Measurement Challenges for Optical Printed Circuit Boards
Invited Talk

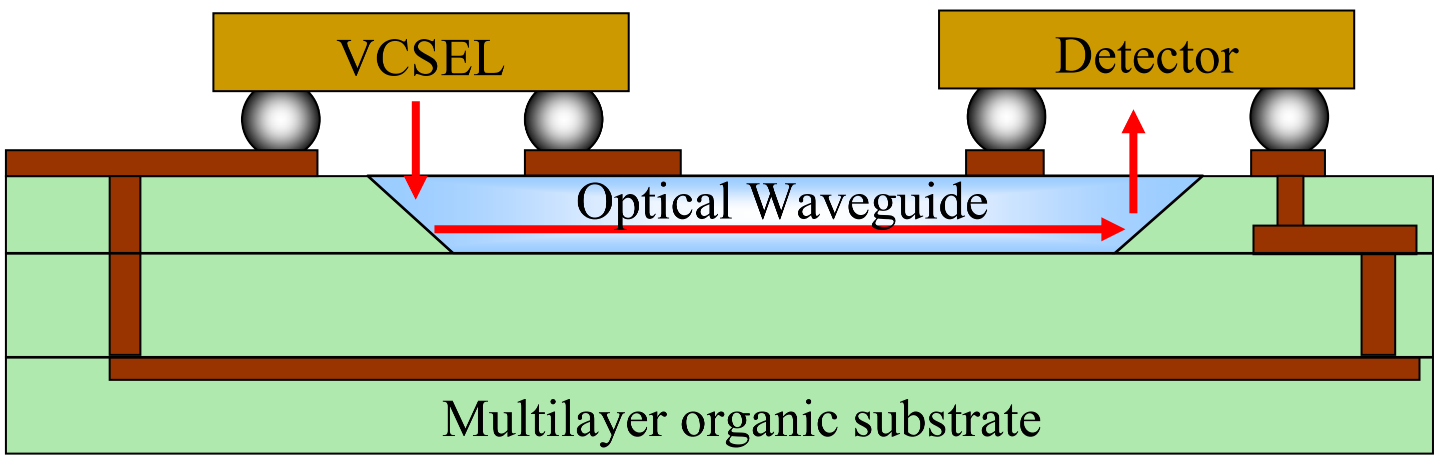
David R. Selviah
Department of Electronic and Electrical Engineering,
University College London, UCL

OFMC Conference 15th October 2007

d.selviah@ee.ucl.ac.uk

Integration of Optics and Electronics

- Polymer multimode waveguides
- On or in the PCB substrate or laminated between PCB boards
- Out of plane mid-board connection



Integrated Optical and Electronic Interconnect PCB Manufacturing (OPCB) Project Aims

1. Establish waveguide design rules
   - Build into commercial CAD layout software to ease the design of OPCBs and to ensure widespread use.
   - Understand the effect of waveguide wall roughness and cross sectional shape on loss and bit error rate.
2. Develop low cost, PCB compatible manufacturing techniques for OPCBs
   - Compare the commercial and technological benefits of several high and low risk manufacturing technologies
   - Environmental testing, reproducibility
3. Design an optical-electrical connector
   - Low cost, dismountable, passive, self-aligning, mid-board, multichannel, duplex, long life

Project Partners

Academic Partners

UCL (Lead)	– Optical modelling & characterisation
Heriot-Watt University	– Laser writing and polymer chemistry
Loughborough University	– Laser ablation, ink jet printing, flip-chip assembly

Industrial Partners

Xyratex (Lead)	– End user – mass data storage
BAE Systems	– End user – aerospace applications
Renishaw	– End user – optical sensor applications
Exxelis	– Polymer development and fabrication
Stevenage Circuits (SCL)	– PCB manufacturers
Cadence	– Design tools for PCBs
Rsoft Design	– Modelling tools
Xaar	– Print head technology
NPL	– Waveguide/material characterisation

Polymer Formulation

- Truemode^{TM} acrylate – Exxelis
- Dry film –Exxelis, Heriot Watt, SCL
- High UV curing rate polymer – Heriot Watt
- Polymer viscosity control – Loughborough, Xaar
- Surface wetting control - Loughborough
- Polysiloxane

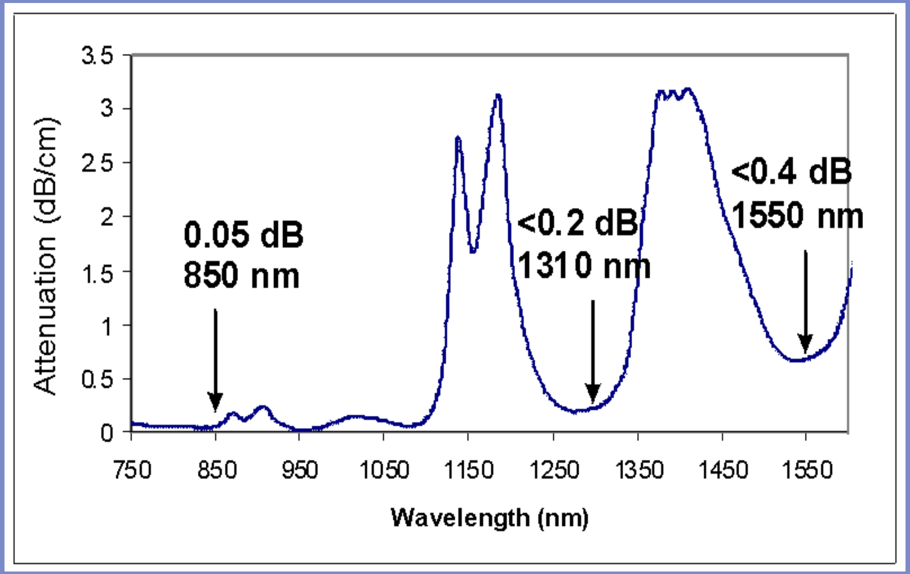
Polymer Measurements

- Refractive index of core and cladding
- Refractive index uniformity across wafer
  - 2D and 3D refractive index mapping
- Glass transition temperature
- Viscosity
- Absorption Spectrum
- Effect of humidity, temperature cycling, vibration
- Aging Characteristics

Polymer Waveguides

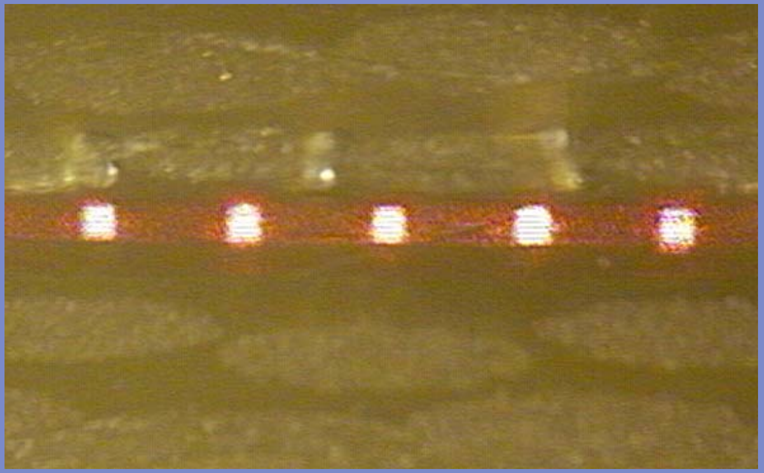
Waveguide losses

The measured attenuation spectrum for the multifunctional acrylate polymer waveguides.



Waveguide loss measured by Terahertz Photonics using the cutback method: 0.05 dB/cm at 850 nm

Environmental Stability

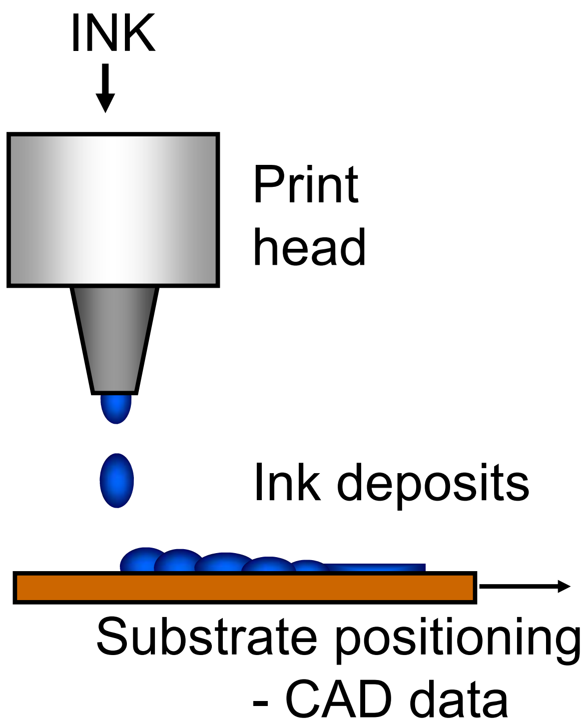


Guide unaffected by:

- Board lamination: 1 hour at 180ºC
- Solder reflow:160 seconds at 288ºC
- Damp heat: 85% RH @ 85ºC
- Temperature cycling: -40 to 85ºC (2 wks)
- High degradation temperature: ~ 400ºC

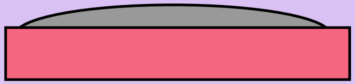
Ink Jet Deposition of Polymer Waveguides

- Localised deposition of cladding and / or core materials
  - More materials efficient
  - Active response to local features
- Materials
  - Solutions
    - e.g. PMMA in solvent
    - Limited deposition rate
  - Functional materials

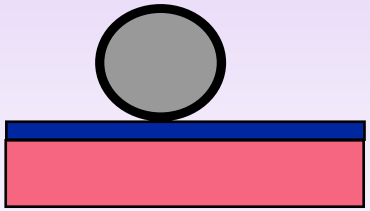


Control of Surface Wetting

- Need to control contact angle of polymer droplet on surface
  - Wetting angle determines waveguide cross-section and printing resolution
  - Control of surface chemistry (balance of wetting and adhesion)



Wettable surface
leads to broad droplet



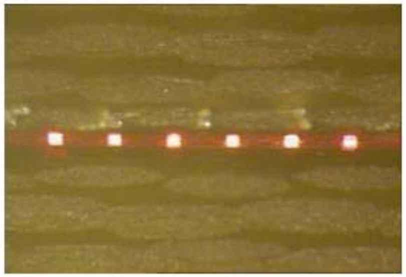
Non-wettable
surface
leads to high
contact angle, but
limited adhesion

OPCB Waveguide Fabrication Methods

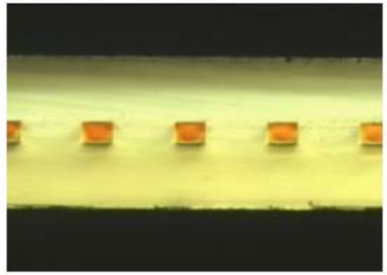
- UV Photolithography – Exxelis $\Rightarrow$ SCL
- UV Laser Direct Write – Heriot Watt $\Rightarrow$ SCL
- Excimer Laser ablation – Loughborough $\Rightarrow$ SCL
- Ink Jet Printing – Loughborough $\Rightarrow$ SCL
- UV embossing/stamping – Exxelis/EPIGEM
- Polymer Extrusion – BAE Systems

SCL – Stevenage Circuits Ltd.

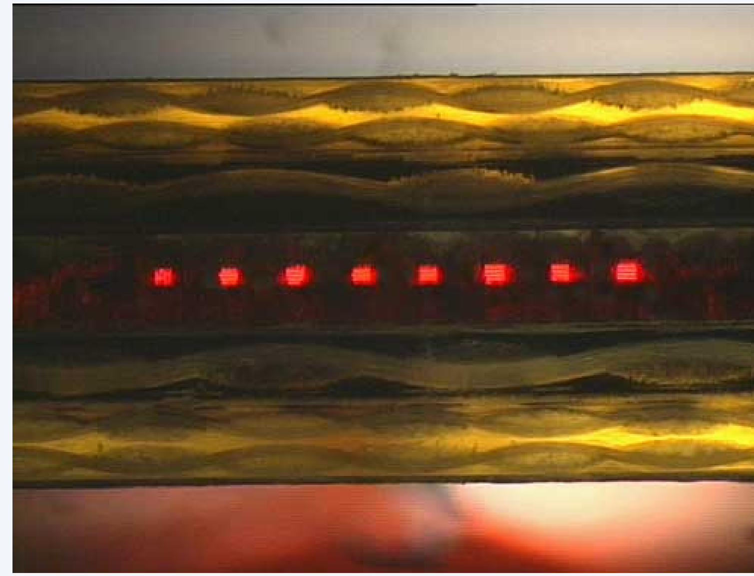
ELECTRO-OPTICAL PRINTED CIRCUIT BOARD MANUFACTURING TECHNIQUES



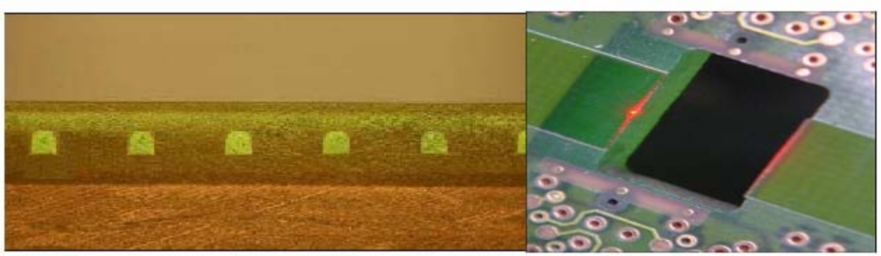
Source: Exxelis Ltd



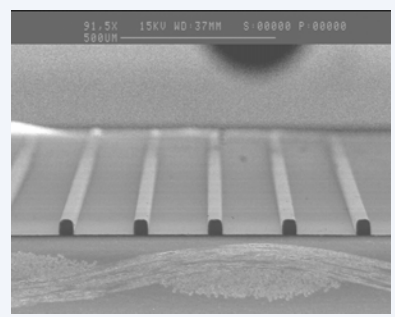
Source: Fraunhofer IZM

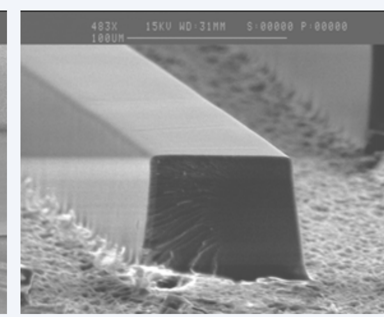


Source: Varioprint AG



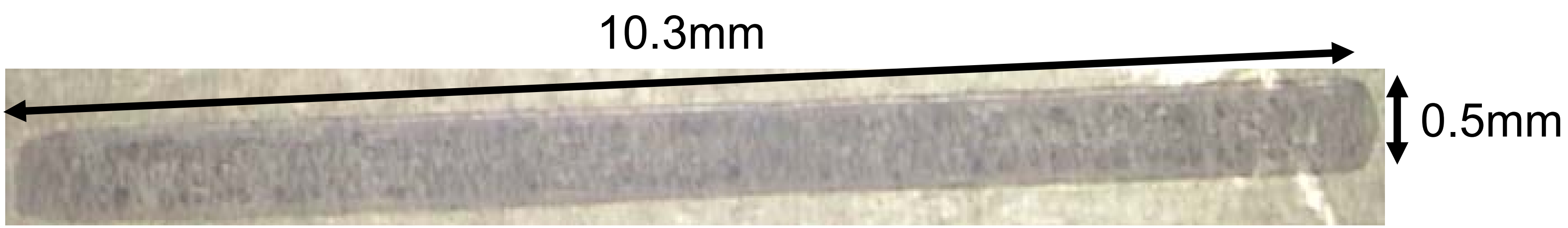
Source: IBM Zürich





Preliminary Work

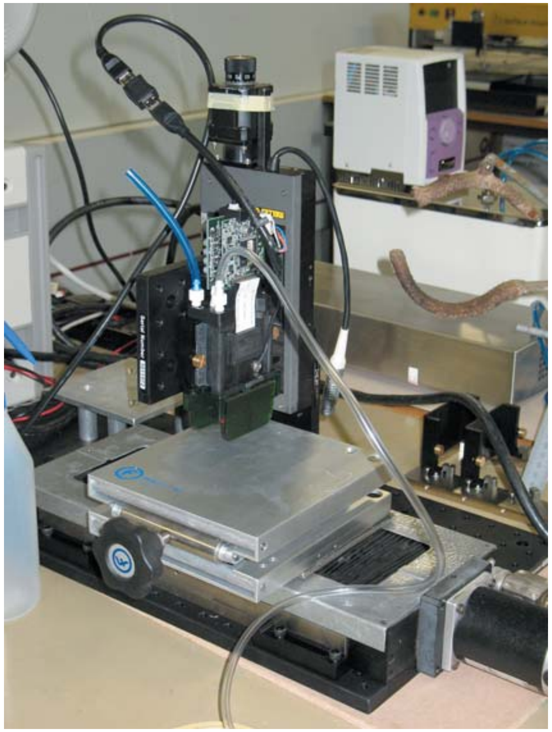
- Strong absorption of Excimer laser by polymer
  - Efficient ablation
  - Minimal heating
- Characterisation of laser machining parameters
  - Control ablation rate / depth
  - Minimisation of debris
  - Side wall roughness

