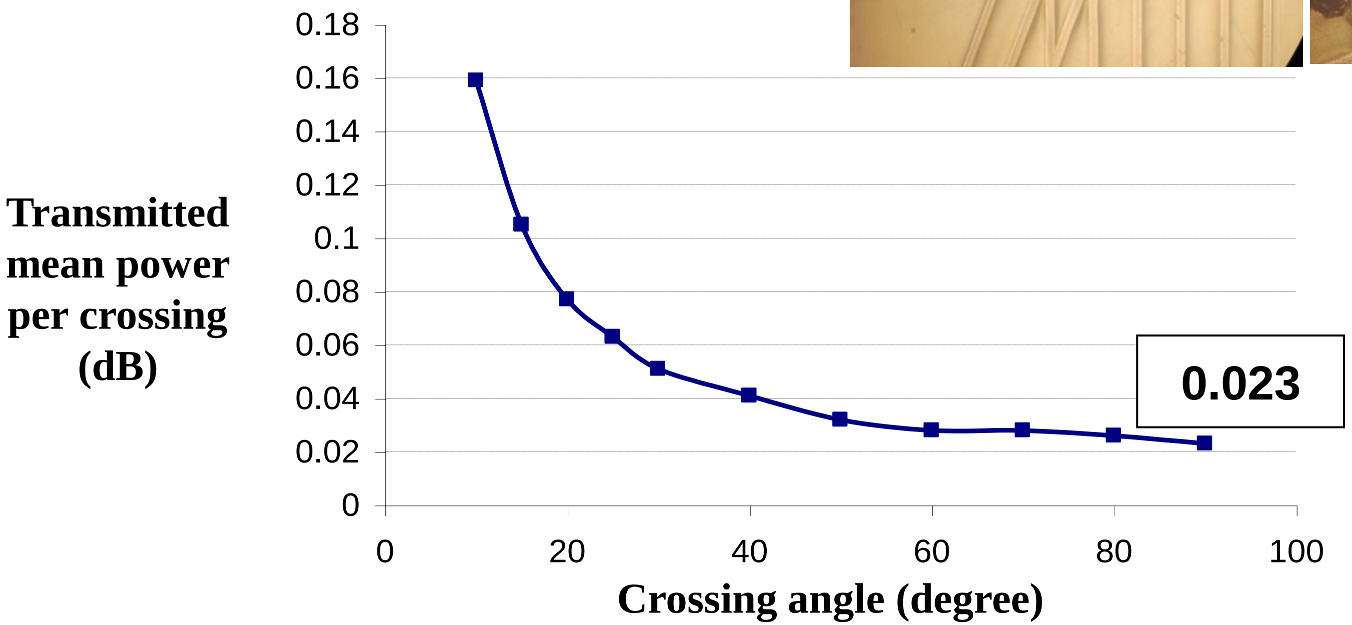
Misalignment Tolerance Of A Tapered Bend



- ❑ Dashed lines correspond to the boundaries of the w_{in} = 50 μm tapered bend
- ❑ Dotted lines correspond to the boundaries of the 20 μm bend
- ❑ Tapered bend has more misalignment tolerance for a slight loss penalty

