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
On-board Platform Applications

Reconfigurable Network Interconnections

- Core processor
- RF/EO Sensors & comms data
- High Bandwidth Signals
- Aircraft utilities
- Signal concentrator
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

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 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

TEM₀₀

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: \(~75 \mu m / s\)
- Optical power: \(~100 \mu W\)
- 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

OPTICAL INPUT
Current Results

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

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

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

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

- 600 x 300 mm travel
- Requires a minimum of 700 x 1000 mm space on optical bench
- Height: ~250 mm
- Mass:
  - 300 mm: 21 kg
  - 600 mm: 33 kg
- Vacuum tabletop
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 \(~1.4\,\text{m}\). 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

**Side view of machined trench**

**Waveguides (side view)**
UV Nd:YAG machining in collaboration with Stevenage Circuits Ltd

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

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**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](image1)

![Waveguide structure](image2)
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
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

- 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.
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 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

6~7dB 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 (+) and (-) Directions](image)

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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 dB, corresponded to $x = 0$, $y = 0$, $z = 0$.

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

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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

850 nm VCSEL

50/125 μm step index fibre

mode scrambler

Index matching fluid

70 μm pinhole

Integrating sphere photodetector

nW Power Meter

0 dBm

-1.63 dBm

-1.63 dBm
VCSEL Array for Crosstalk Measurement

Source: Microsemi Corporation

Source: ULM Photonics GmbH

Source: GRINTech GmbH

MT compatible interface

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• 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 $90^\circ$ and at an Arbitrary Angle, $\theta$
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 ($\theta$), $L_c = 1.0779 \cdot \theta^{-0.8727}$

<table>
<thead>
<tr>
<th>Crossings angle (degree)</th>
<th>Power drops (dB)</th>
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<tbody>
<tr>
<td>20</td>
<td>0.08</td>
</tr>
<tr>
<td>90</td>
<td>0.023</td>
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\[
y = 1.0779x^{-0.873}
\]
Loss of Waveguide Bends

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

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System Demonstrator

Fully connected waveguide layout using design rules
# Power Budget

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<tr>
<th>Input power (dBm/mW)</th>
<th>-2.07 / 0.62</th>
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<tbody>
<tr>
<td><strong>Bend 90°</strong></td>
<td></td>
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<tr>
<td>Radii (mm)</td>
<td>15.000</td>
</tr>
<tr>
<td></td>
<td>15.250</td>
</tr>
<tr>
<td></td>
<td>15.500</td>
</tr>
<tr>
<td></td>
<td>15.725</td>
</tr>
<tr>
<td></td>
<td>16.000</td>
</tr>
<tr>
<td></td>
<td>16.250</td>
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<tr>
<td>Loss per bend (dB)</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>0.91</td>
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<tr>
<td></td>
<td>0.94</td>
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<td>0.95</td>
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<td></td>
<td>0.95</td>
</tr>
<tr>
<td><strong>Crossings</strong></td>
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<tr>
<td>Crossing angles (°)</td>
<td>22.27</td>
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<td>29.45</td>
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<td></td>
<td>36.23</td>
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<td></td>
<td>42.10</td>
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<td>47.36</td>
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<tr>
<td>Loss per crossing (dB)</td>
<td>0.078</td>
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<td>0.056</td>
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<td></td>
<td>0.047</td>
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<td></td>
<td>0.041</td>
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<td></td>
<td>0.037</td>
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<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>
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Demonstrator Dummy Board
The Shortest Waveguide Illuminated by Red Laser
Waveguide with 2 Crossings Connected 1<sup>st</sup> to 3<sup>rd</sup> 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
Research and Development Overview  |  Richard Pitwon

High Speed Switching Line Card

- Compact PCI bus connector
- PCI Bridge
- XFP ports
- FPGA
- SMP connector sites
- 8 x 8 Crosspoint switch
- Array connector for pluggable active optical connector
- Transceiver programming port

Compact PCI bus connector

XFP ports

8 x 8 Crosspoint switch

Array connector for pluggable active optical connector

SMP connector sites
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

- Spring loaded platform
- Microcontroller

Connector module
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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