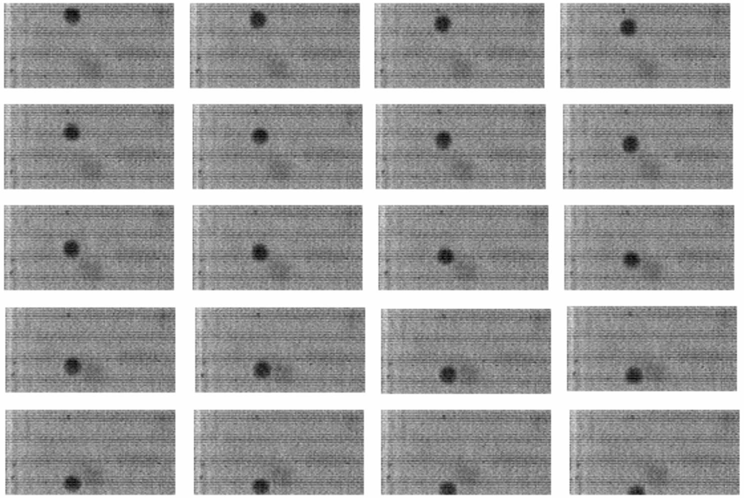


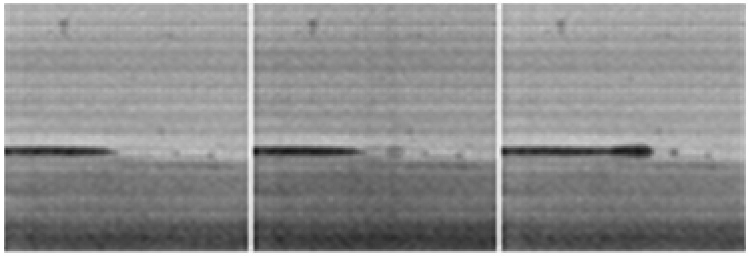
Groove machined in acrylic – test structure

Ink Jet System

- Ink Jet printing system established
- Head stationary, substrate moved
- High speed camera on loan from EPSRC – droplet imaging







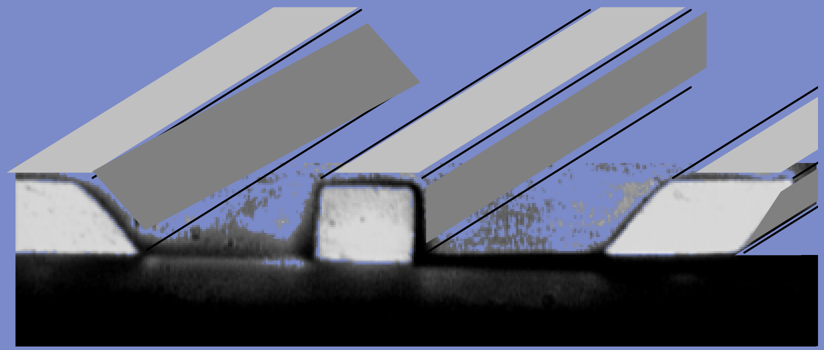
Large area writing

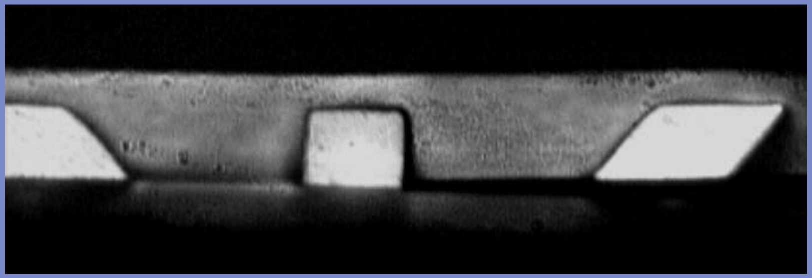
Aerotech sub-μm precision stages
600 x 300 mm travel

OPCB Waveguide Mirror Fabrication Methods

- UV Laser Direct Write – Heriot Watt
- Eximer Laser ablation - Loughborough

Laser written polymer structures



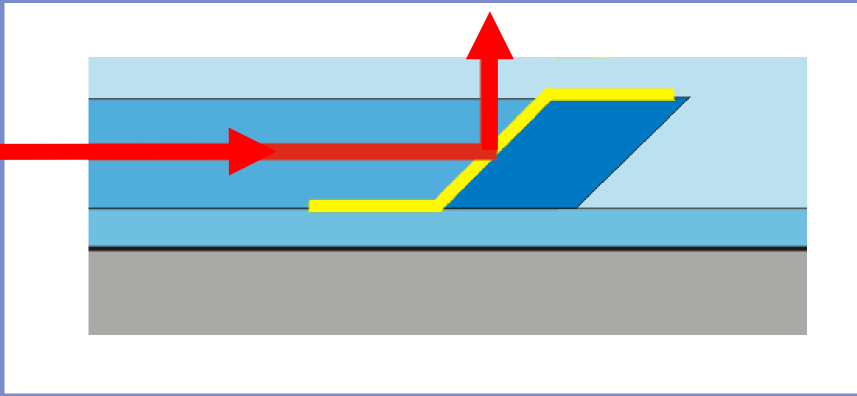


Optical microscope image showing end on view of vertical and 45º surfaces

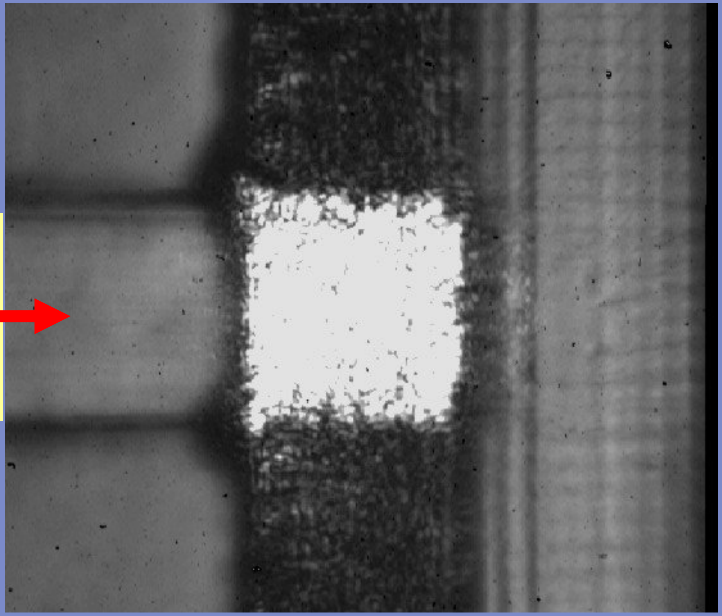
Cladding spun over waveguide cores (and other features): same polymer Δn ~ 1%, blanket cured under UV lamp (N_2 atmos.)

Waveguide terminated with 45-deg mirror

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



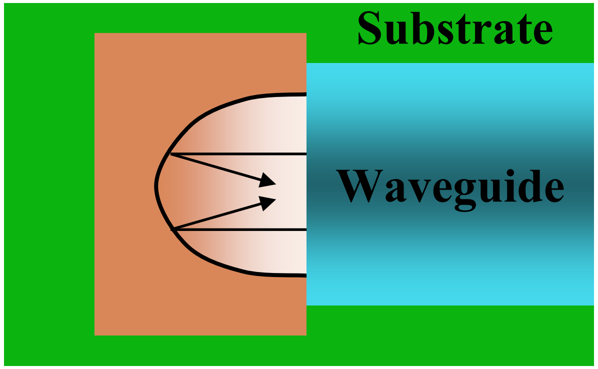
Microscope image looking
down on mirror
coupling light towards camera



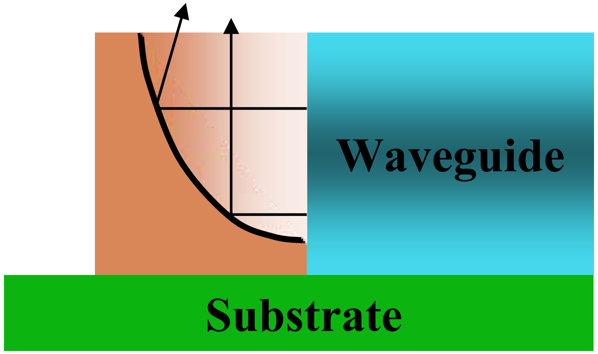
OPTICAL INPUT

Waveguide Termination

- Investigating the formation of profiled mirrors to direct light
- More efficient light capture and transmission than traditional 45^o mirrors
- Careful characterisation of machining rates and design of beam delivery system required
- Metal coating to form mirror surfaces



Plan View



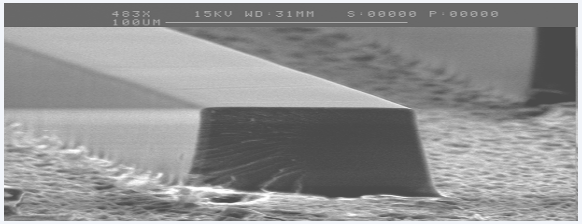
Cross-section Side View

Measurement Challenges for Optical Printed Circuit Boards – Physical measurements

- Waveguide Side Wall Roughness
- 45 degree mirror roughness
- Waveguide cross sectional shape
- Refractive index in three dimensions
- Refractive index (humidity, temperature, vibration)
- Polymer aging, delamination properties
- Connector misalignment tolerance

POLYMER WAVEGUIDE CHARACTERISTICS

EXXELIS

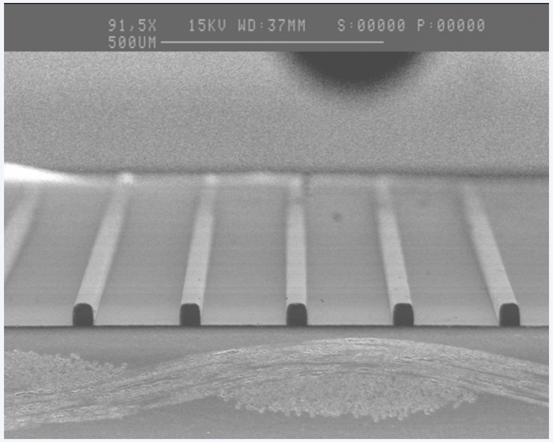


Waveguide Material

UV-curable polymeric acrylate (Truemode®)

