Optical printed circuit board and connector technology

Dr David R. Selviah
Department of Electronic and Electrical Engineering,
University College London, UCL, UK,
d.selviah@ee.ucl.ac.uk

And

Richard C. A. Pitwon
Xyratex Technology Ltd
Havant, UK
rpitwon@xyratex.com
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

High Bandwidth Signals

RF/EO Sensors & comms data

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
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
End Users

- Xyratex: Network storage interconnect
- BAE Systems: In-flight interconnect
- Renishaw: Precision measurement

\[ \text{Exxelis} \quad \text{Cadence} \quad \text{Dow Corning} \]

- Exxelis: Polymer supply and photolithography
- Cadence: PCB design tools and rules
- Dow Corning: Polymer supply and photolithography

\[ \text{Heriot-Watt University} \quad \text{UCL} \quad \text{Loughborough University} \]

- 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

\[ \text{NPL} \quad \text{Stevenage Circuits Ltd} \]

- NPL: Physical Measurements
- Stevenage Circuits Ltd: Sample PCBs, dry film, CAD conversion, laser work
- 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
Results with a Gaussian spot profile (2)

Laser-writing Parameters:
- Profile: Gaussian, 1 mm 1/e² TEM₀₀ beam with 40 mm EFL lens
- Optical power available: ~9 mW
- Cores written in air
- Variable writing speed

Approximate height of waveguide cores: 45 - 50 µm
Approximate width (µm)

Writing speed (mm/s) (Waveguide cores on a 125 µm pitch)
Results with an imaged circular aperture

Laser-writing Parameters:

- Profile: imaged aperture, 100 µm diameter, illuminated by Gaussian truncated at ~50% peak, 0.5 magnification onto writing plane
- Optical power available for writing: ~2 mW
- Cores written in air, on a 125 µm pitch

End-on view of back-illuminated guides

Speed: 10 mm/s

Speed: 25 mm/s
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
Test Structures

**Spirals:**
- x5, 250 μm pitch
- 700 mm long

**Curves:**
- x10, 250 μm pitch
- 170 mm long

** Straights:**
- x20, 125 μm pitch
- 100 mm long
The guides shown include two parallel spirals plus a number of “straight through” waveguides.

Each spiral has a total path length of ~650 mm.

Minimum bend radius is 16 mm (input/output regions & spiral reversal). Large radius is ~ 32 mm.

Spiral cores are on a 250 µm pitch, straight waveguides are on a 125 µm pitch.
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

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Waveguides (side view)

Machined trench

Ablated profile

FR4 layer

Side view of machined trench
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

![Graph showing viscosity vs. temperature]

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

![Image of a 2x2 array of inkjet printed drops]

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

Core material on cladding

Large wetting - broad inkjetted lines

Identical inkjetting conditions - spreading inhibited on modified surface

Core material on modified glass surface (hydrophobic)

Reduced wetting – discrete droplets

Contact Angles
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.

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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

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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
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

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

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Photolithographic Fabrication of Waveguides

- **UV Exposure**
  - Lower cladding
  - FR4
  - Mask
  - Spacer
  - Core layer
  - FR4

- **Waveguide**
  - FR4

- **UV Exposure**
  - Upper cladding
  - FR4

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Optical Loss Measurement

- 850 nm VCSEL
- 50/125 μm step index fibre
- Mode scrambler
- Index matching fluid
- 70 μm pinhole
- Integrating sphere photodetector
- 0 dBm
- -1.63 dBm

nW Power Meter

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VCSEL Array for Crosstalk Measurement

- PIN Array
  Source: Microsemi Corporation

- VCSEL Array
  Source: ULM Photonics GmbH

- GRIN Lens Array
  Source: GRINTech GmbH

MT compatible interface

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Design Rules for Inter-waveguide Cross Talk

- 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, $\theta$
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 ($\theta$), $L_c = 1.0779 \cdot \theta^{-0.8727}$

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Loss of Waveguide Bends

<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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</tbody>
</table>

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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>15.000</td>
</tr>
<tr>
<td>Loss per bend (dB)</td>
<td>0.94</td>
</tr>
<tr>
<td><strong>Crossings</strong></td>
<td></td>
</tr>
<tr>
<td>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>
Demonstrator Dummy Board
The Shortest Waveguide Illuminated by Red Laser
Waveguide with 2 Crossings Connected 1st to 3rd Linecard Interconnect
Output Facet of the Waveguide Interconnection
Data storage protocol and form factor trends

Hard Disk Drive Sizes 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

Optical Printed Circuit Board and Connector Technology

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Design and performance constraints
Embedded copper and optical architectures

- Copper layers for power distribution
- Copper layers for low speed communication
- Optical layers for high speed communication
Optical polymer
- Low loss at 850 nm

Waveguide characteristics
- $n_{\text{core}} = 1.56$
- $n_{\text{cladding}} = 1.524$
- $\Delta n = 2.3\%$
- N.A. = 0.33

Core dimensions
- $\varnothing = 70 \, \mu m \times 70 \, \mu m$
Active optical midplane connector
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
Connector engagement mechanism

Docked

Cam followers

Ramped plug

Cam track
VCSEL
\[ \lambda = 850 \text{ nm} \]
\[ \varnothing = 7 \mu\text{m} \]
\[ \text{Div} = 25^\circ \]

PIN
\[ \lambda = 850 \text{ nm} \]
\[ \varnothing = 70 \mu\text{m} \]

Free space coupling
- Optimised for loss minimisation
- Maximum beam expansion

Dual lens coupling interface

Dual lens coupling solution
- Beam expansion at coupling interface
- Reduces susceptibility to contamination

Interface loss: 0.72 dB
Interface loss: 1.11 dB

Optimised for loss minimisation

Polymer waveguides
\[ \varnothing = 70 \mu\text{m} \times 70 \mu\text{m} \]
\[ n_{\text{core}} = 1.56 \]
\[ n_{\text{cladding}} = 1.524 \]
\[ \text{NA} = 0.33 \]
Demonstration and evaluation platform
Peripheral test cards

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

Optical Printed Circuit Board and Connector Technology
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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
High speed data transmission measurements

Test data captured on 8 waveguides

- Data rate: 10.3 Gb/s
- Typical Pk to Pk jitter: 26 ps

BERT on waveguides

- Measured by UCL and Xyratex on all waveguides
- BER less than $10^{-12}$ measured
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