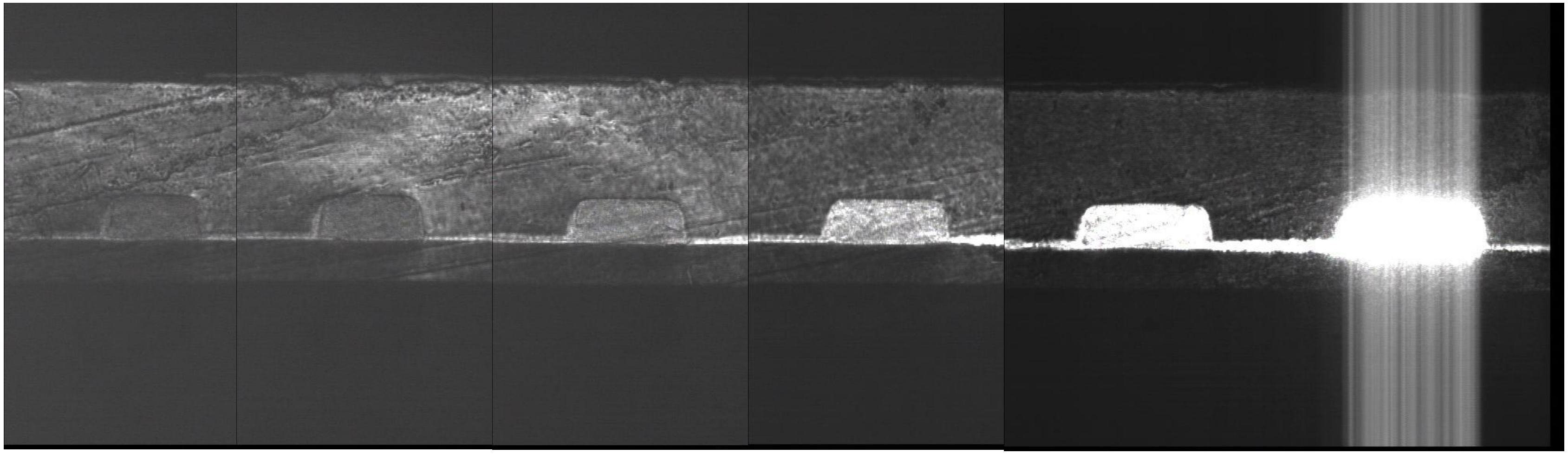
Design Rules For Waveguide Crossings





- Loss of 0.023 dB per 90 crossing consistent with other reports
- The loss per crossing (L_c) depends on crossing angle (θ), $L_c = 1.0779 \cdot \theta^{-0.8727}$.

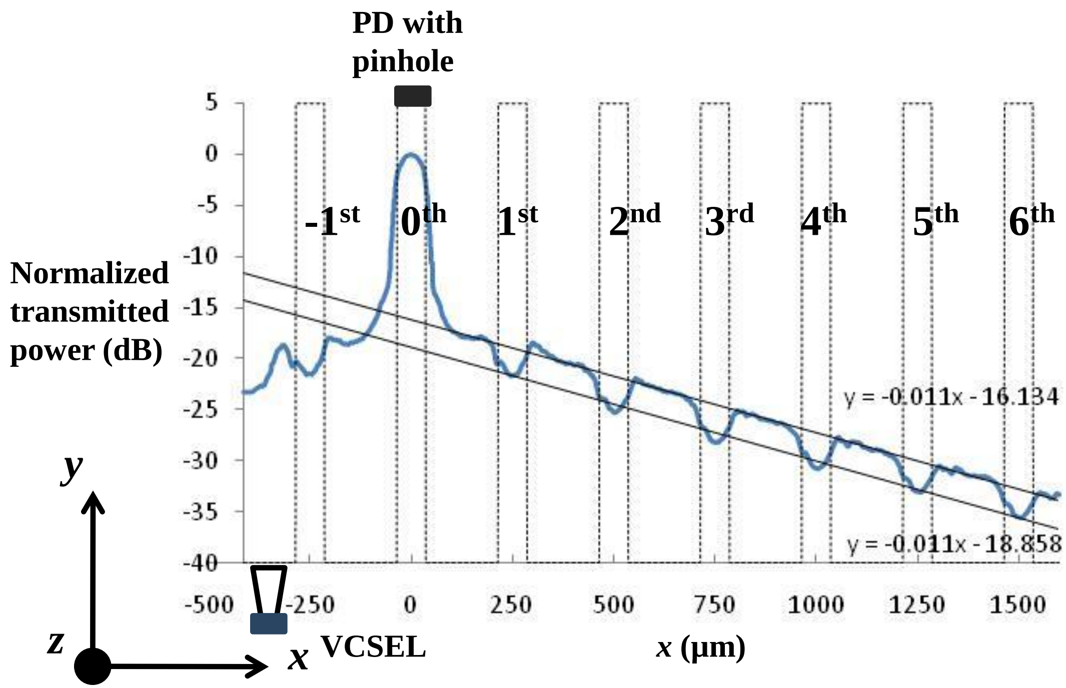
Crosstalk in Chirped Width Waveguide Array