Propagation loss @ 850 nm: 0.04 dB/cm

Heat degradation resilience: up to 350°C



Waveguide properties

Size: 70 µm x 70 µm

Core index: 1.556

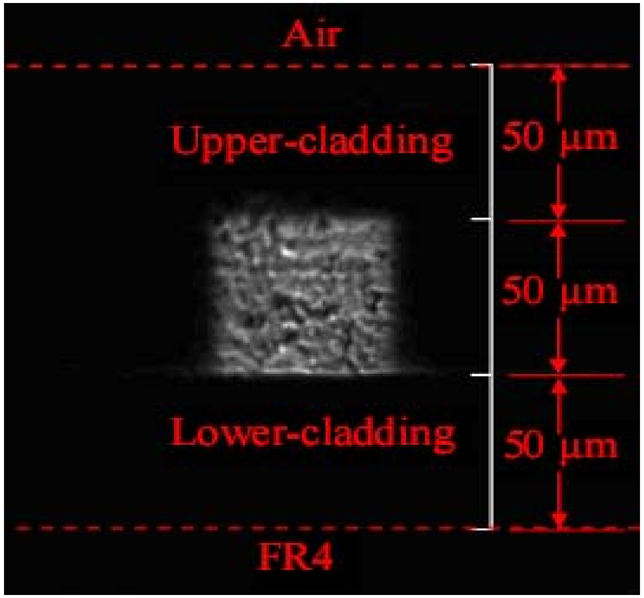
Cladding index: 1.526

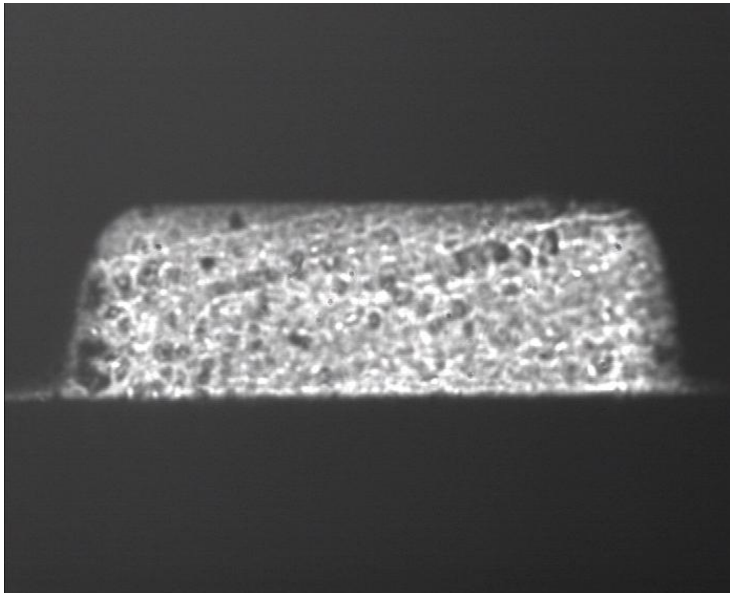
Numerical aperture: 0.302

Waveguide Array

Centre to centre pitch: 250 µm

Waveguide Output Face Photographs



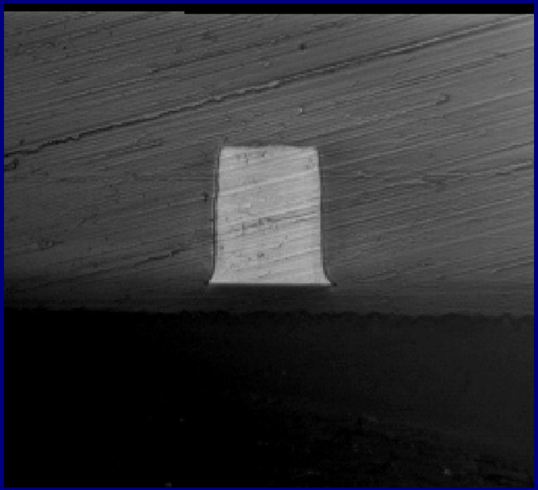


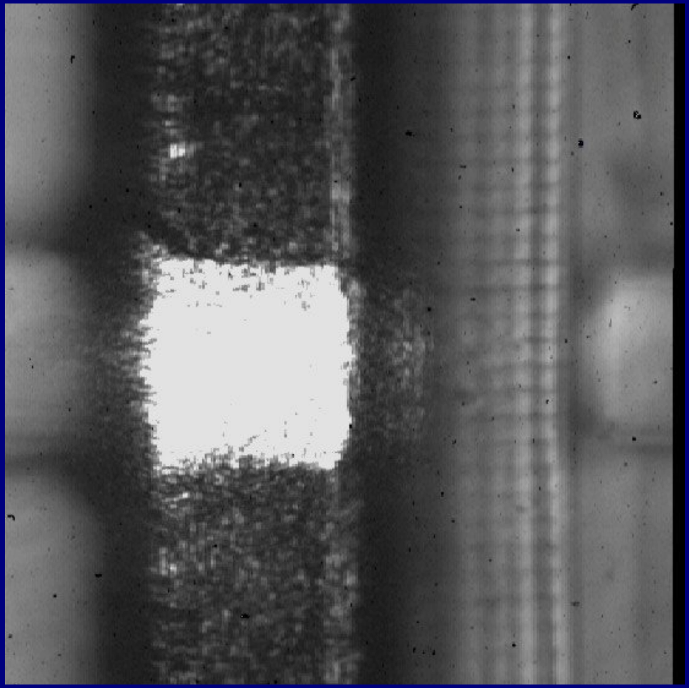
50 µm × 50 µm Waveguide

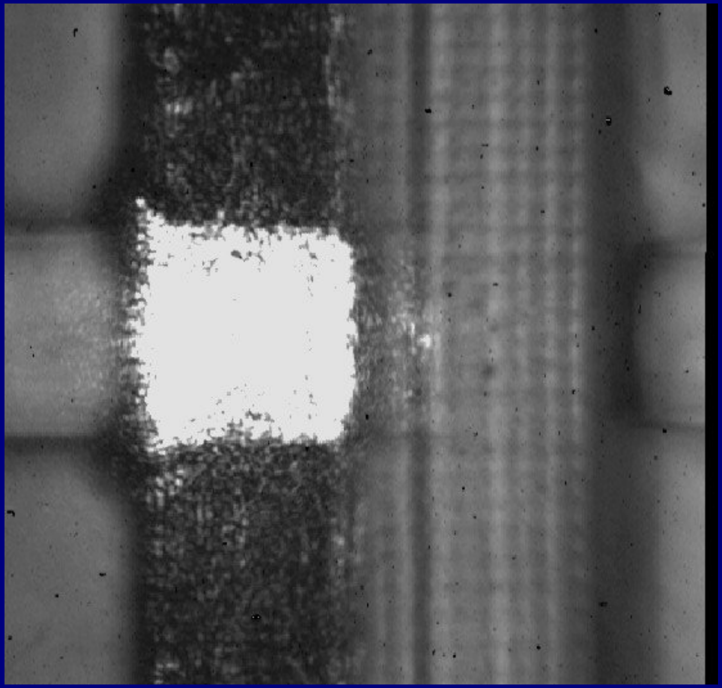
50 µm × 140 µm Waveguide

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

HERIOT WATT UNIVERSITY



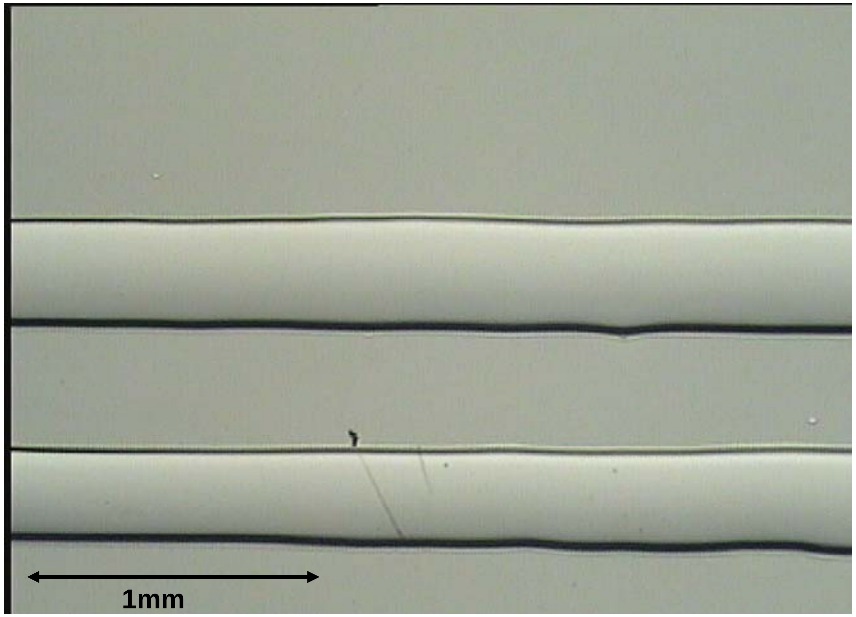


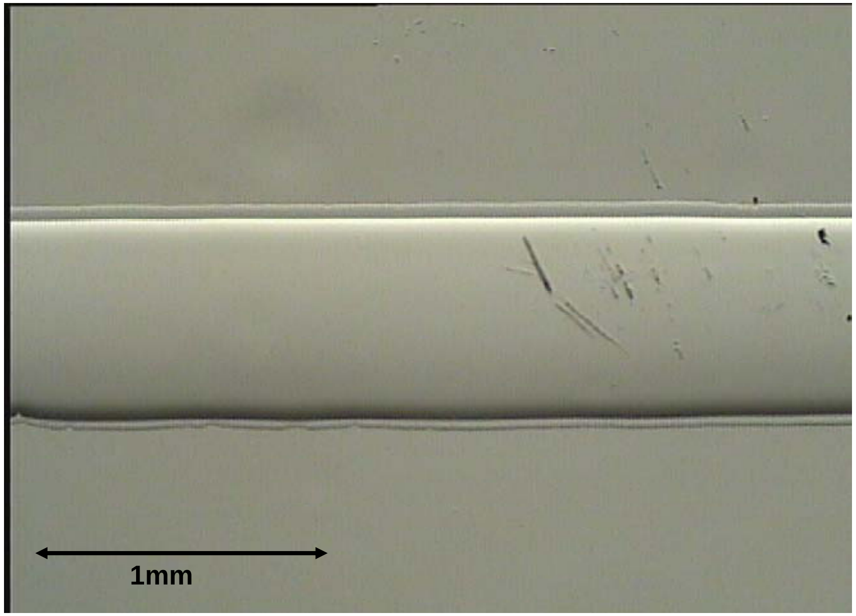


OPCB

Ink Jet Printing Preliminary Results

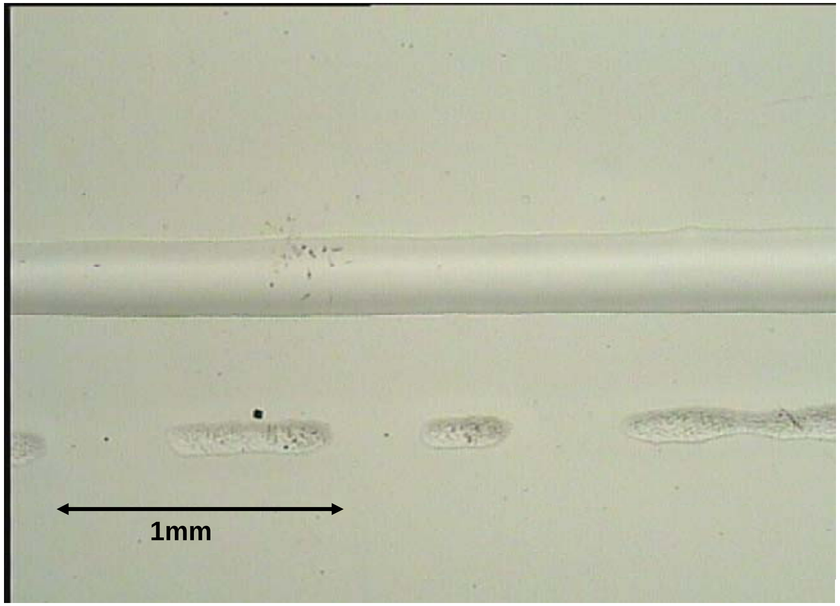
- Functional materials ink jetted
- Extensive spreading
- Further characterisation of process required

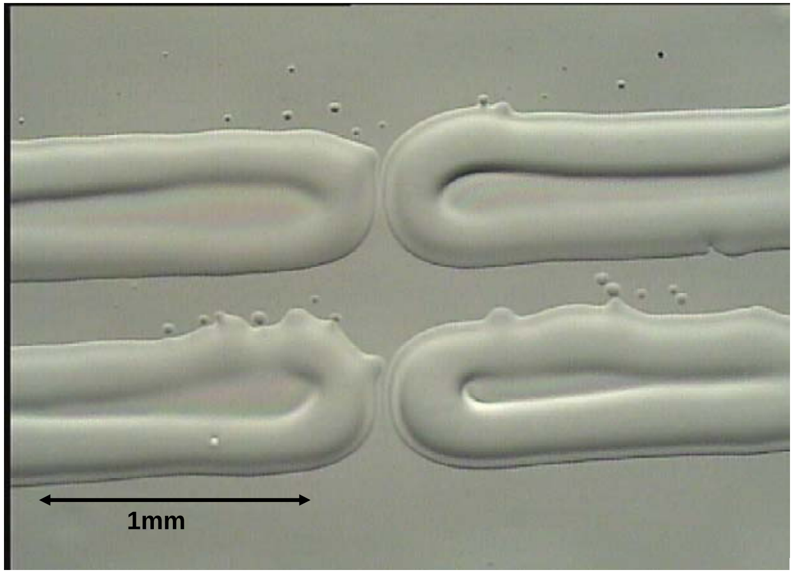




Preliminary Results

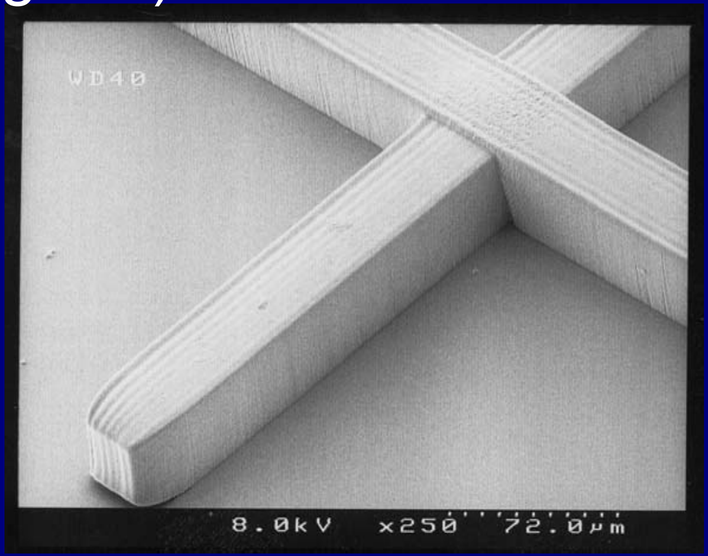
- Investigating process parameters to influence deposit size and spread
- Many defects to be understood

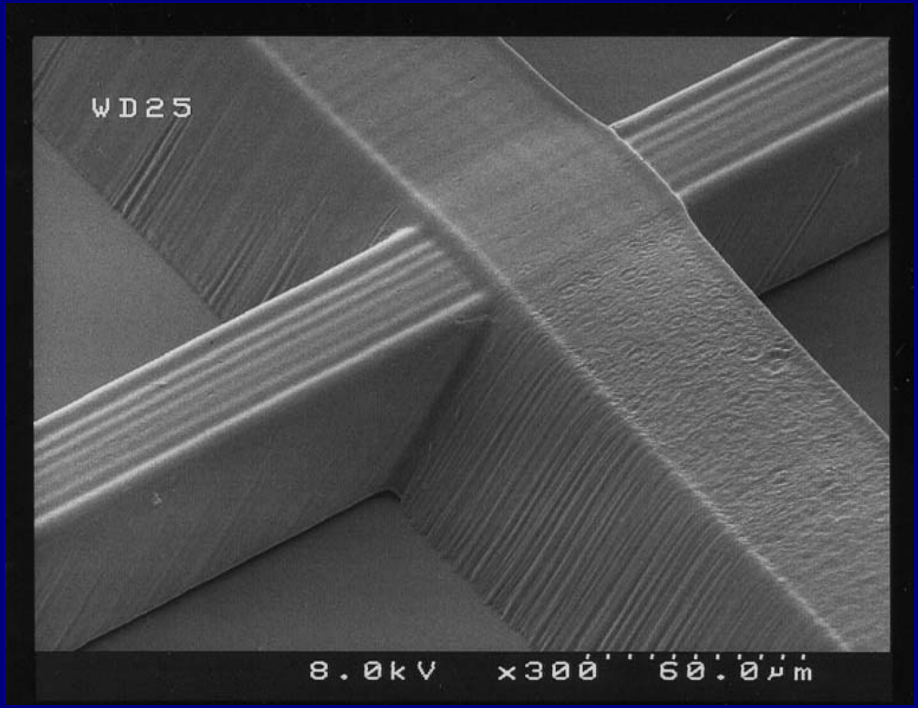




Laser written polymer structures

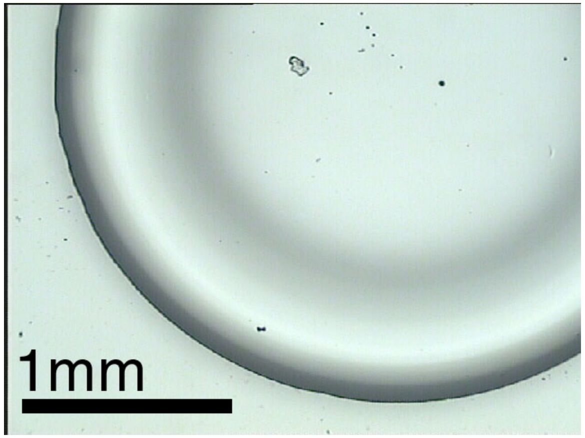
SEM images of polymer structures written using imaged 50 µm square aperture (chrome on glass)



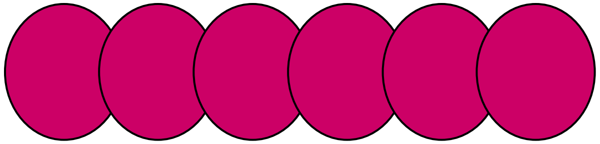


Ink Jet Challenges

- Ink formulation
  - Viscosity, surface tension
- Drying effects
  - Coffee stain
- Wall roughness caused by multiple droplets
- Wetting and droplet spread



PMMA on glass.
Deposited by pipette.



