Polymer Wave Guide Optical Interconnect Manufacturing

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Outline

- Electronic versus Optical interconnects
- The OPCB project
- OPCB University Research Overview
  - Heriot Watt
  - Loughborough
  - UCL
- System Demonstrator
Copper Tracks versus Optical Waveguides for High Bit Rate Interconnects

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

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

- Reconfigurable Network Interconnections
- RF/EO Sensors & comms data
- High Bandwidth Signals

Aircraft utilities

Signal concentrator

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

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

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

- Out-of-plane connection
  - 45 mirrors
  - Chip to chip connection possible
Exxelis
Polymer supply and photolithography

Cadence
PCB design tools and rules

Dow Corning
Polymer supply and photolithography

Heriot-Watt University
Polymer formulation
Supply of laser written waveguides

UCL
Optical modelling
Waveguide design rules
Optical measurements

NPL
Physical Measurements

Loughborough University
Laser ablation and ink-jet printing of waveguides

Stevenage Circuits Ltd
Sample PCBs, dry film
CAD conversion, laser work

End Users

Xyratex
Network storage interconnect

BAE Systems
In-flight interconnect

Renishaw Systems
Precision measurement
• **Slotted baseplate** mounted vertically over translation, rotation & vertical stages; components held in place with magnets

• By using two opposing 45° beams we minimise the amount of substrate rotation needed
Writing sharply defined features
– flat-top, rectangular laser spot

Gaussian beam diameter = 1.1 mm

Imaging system / lenses

60 μm square aperture

TEM\(_{00}\)

Gaussian Beam

Imaged aperture

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 45° surfaces
Waveguide terminated with 45-deg mirror

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

Microscope image looking down on mirror coupling light towards camera
Current Results

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

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

(Substrate: FR4 with polymer undercladding)
Large Board Processing: Writing

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

- 600 x 300 mm travel
- Requires a minimum of 700 x 1000 mm space on optical bench
- Height: ~250 mm
- Mass:
  - 300 mm: 21 kg
  - 600 mm: 33 kg
- Vacuum tabletop
The spiral was fabricated using a Gaussian intensity profile at a writing speed of 2.5 mm/s on a 10 x 10 cm lower clad FR4 substrate. Total length of spiral waveguide is \(~1.4\) m. The spiral was upper cladded at both ends for cutting.
Laser Ablation of Optical Waveguides

- **Research**
  - Straight waveguides
  - 2D & 3D integrated mirrors

- **Approach**
  - Excimer laser – Loughborough
  - CO₂ 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
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

**System**
- 355 nm (UV) Pulsed laser with 60 ns pulse width and Gaussian beam (TEM$_{00}$) or “Tophat” profile at Stevenage Circuits Ltd.

**Process**
- Photochemically-dominated ablation process.

**Waveguide quality**
- Minimum Heat Affected Zone
- Propagation loss measurement underway
Machining of Optical Polymer with Excimer Laser

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

Machined trenches  Waveguide structure
Inkjetting as a Route to Waveguide Deposition

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

Deposit Lower Cladding

Deposit Core

Deposit Upper Cladding
Challenges of Inkjet Deposition

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

![Viscosity vs Temperature Graph]

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

A 2 x 2 array of inkjet printed drops
Changing Surface Wettability

Contact Angles

Core material on cladding

Core material on modified glass surface (hydrophobic)

Large wetting - broad inkjetted lines

Reduced wetting – discrete droplets

Identical inkjetting conditions - spreading inhibited on modified surface
Towards Stable Structures

Stable line structures with periodic features

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

A balance between wettability, line stability and adhesion
Waveguide components and measurements

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

- Loss
- Crosstalk
- Misalignment tolerance
- Surface Roughness
- Bit Error Rate, Eye Diagram
Optical Power Loss in 90° Waveguide Bends

Schematic diagram of one set of curved waveguides.

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

Light through a bent waveguide of $R = 5.5 \text{ mm} – 34.5 \text{ mm}$

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

\[ w = 50 \, \mu m, \ R = 13 \, mm \]

(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

- 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

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

6~7 dB for a 70 μm width waveguide
Bit error rate for laterally misaligned 1550 nm 2.5 Gb/s DFB laser

![Graph showing BER vs. Power at the receiver for different radii and directions.](Image)

**(+):** Direction

**(-):** Direction

*Power at the receiver (dBm)*

-30 -28 -26 -24 -22 -20 -18

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Contour map of VCSEL and PD misalignment

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

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

(b) Same for PD misalignment at $z = 0$. Resolution step was $\Delta x = \Delta y = 1 \, \mu\text{m}$.
Coupling Loss for VCSEL and PD for misalignments along optic axis

- VCSEL
- Photo Detector

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Fabrication Techniques and Waveguides Samples

Straight waveguides – Optical InterLinks

90° Crossings – Dow Corning

90° Crossings – Heriot Watt University

50° Crossings – Exxelis

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Photolithographic Fabrication of Waveguides

