The IeMRC Opto-PCB Manufacturing Project

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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

RF/EO Sensors & comms data

High Bandwidth Signals
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
- 2.9 years into the 3 year, £1.3 million project
Integration of Optics and Electronics

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

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

Cadence
PCB design tools and rules

Dow Corning
Polymer supply and photolithography

Heriot-Watt University
Polymer formulation
Supply of laser written waveguides

UCL
Optical modelling
Waveguide design rules
Optical measurements

Loughborough University
Laser ablation and ink-jet printing of waveguides

NPL
Physical Measurements

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

End Users

Xyratex
Network storage interconnect

BAE Systems
In-flight interconnect

Renishaw
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

TEM$_{00}$

60 µm square 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

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 \(~1.4\) 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](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
Challenges of Inkjet Deposition

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

Core material on cladding

Core material on modified glass surface (hydrophobic)

Large wetting - broad inkjetted lines

Identical inkjetting conditions - spreading inhibited on modified surface

Reduced wetting – discrete droplets
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 $R = 5.5 \text{ mm} – 34.5 \text{ mm}$
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

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

(+/-) Direction

Power at the receiver (dBm)

BER

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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

- 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 down
Lower cladding
FR4

UV Exposure down
Mask
Spacer
Core layer
FR4

Waveguide
FR4

UV Exposure down
Upper cladding
FR4

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Optical Loss Measurement

- 850 nm VCSEL
- 0 dBm
- 50/125 μm step index fibre
- Mode scrambler
- Index matching fluid
- 70 μm pinhole
- Integrating sphere photodetector
- nW Power Meter
- -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

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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° and at an Arbitrary Angle, θ
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: Optimum Radii and Maximum Power

<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>
</tr>
</tbody>
</table>

### Graph:
- **Bend radius (mm):** 0 to 35
- **Transmitted power (dB):** -1 to -7
- **Widths:** 50 μm × 50, 75 μm × 50, 100 μm × 50
- **Recommended:** 50 μm × 50
- **Used:** 75 μm × 50, 100 μm × 50

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Fully connected waveguide layout using design rules
## Power Budget

<table>
<thead>
<tr>
<th>Input power (dBm/mW)</th>
<th>-2.07 / 0.62</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bend 90°</strong>&lt;br&gt;Radii (mm)</td>
<td>15.000</td>
</tr>
<tr>
<td>Loss per bend (dB)</td>
<td>0.94</td>
</tr>
<tr>
<td><strong>Crossings</strong>&lt;br&gt;Crossing angles (°)</td>
<td>22.27</td>
</tr>
<tr>
<td>Loss per crossing (dB)</td>
<td>0.078</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>
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
Backplane and Line Cards Orthogonal

- Lens Interface
- Backplane
- Connector housing
- Parallel optical transceiver
- Copper layers
- FR4 layers
- Optical layer
Butt-coupled connection approach without 90° deflection optics
**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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- 12 electrical layers for power and C-PCI signal bus and peripheral connections
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- Dedicated point-to-point optical waveguide architecture
Parallel optical transceiver circuit
- Small form factor quad parallel optical transceiver
- Microcontroller supporting I²C interface
- Samtec “SEARAY™” open pin field array connector
- Spring loaded platform for optical engagement mechanism
- Custom heatsink for photonic drivers

Backplane connector module
- Samtec / Xyratex collaborate to develop optical PCB connector
- 1 stage insertion engagement mechanism developed
- Xyratex transceiver integrated into connector module
**Engagement process**

- Optical transceiver interface floats
- Backplane receptacle “funnels” connector
- Cam followers force optical interface up
- Optical transceiver lens butt-couples to backplane lens
Research and Development Overview | Richard Pitwon
Demonstrator with Optical Interconnects
Demonstration Assembly

- Electro-optical backplane
- Pluggable optical backplane connectors
- Compact PCI chassis
- High speed switch line cards
- XFP front end
- Single board computer

Research and Development Overview | Richard Pitwon
GUI control interface

- Remote admin
- XFP control
- Crosspoint switch configuration
- Full transceiver control (VCSEL/PIN settings)
- Selectable between any line card in system
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