Droplet merging, effect on wall roughness

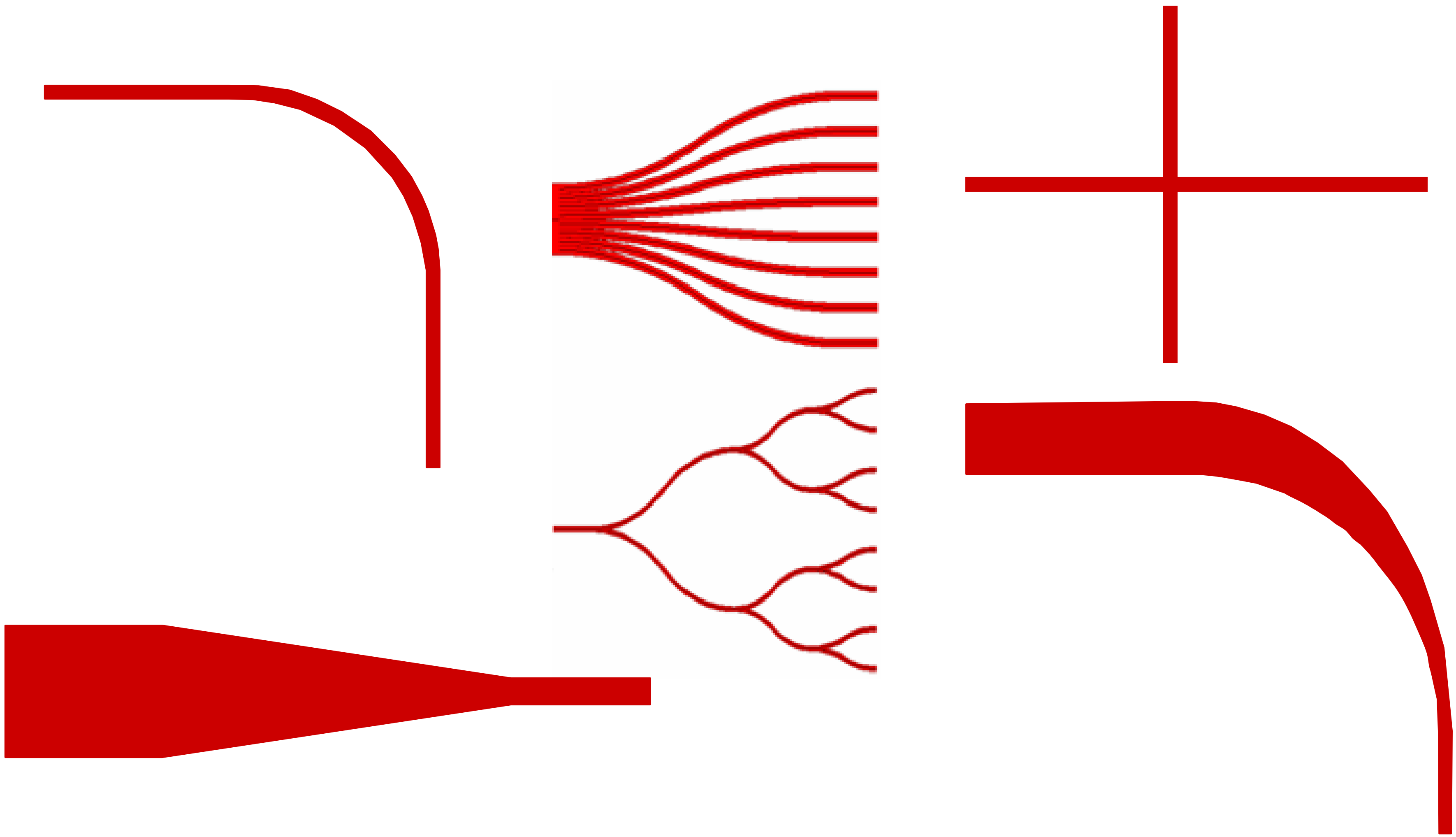
Measurement Challenges for Optical Printed Circuit Boards – Optical measurements

- Propagation Loss
- Transition Loss
- Bend Radiation Loss
- Waveguide Input/Output Coupling Loss
- Waveguide Cross Talk
- Waveguide output face photograph
- 45 degree mirror loss
- Connector misalignment effect on loss
- Equilibrium length

Waveguide Structures

- 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
- In plane mirrors

Waveguide Structures

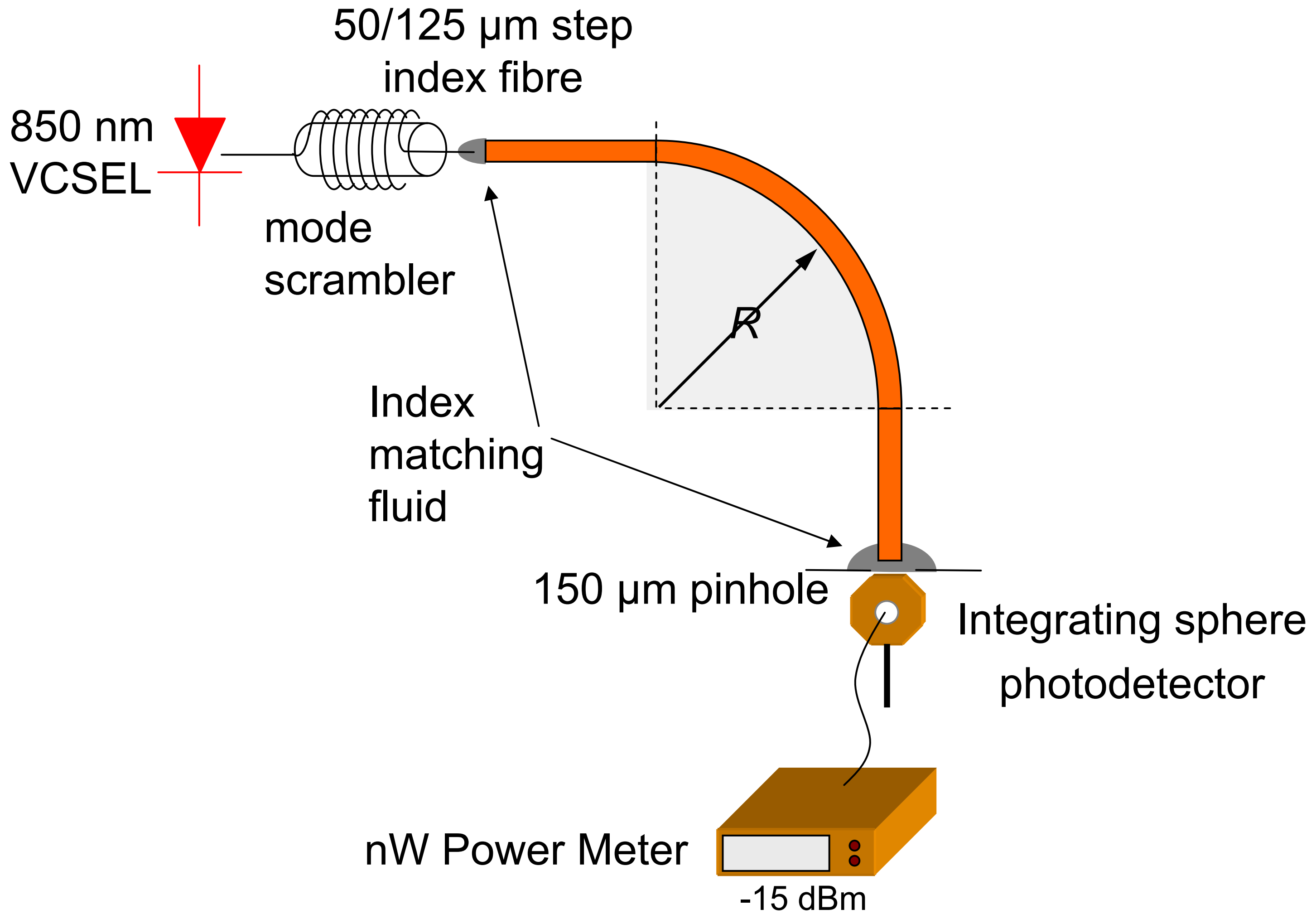


Optical Loss Measurement Technique

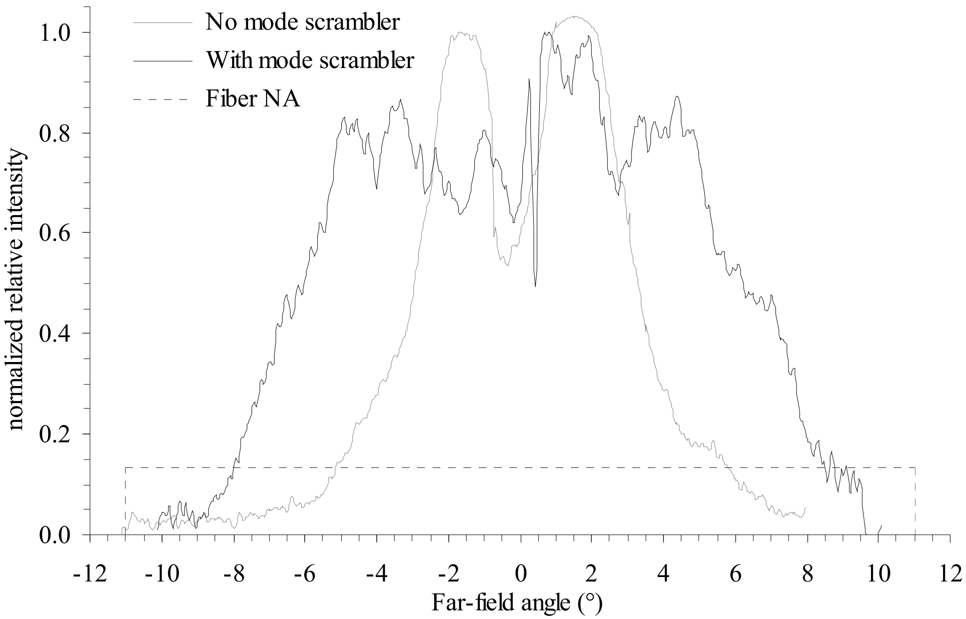
- Standard measurement
  - Input mode scrambled multimode fibre
  - Output integrating sphere
- Practical Measurement
  - Input VCSEL illumination
  - Output photodiode
- VCSEL simulation measurement
  - Input “single mode” fibre

Image of “single mode” fibre output with 850 nm VCSEL input

Optical Loss Measurement



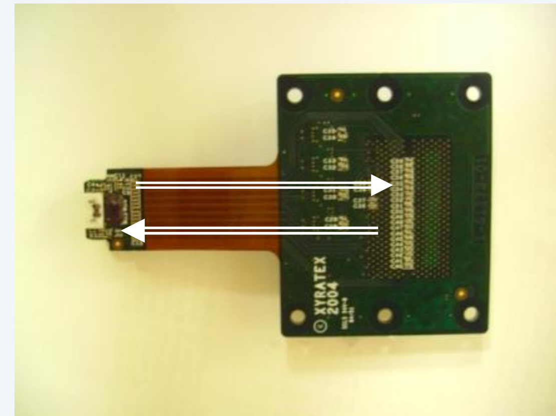
Far Field from 50/125 µm fibre with and without mode scrambling

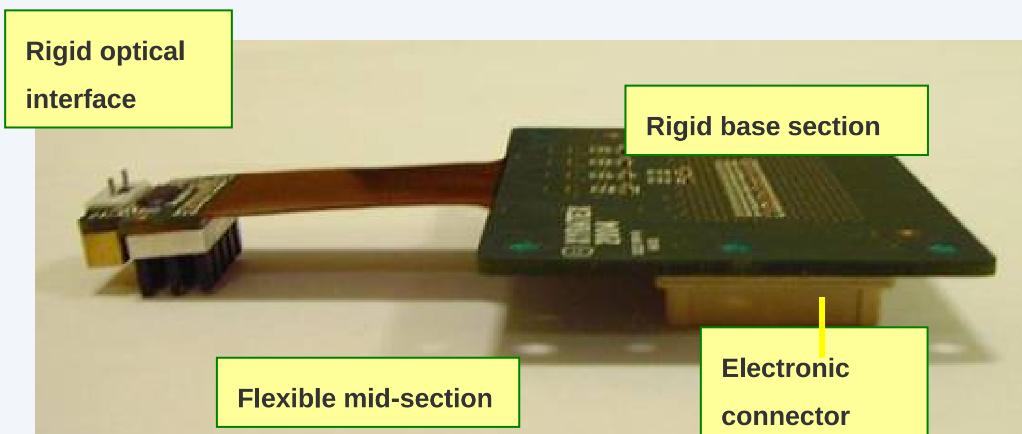


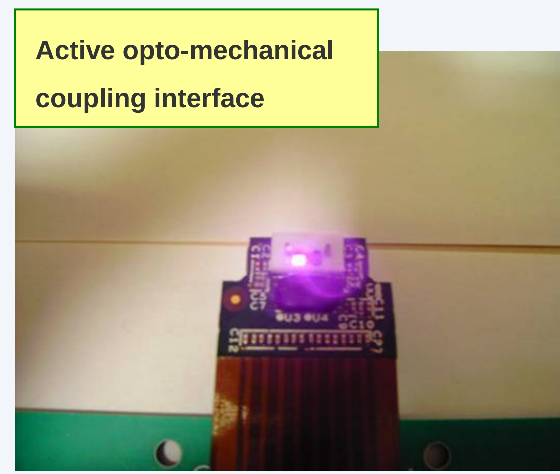
PARALLEL OPTICAL TRANSCEIVER DESIGN

xyratex

- Quad duplex parallel optical transceiver
- 10.3 Gbps per channel (82 Gb/s aggregate bandwidth)
- Electronic daughtercard connector
- Flexible and rigid PCB sections
- Optical backplane interface



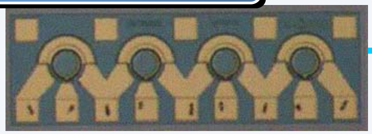




xyratex

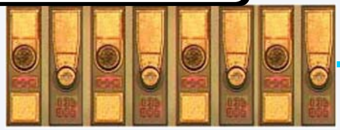
PHOTONIC INTERFACE DESIGN

PIN Array

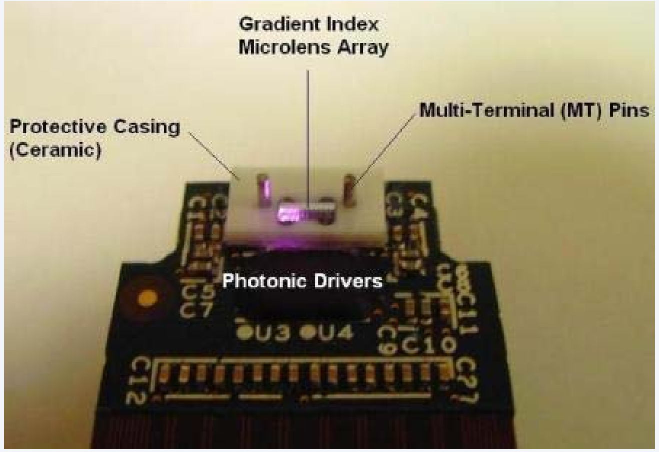


Source: Microsemi Corporation

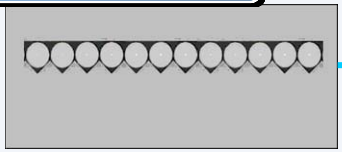
VCSEL Array



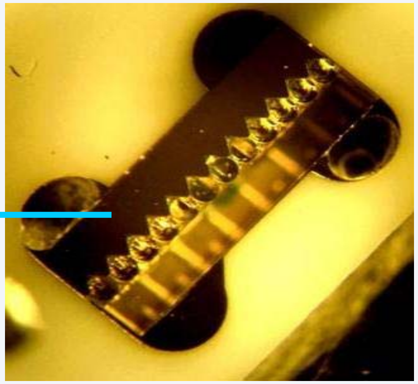
Source: ULM Photonics GmbH

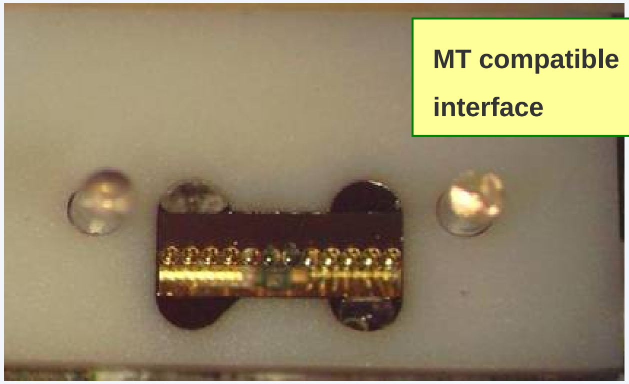


GRIN Lens Array



Source: GRINTech GmbH

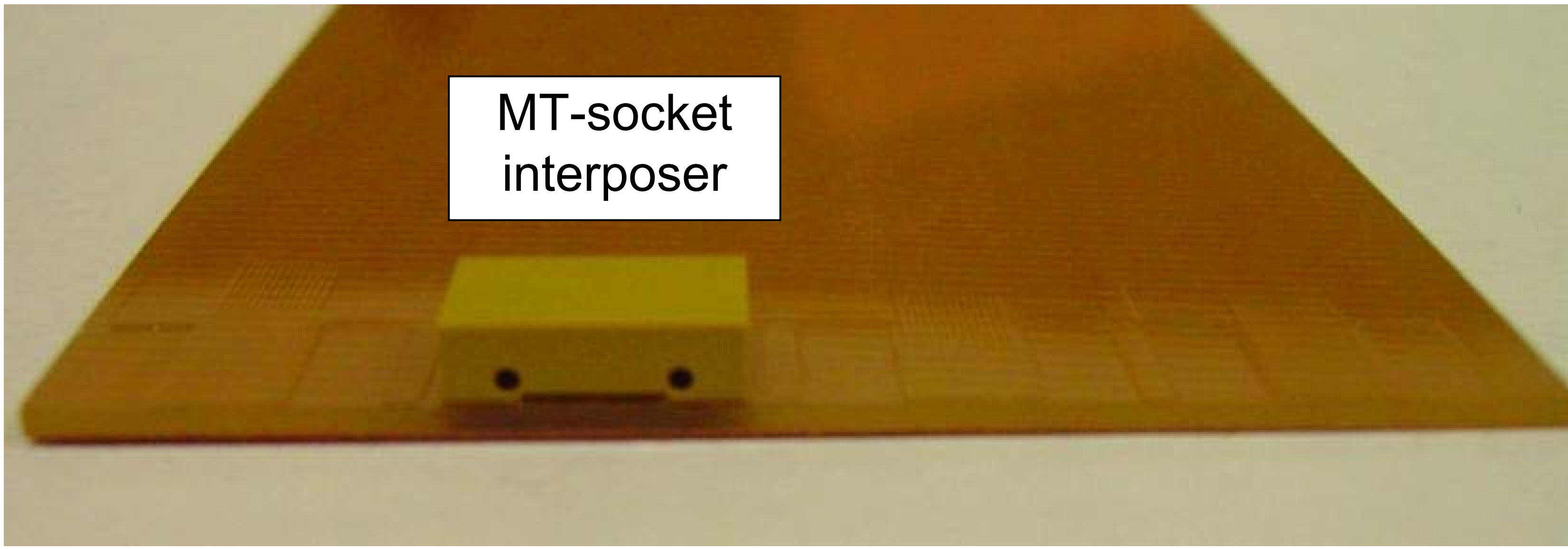




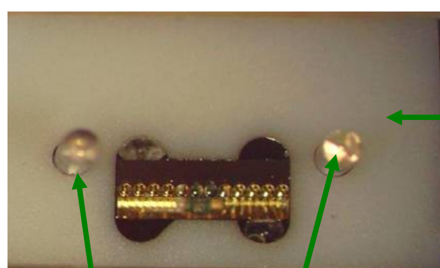
MT compatible interface

OPCB with MT - socket interposer

(a)