UV Exposure
Lower cladding
FR4

UV Exposure
Mask
Spacer
Core layer
FR4

Waveguide
FR4

UV Exposure
Upper cladding
FR4
Optical Loss Measurement

850 nm VCSEL

0 dBm

50/125 µm step index fibre

Index matching fluid

70 µm pinhole

mode scrambler

R

Integrating sphere photodetector

nW Power Meter

-1.63 dBm

-1.63 dBm

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VCSEL Array for Crosstalk Measurement

**Source:** Microsemi Corporation

**Source:** ULM Photonics GmbH

**Source:** GRINTech GmbH

MT compatible interface
• 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 ($\theta$), $L_c=1.0779 \cdot \theta^{-0.8727}$
### Loss of Waveguide Bends

#### Table

<table>
<thead>
<tr>
<th>Width (μm)</th>
<th>Optimum Radius (mm)</th>
<th>Maximum Power (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>13.5</td>
<td>-0.74</td>
</tr>
<tr>
<td>75</td>
<td>15.3</td>
<td>-0.91</td>
</tr>
<tr>
<td>100</td>
<td>17.7</td>
<td>-1.18</td>
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System Demonstrator

Fully connected waveguide layout using design rules

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## Power Budget

<table>
<thead>
<tr>
<th>Input power (dBm/mW)</th>
<th>-2.07 / 0.62</th>
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</thead>
<tbody>
<tr>
<td><strong>Bend 90°</strong></td>
<td></td>
</tr>
<tr>
<td>Radii (mm)</td>
<td></td>
</tr>
<tr>
<td>15.000</td>
<td>15.250</td>
</tr>
<tr>
<td>15.500</td>
<td>15.725</td>
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<tr>
<td>16.000</td>
<td>16.250</td>
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<tr>
<td>Loss per bend (dB)</td>
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</tr>
<tr>
<td>0.94</td>
<td>0.91</td>
</tr>
<tr>
<td>0.94</td>
<td>0.94</td>
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<tr>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td><strong>Crossings</strong></td>
<td></td>
</tr>
<tr>
<td>Crossing angles (°)</td>
<td></td>
</tr>
<tr>
<td>22.27</td>
<td>29.45</td>
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<tr>
<td>36.23</td>
<td>42.10</td>
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<tr>
<td>47.36</td>
<td></td>
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<tr>
<td>Loss per crossing (dB)</td>
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</tr>
<tr>
<td>0.078</td>
<td>0.056</td>
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<tr>
<td>0.047</td>
<td>0.041</td>
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<tr>
<td>0.037</td>
<td></td>
</tr>
<tr>
<td>Min. detectable power (dBm)</td>
<td>-15 / 0.03</td>
</tr>
<tr>
<td>Min. power no bit error rate</td>
<td>-12 / 0.06</td>
</tr>
</tbody>
</table>
Demonstrator Dummy Board
The Shortest Waveguide Illuminated by Red Laser
Waveguide with 2 Crossings Connected 1\textsuperscript{st} to 3\textsuperscript{rd} Linecard Interconnect
Output Facet of the Waveguide Interconnection
Data storage protocol and form factor trends

Disk drive form factors decreasing

- 3.5” HDD
- 2.5” HDD
- 2.5” SSD
- 1.8” SSD

Data storage interconnect speeds increasing

- 3Gb/s SAS
- 6Gb/s SAS
- 12Gb/s SAS

Source: SCSI Trade Association Sep 08

www.scsita.org
Design and performance constraints
Hybrid Electro-Optical Printed Circuit Board

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

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Polymer optical waveguides on optical layer

- Optical connector site
- Compact PCI slot for single board computer
- Compact PCI slots for line cards
High Speed Switching Line Card

Array connector for pluggable active optical connector

Compact PCI bus connector

SMP connector sites

PCI Bridge

FPGA

8 x 8 Crosspoint switch

XFP ports

Transceiver programming port
Active optical backplane connector
Optical backplane connection architecture

Orthogonal docking

- Lens Interface
- Backplane
- Connector housing
- Parallel optical transceiver
- Copper layers
- FR4 layers
- Optical layer
Optical backplane connection architecture

Butt-coupled in-plane connection

Single waveguide illuminated
Parallel optical transceiver

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

Parallel optical transceiver

Connector module

Spring loaded platform

Microcontroller
Connector engagement mechanism

Docked

Cam followers

Ramped plug

Cam track
Peripheral test cards

- Optical connector site
- C-PCI connector
- PCI bridge
- Array connector
- 8 x 8 crosspoint switch
- FPGA
- XFP front end
Demonstration platform

- Compact PCI chassis
- Electro-optical midplane
- Pluggable optical connector
- Peripheral test card
- Single board computer
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

Xyratex Optical Research and Development
R. Pitwon
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