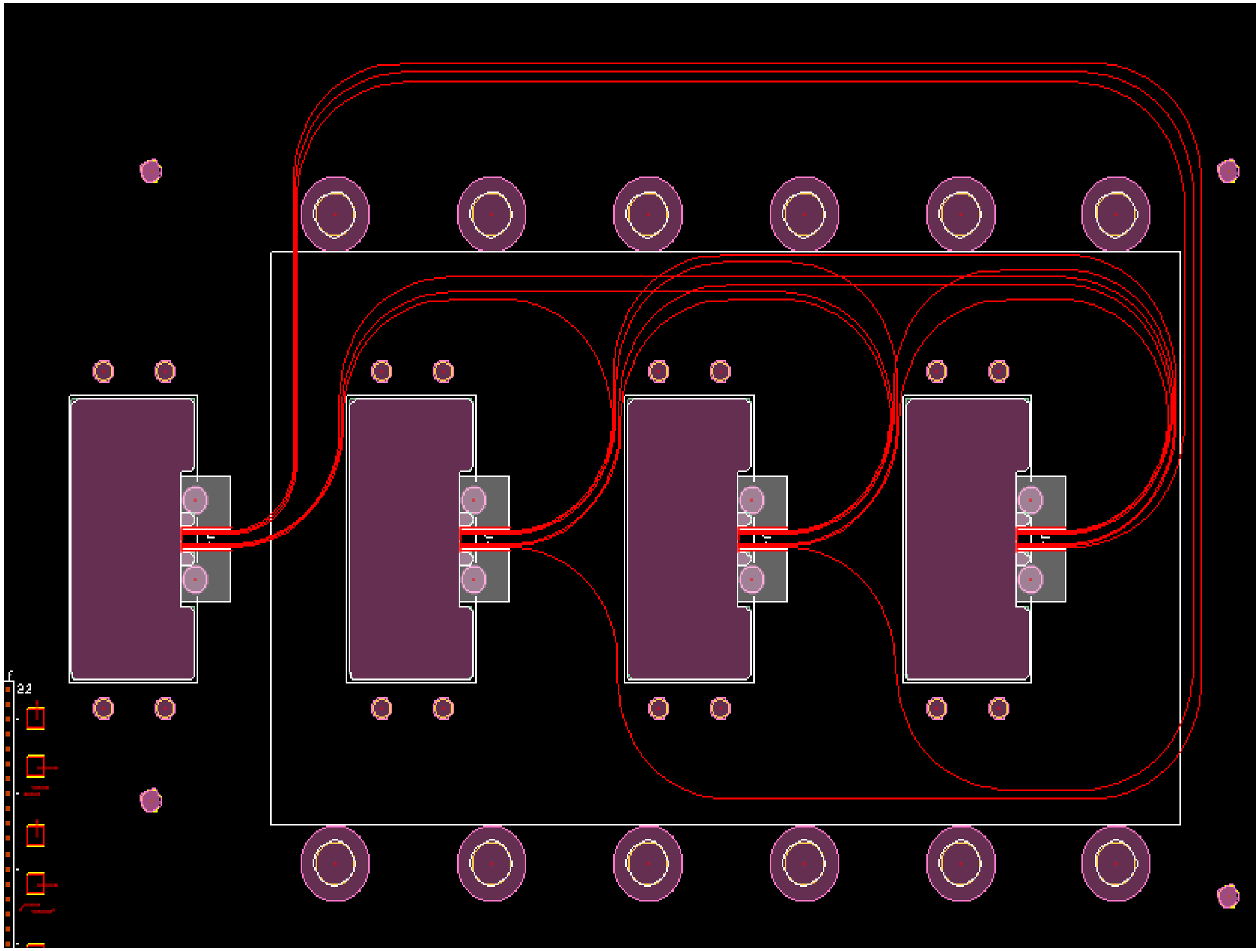
100 µm 110 µm 120 µm 130 µm 140 µm 150 µm

- 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

Design Rules For Inter-Waveguide Cross Talk



- 70 µm 70 µm waveguide cross sections
- Waveguide end facets diced but unpolished scatters light into cladding
- In the cladding power drops linearly at a rate of 0.011 dB/µm
- Crosstalk reduced to -30 dB for waveguides 1 mm apart



Fully connected waveguide layout using design rules

❑ Papakonstantinou,I., et al., (2008). Low cost, precision, self-alignment technique for coupling laser and photodiode arrays to waveguide arrays. *IEEE Transactions on Advanced Packaging* . ISSN: 1521-3323

❑ Papakonstantinou,I., et al., (2008). Insertion Loss and Source Misalignment Tolerance in Multimode Tapered Waveguide Bends. *IEEE Photonics Technology Letters* 20(12), 1000-1002. ISSN: 1041-1135

❑ Papakonstantinou,I., et al., (2008). Optical 8-Channel, 10 Gb/s MT Pluggable Connector Alignment Technology for Precision Coupling of Laser and Photodiode Arrays to Polymer Waveguide Arrays for Optical Board-to-Board Interconnects. *ECTC, May 27-30, Florida, USA*,

❑ Selviah,D.R. (2008). Invited Conference Plenary Paper: Integrated Optical and Electronic PCB Manufacturing. *IEEE Workshop on Interconnections within High Speed Digital Systems, Santa Fe, USA, 18-21 May 2008*, Santa Fe, New Mexico, USA:IEEE

❑ Selviah,D.R. (2008), *UK Displays and Lighting, Korean Trade Visit, Department of Business, Enterprise and Regulatory Reform, 1.*

❑ Selviah,D.R., et al., (2008). Integrated Optical and Electronic Interconnect Printed Circuit Board Manufacturing. *Circuit World* 34(2), 21-26. ISSN: 0305-6120

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- **Selviah,D.R.(2008).** ***19th IEEE LEOS Workshop on High Speed Interconnections within Digital System, HSD '08, May 18th-21st, Santa Fe, New Mexico, USA***
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Thank you for Your Attention

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Supplemental Slides

How to Make an Optical PCB

1. Deposit lower cladding
2. Cure
3. Deposit core
4. Align mask
5. Cure waveguides
6. Remove uncured material
7. Deposit upper cladding
8. Cure