(b) MT-plug

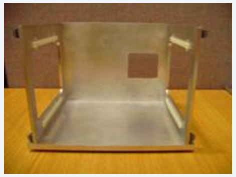


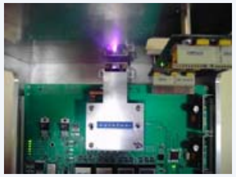
Ceramic lens holder

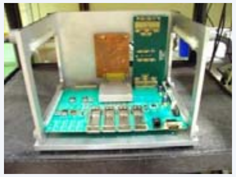
MT-pins

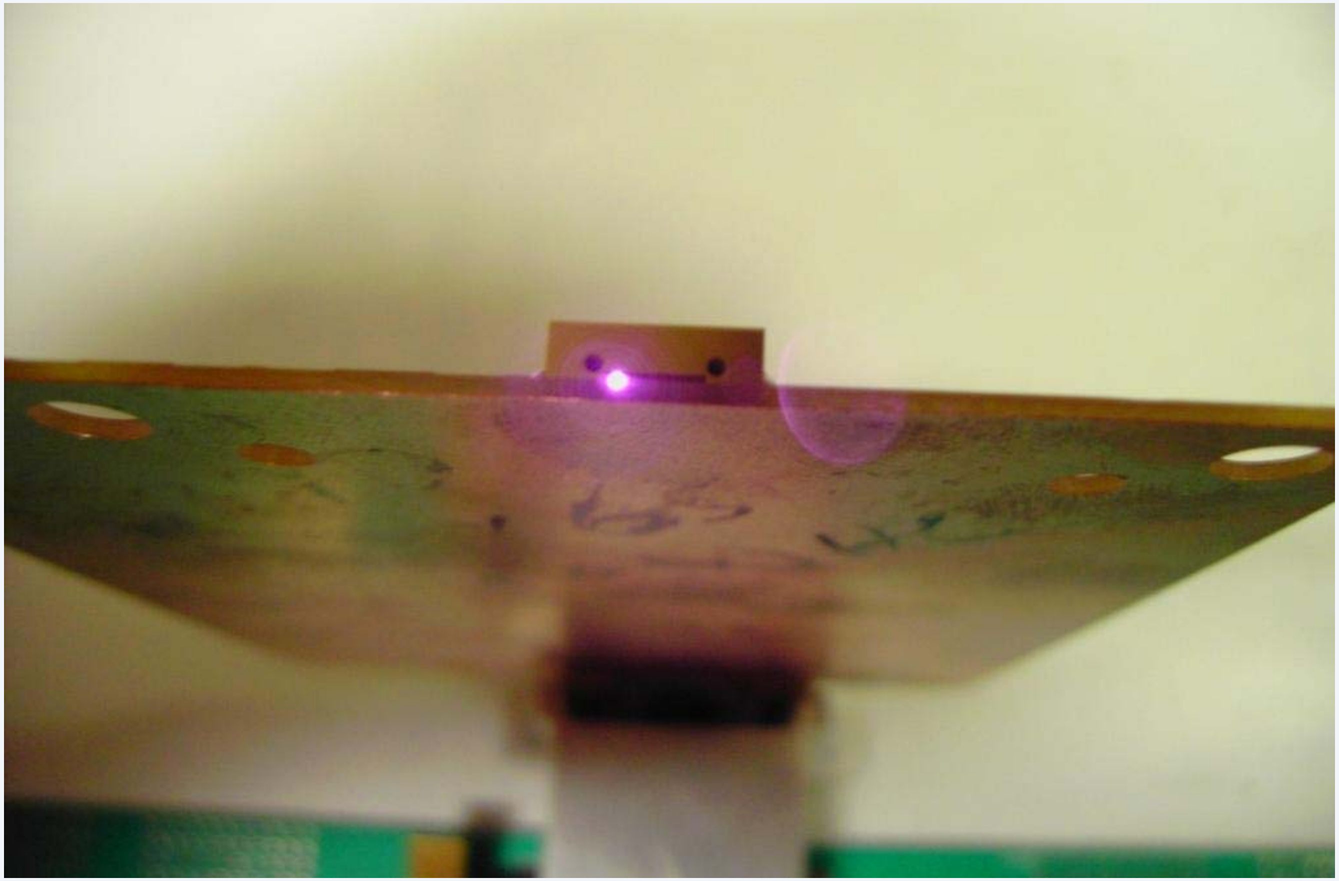
Alignment Precision
x: ± 3 μm
y: ± 4 μm
z: ± 10 μm

Daughtercard to Optical Backplane Coupling Evaluation

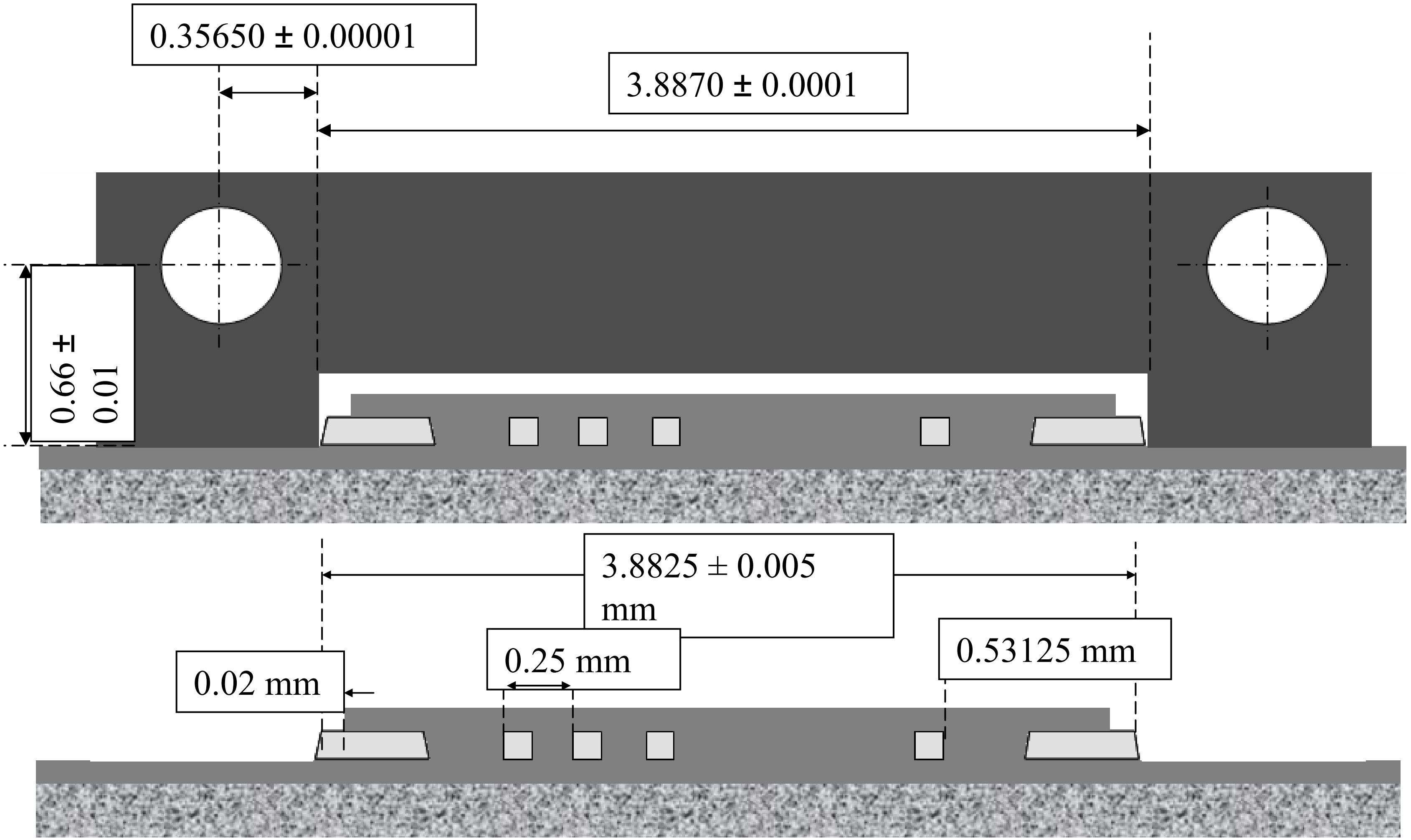




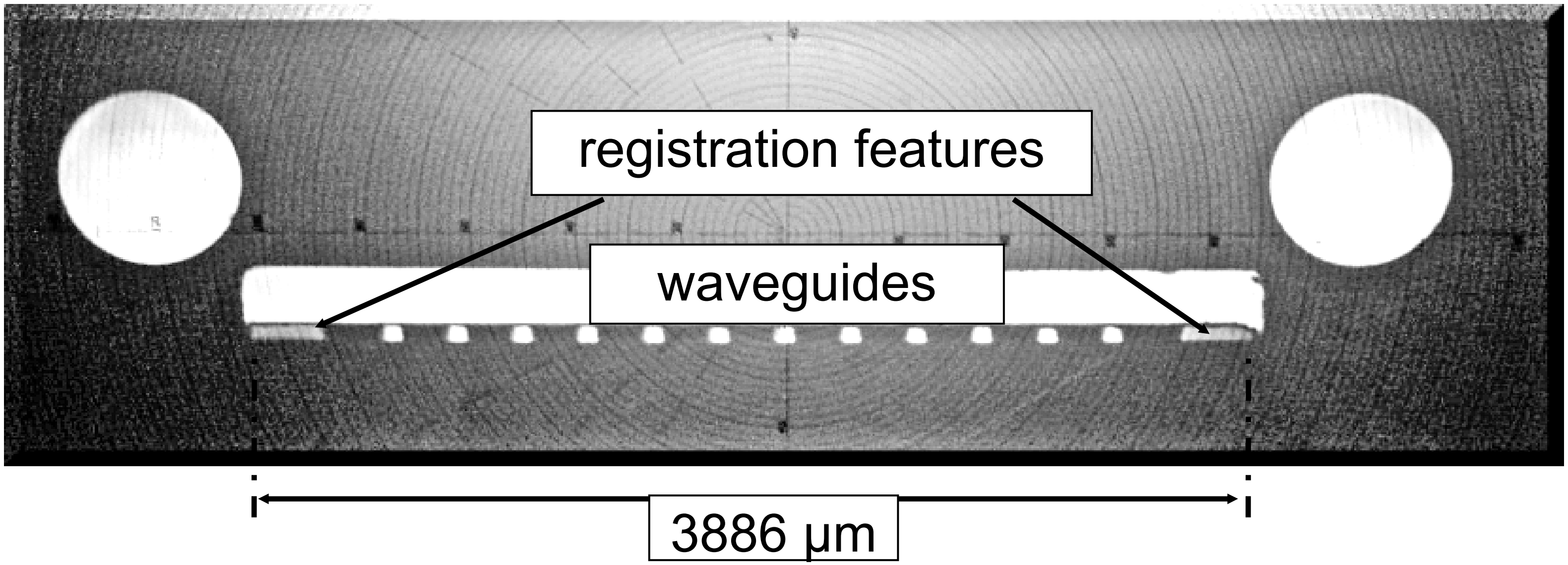




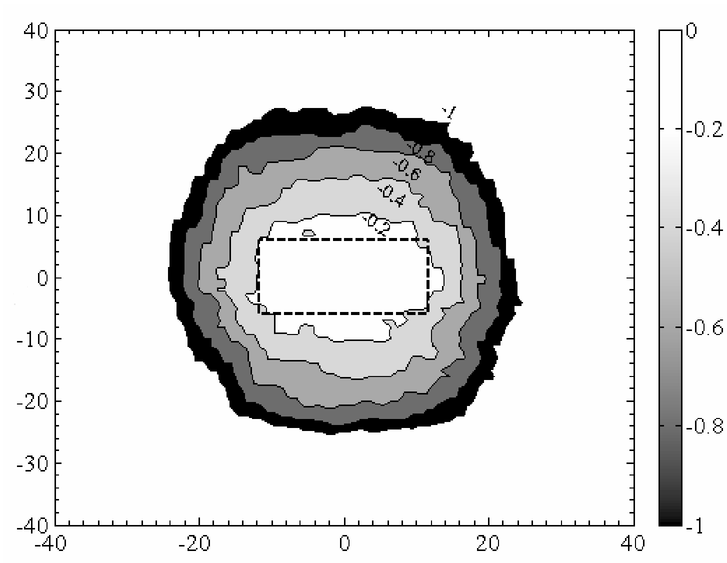
MT - Socket interposer on the top of backplane



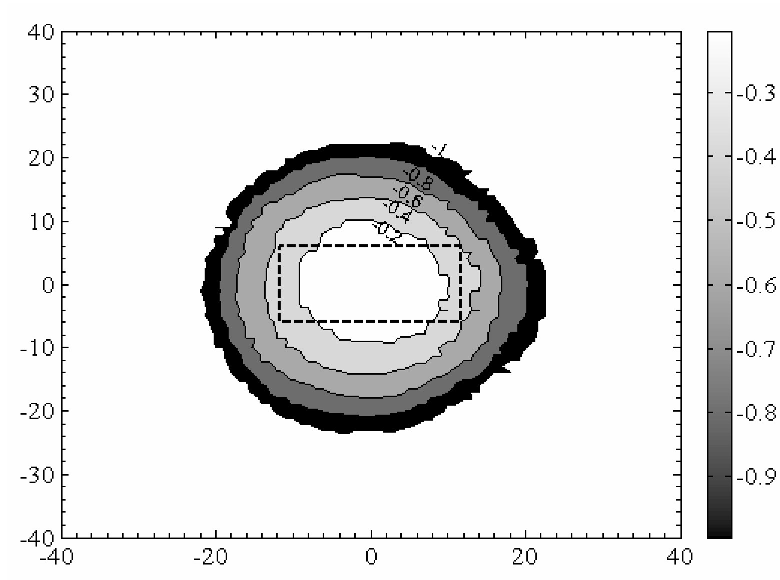
Actual alignment of the component



Contour map of VCSEL and PD misalignment



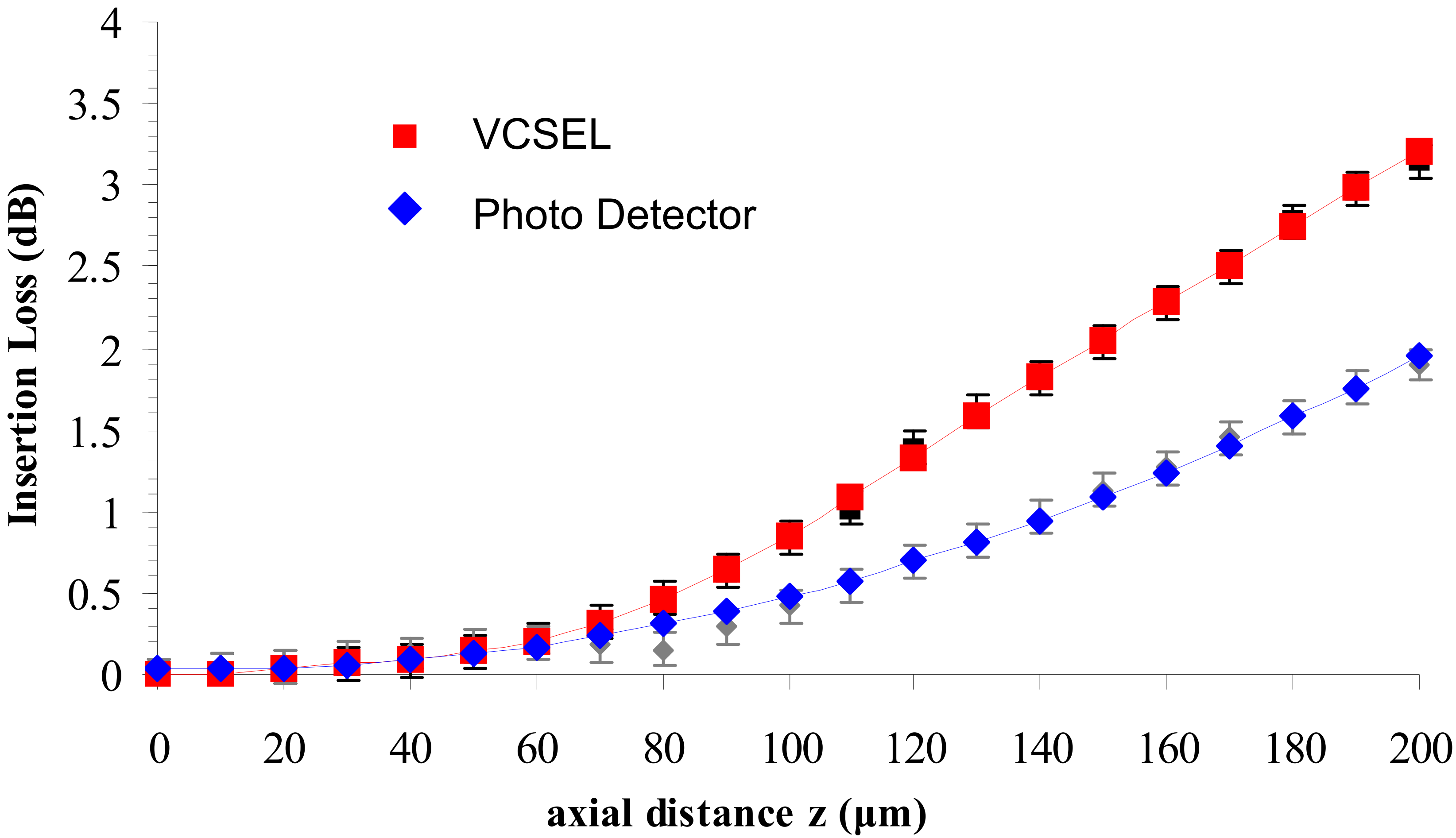
(a) Contour map of relative insertion loss compared to the maximum coupling position for VCSEL misalignment at z = 0.



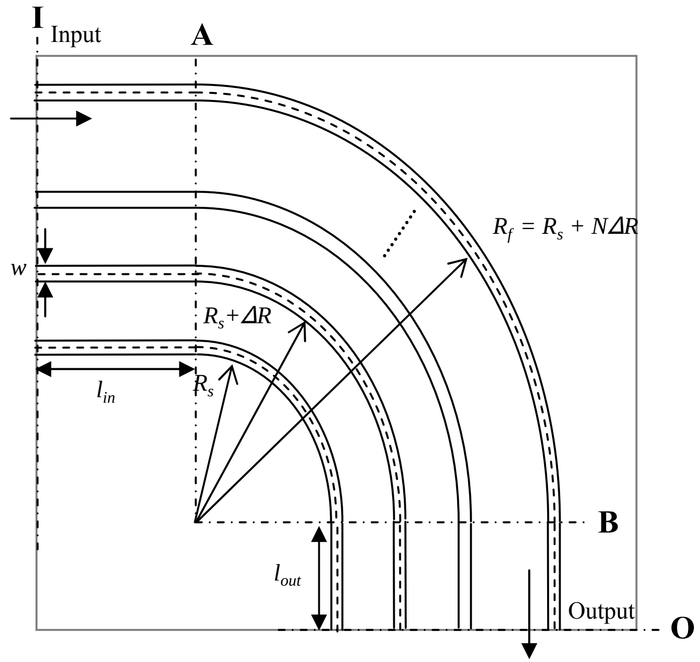
(b) Same for PD misalignment at *z* = 0. Resolution step was *Δx* = *Δy* = 1 μm.

- Dashed rectangle in the middle of the maps corresponds to 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

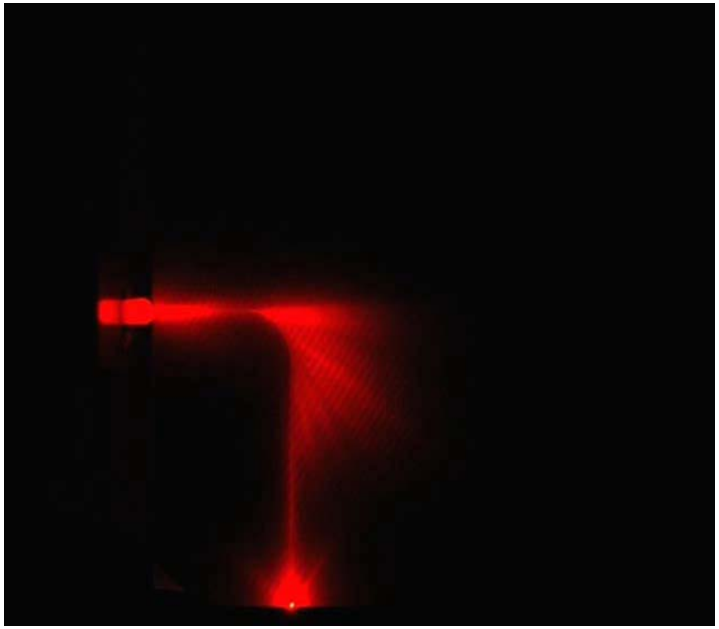
Relative insertion loss of VCSEL and pd as they move away from the OPCB waveguides



Transition loss



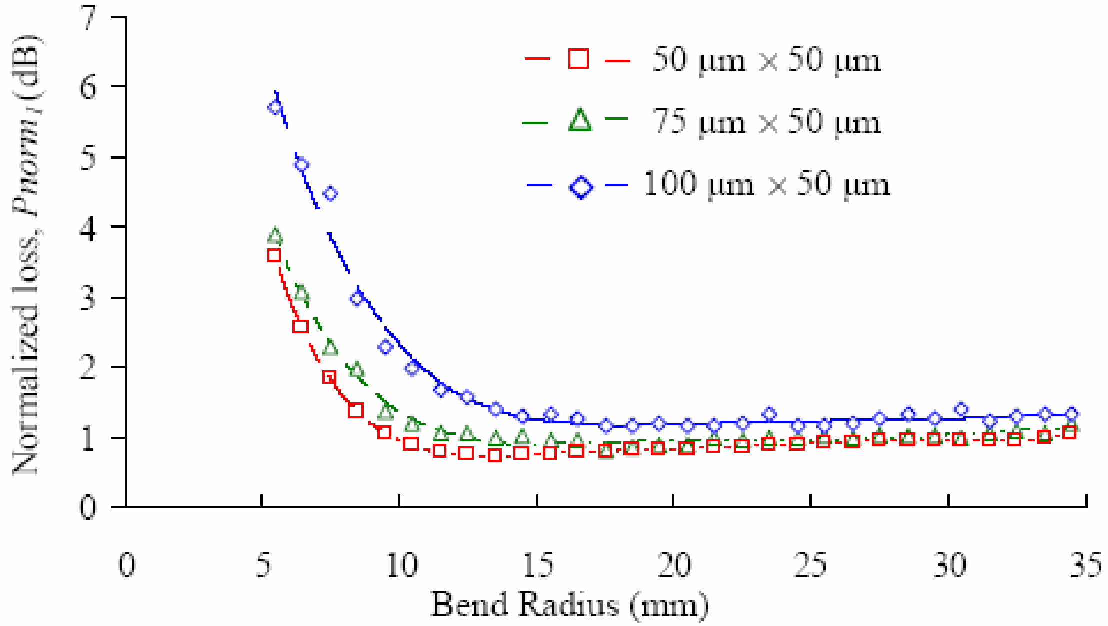
Schematic diagram of one set of curved waveguides.



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

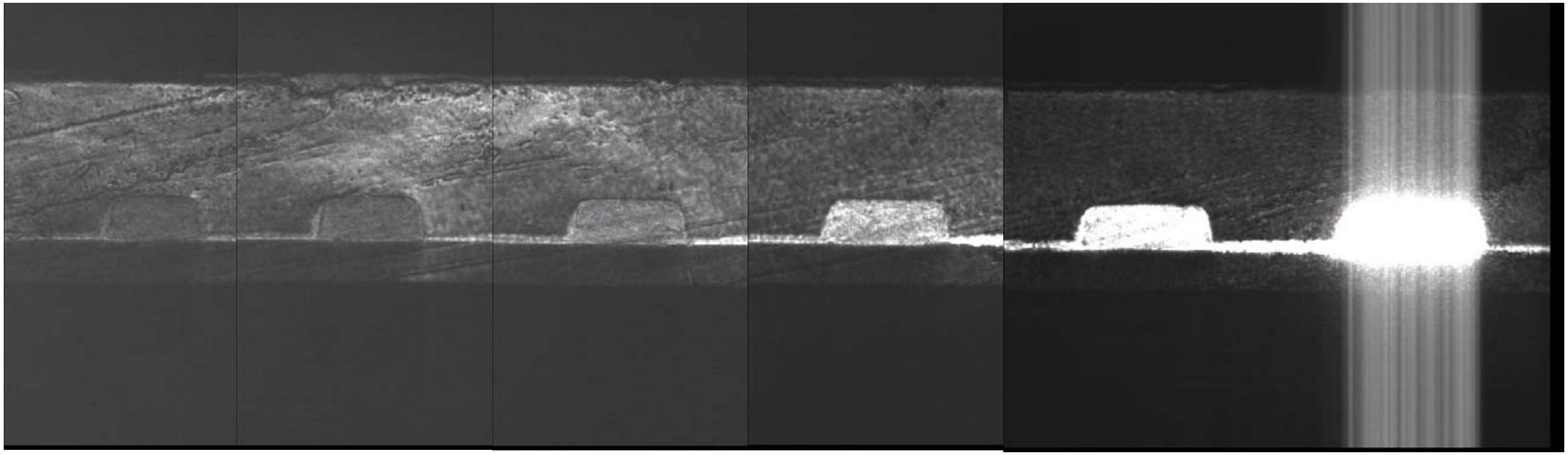
- Radius *R*, varied between 5 mm < *R* < 35 mm, *ΔR* = 1 mm
- Light lost due to scattering, transition loss, bend loss, and reflection and back-scattering
- Illuminated by a MM fiber with a red-laser.

Loss of waveguide bends as a function of bend radius



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

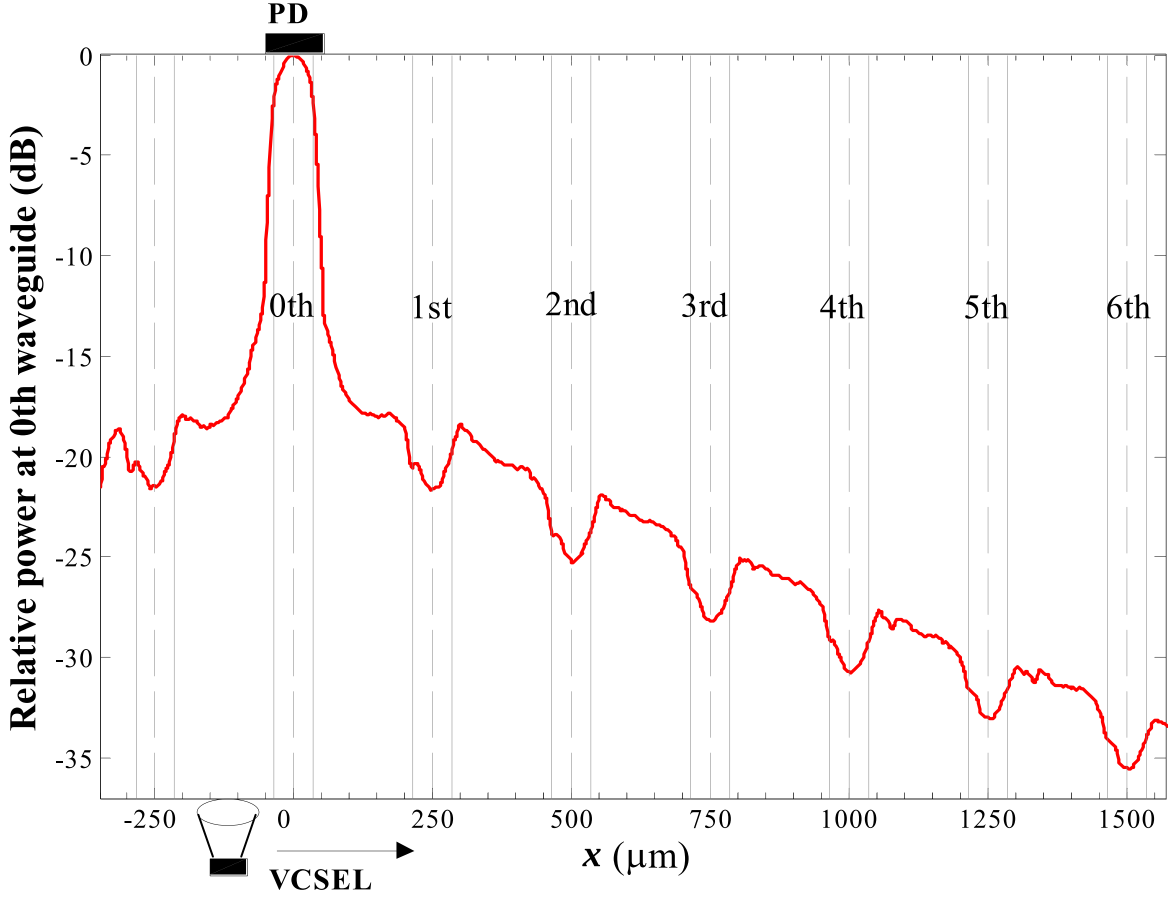
Crosstalk in chirped waveguide array



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

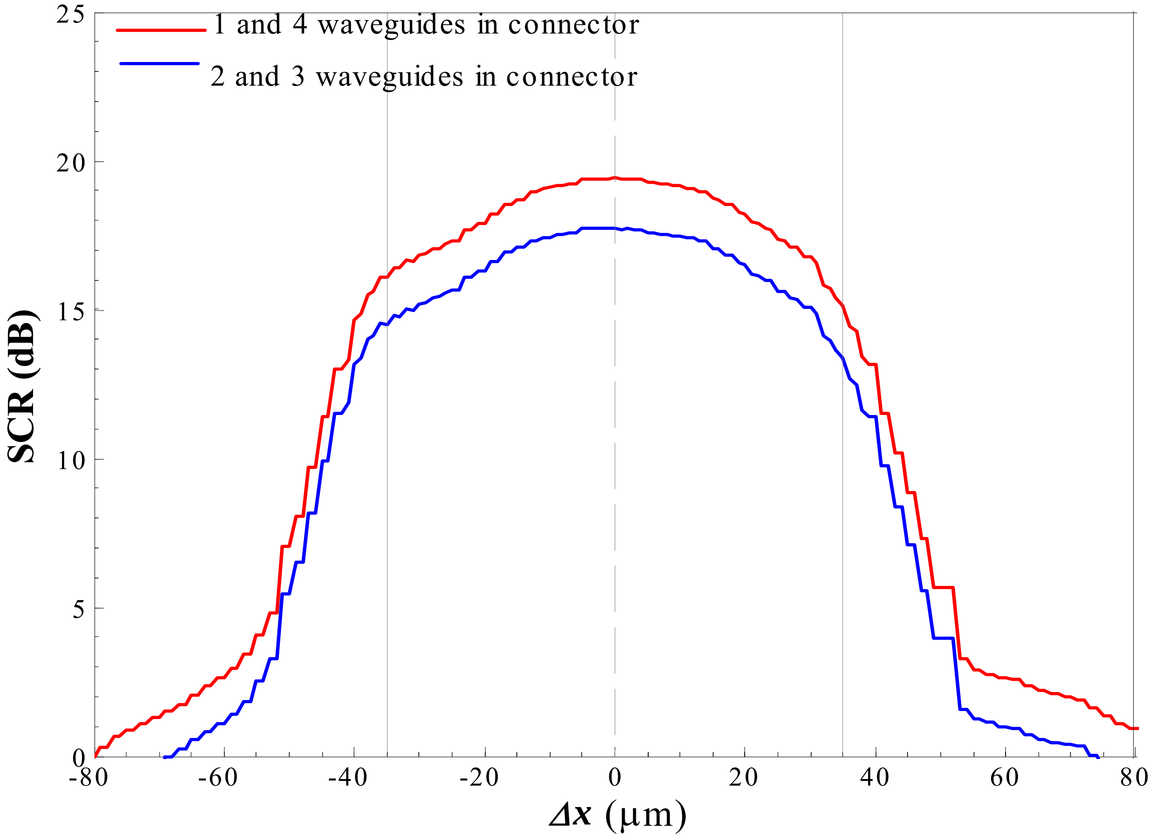
- Light launched from VCSEL imaged via a GRIN lens into 50 µm x 150 µm waveguide
- Photolithographically fabricated chirped waveguide array
- Photomosaic with increased camera gain towards left

Crosstalk measurement 1



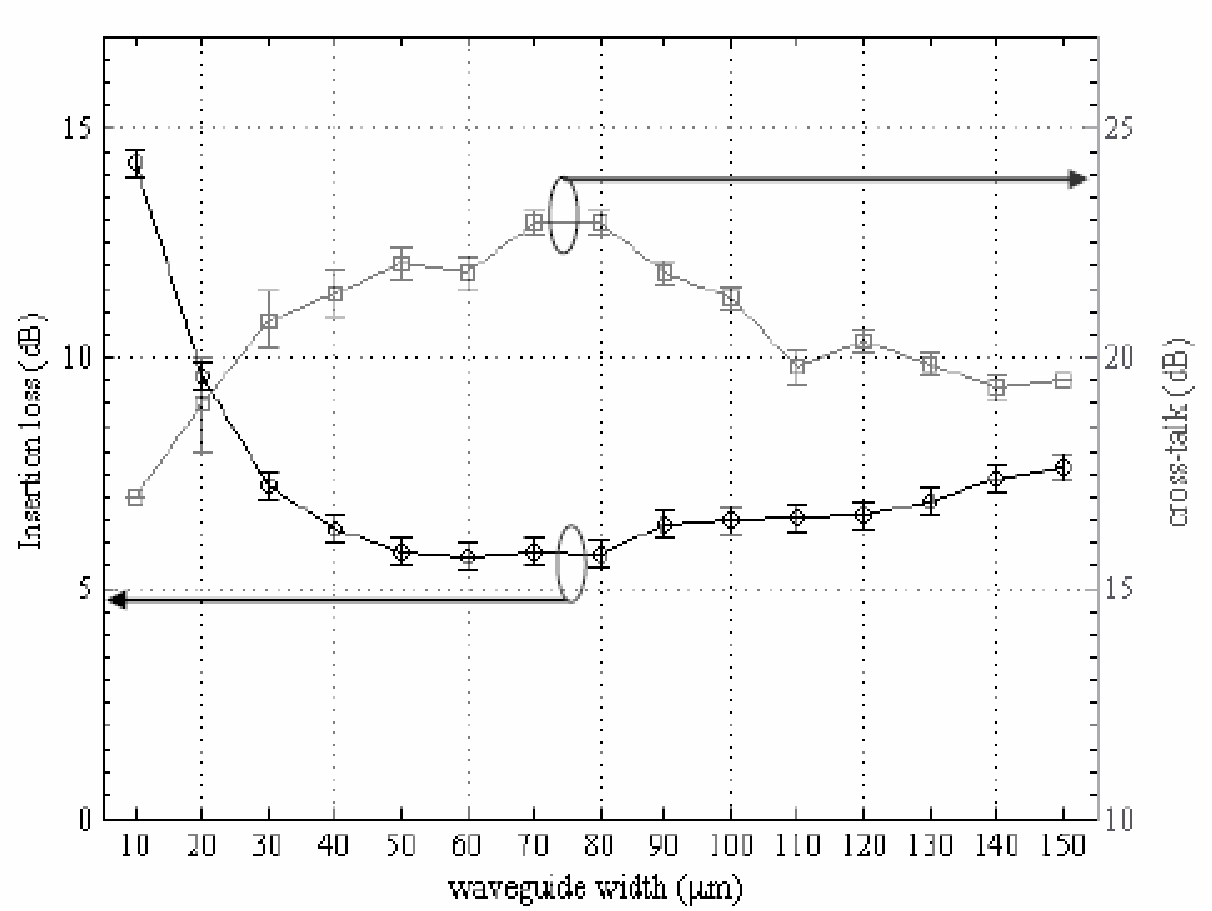
Power received at the end of 0th waveguide as a function of the lateral distance of the VCSEL from its center. The boundaries and the centers of the waveguides on the backplane are marked. In the cladding power drops at a rate of 0.011 dB/μm

Crosstalk measurement 3



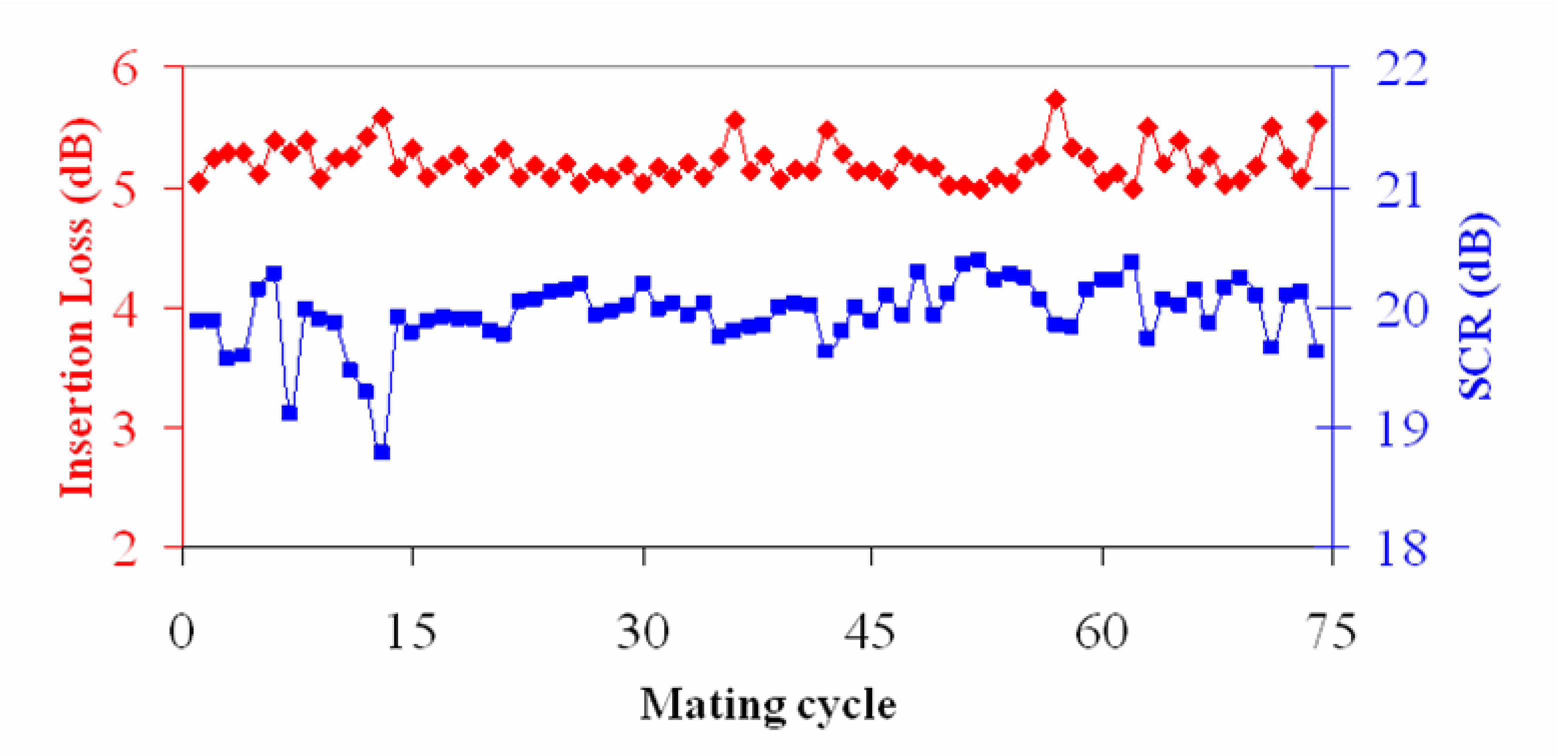
SCR experienced by waveguides number 1 and 4 and of waveguides number 2 and 3 from the array of four in the connector if all are in use. Dashed-dot lines determine the boundaries of the maximum expected cross-talk based on current connector tolerances.

Insertion Loss and cross-talk



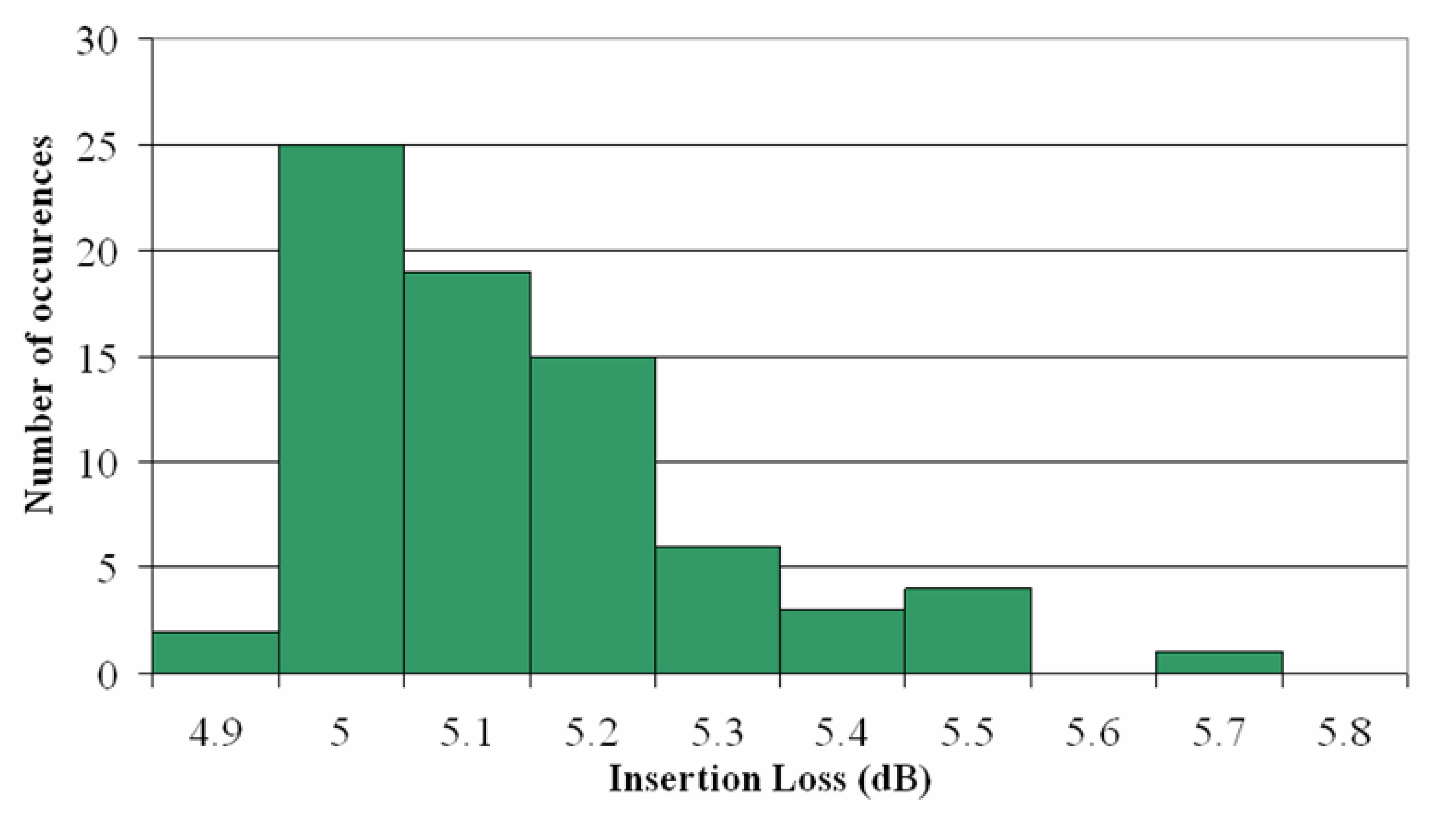
6~7dB for a 70 μm width waveguide

Stability testing of the MT – socket interposer 1



Insertion loss and signal to cross-talk (SCR) as a function of mating cycle for 75 engagements.

Stability testing of the MT – socket interposer 1

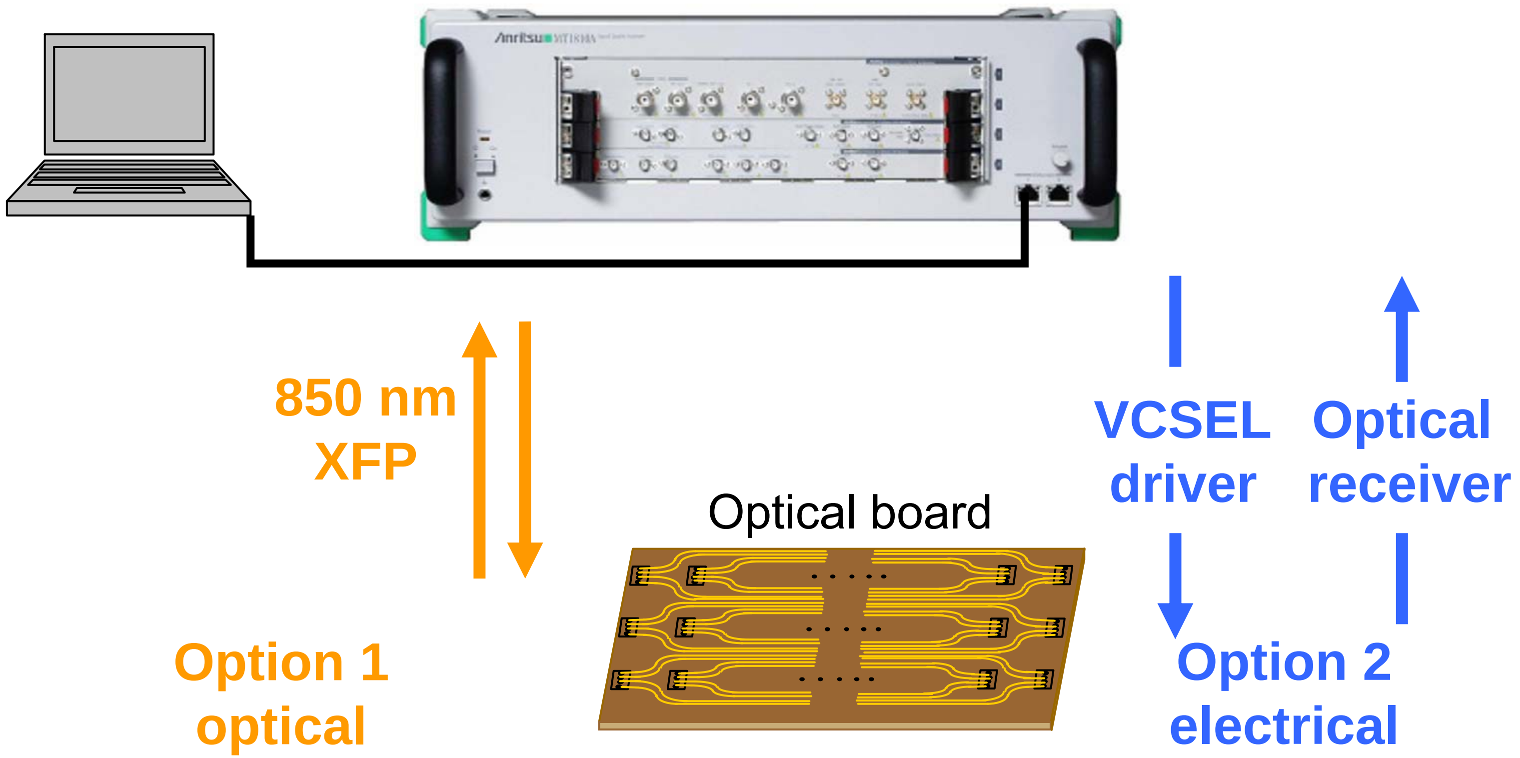


Histogram of insertion loss

Measurement Challenges for Optical Printed Circuit Boards – Communications Measurements

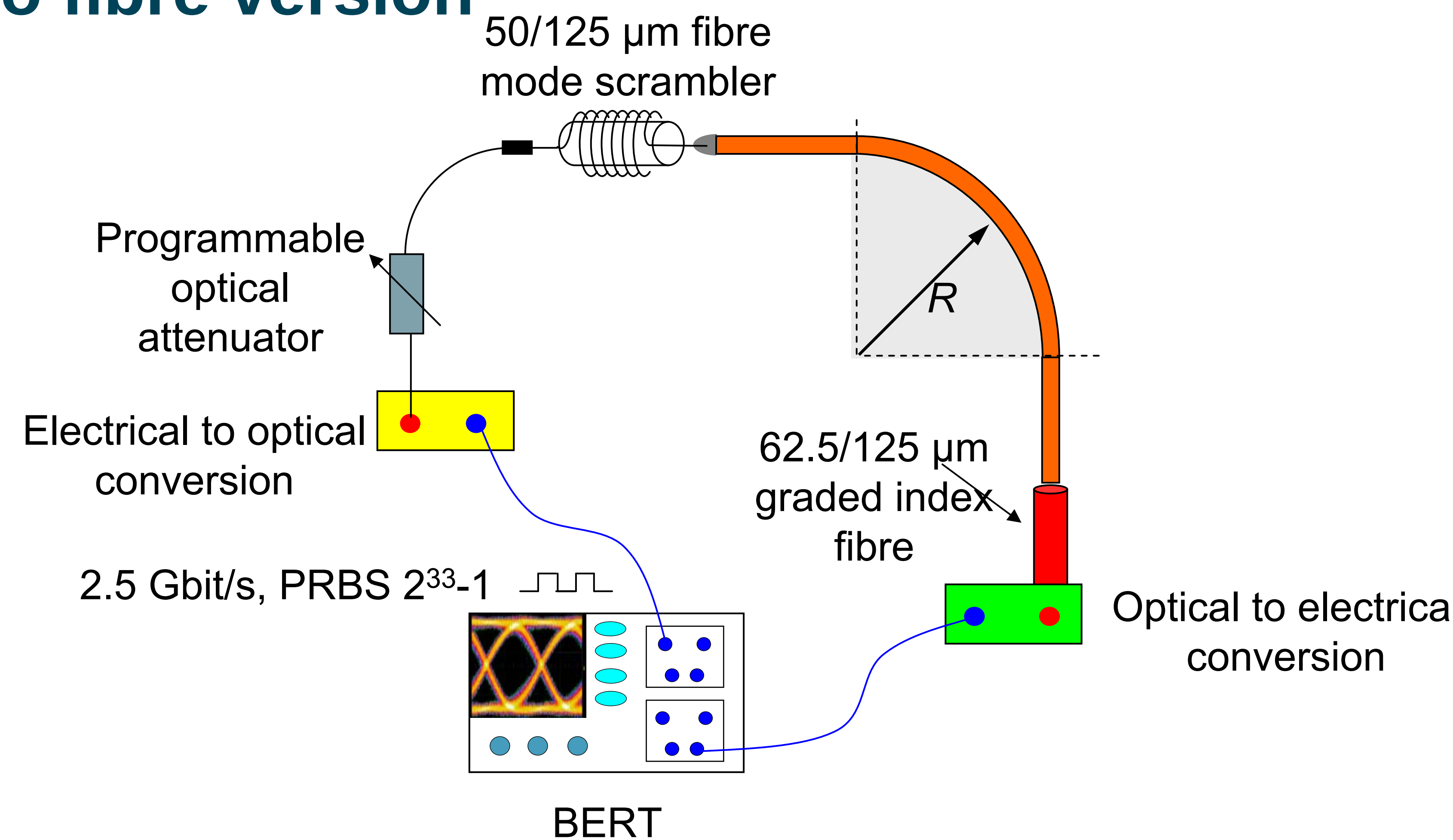
- Bit Error Rate for random bit streams
- Bit Error Rate for Ethernet protocol frames
- Eye Diagram
  - Jitter, Noise
- Modulation Transfer Function – Bandwidth

Measurement system for 10 Gbit/s device

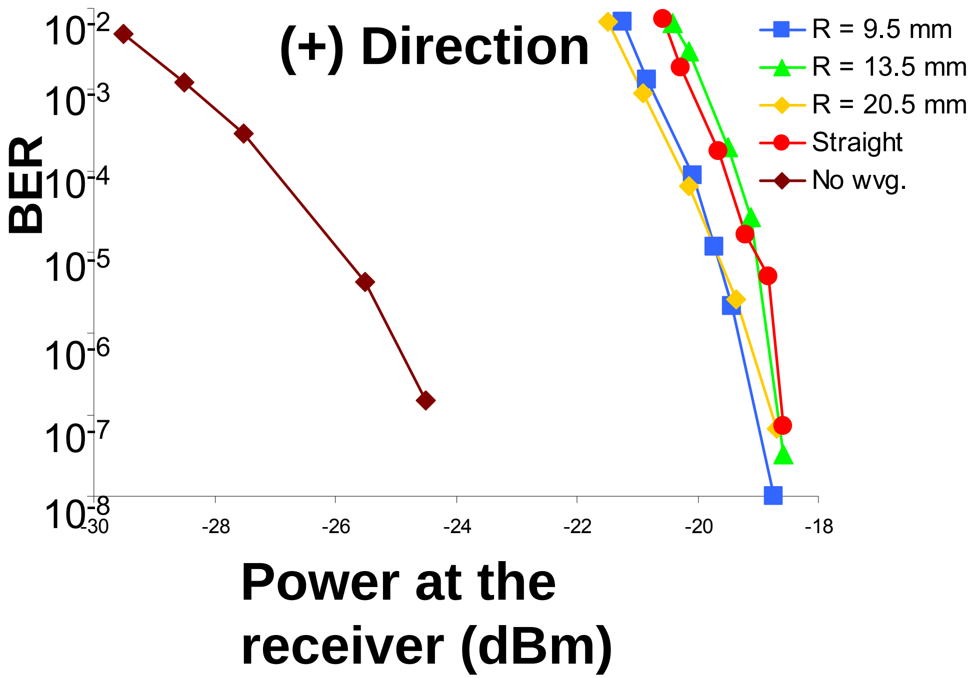


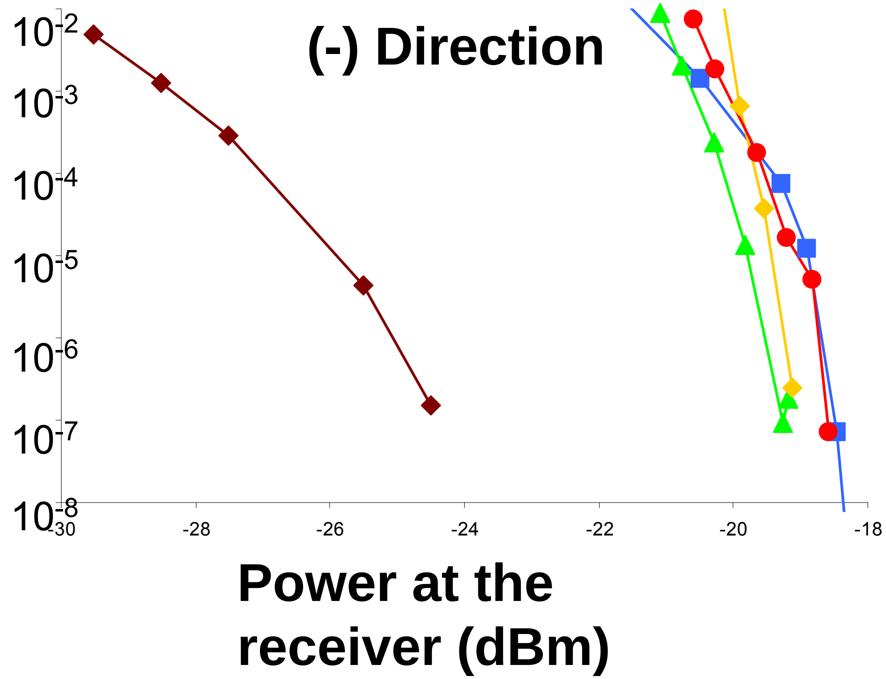
- Operating bit rate 9.95 to 11.10 Gbit/s
- Power -4.0 dBm to -1.08 dBm
- Wavelength range 840 nm to 860 nm

Bit Error Rate Measurement System – Fibre to fibre version



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





CHARACTERISATION SETUP

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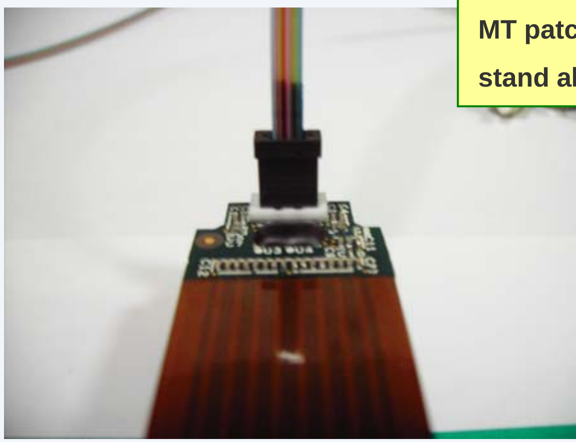
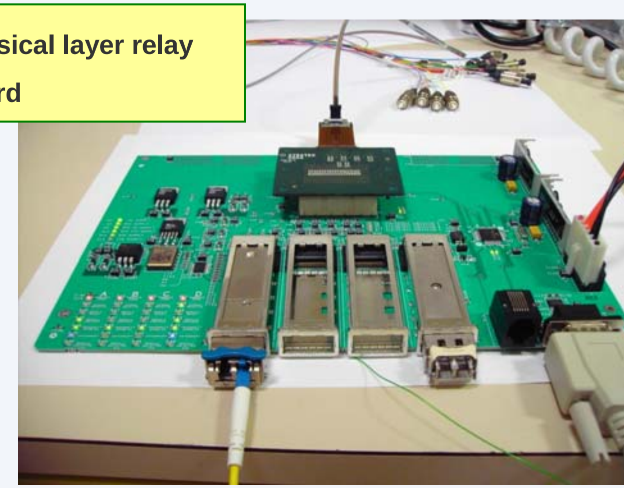
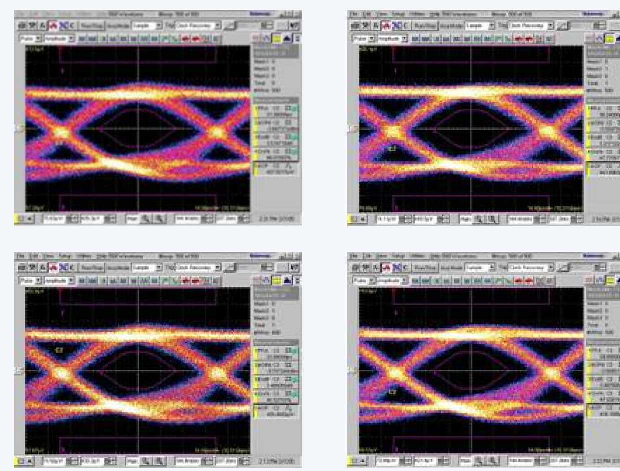
MT patchcord for stand alone testing



Physical layer relay board





- Test traffic: 10 GbE LAN (10.3 Gbps)
- VCSEL bias current: 11.91 mA
- VCSEL modulation current: 9.8 mA
- Divergence: 25°
- Output optical power: 0.43 mW
- Average optical jitter: 31.2 ps (Pk – Pk)

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TEST AND CHARACTERISATION

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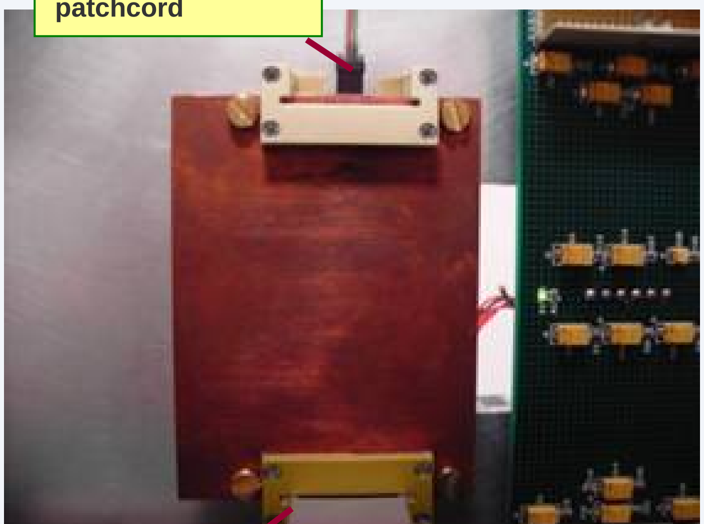
Arrangement:

Active connector – waveguide - patchcord

Multimode MT fibre patchcord



Active prototype connector

Optical Coupling Characterisation

Test traffic: 10 GbE LAN (10.3 Gbps)

Wavelength: 850 nm

Reference Signal – No Waveguide

Jitter : 0.34 UI

Relative Loss: 0 dB

10 cm Waveguide with Isapropanol

Jitter 0.36 UI

Relative Loss 4.5 dB

10 cm Waveguide – Diced and Polished

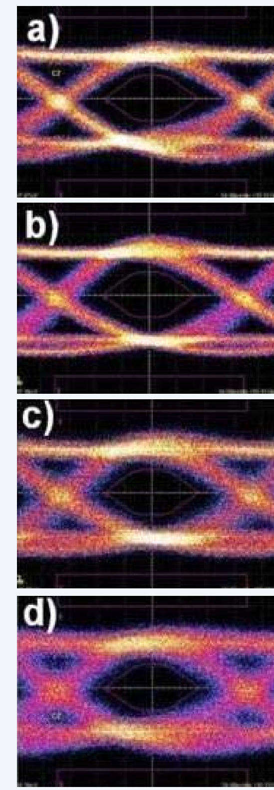
Jitter 0.56 UI

Relative Loss 6.9 dB

10 cm Waveguide – Diced Only

Jitter 0.89 UI

Relative Loss 7.9 dB



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University Acknowledgements

- **University College London (UCL):** David R. Selviah, Kai Wang, Ioannis Papakonstantinou, Michael Yau, Guoyu Yu, F. Anibal Fernández,
- **Heriot-Watt University:** Andy Walker, Aongus McCarthy, Himanshu Suyal, Mohammad Taghizadeh
- **Loughborough University:** David Hutt, Paul Conway, Karen Williams, Shefiu Zakariyah, John Chappell

Conclusions

- Measurement Challenges for Optical Printed Circuit Boards
  - Polymer Formulation
  - Physical Measurements
  - Optical Measurements
  - Communications Measurements