INTEGRATED OPTICAL AND ELECTRONIC INTERCONNECT PCB MANUFACTURING (OPCB)

iE MRC FLAGSHIP PROJECT
1. Enhance fabrication techniques for optical waveguides
2. Integrate optical layers into Printed Circuit Boards (PCBs)
3. Develop technology enablers: Connectors, CAD, Design Rules
4. Deploy Electro-Optical PCBs into end-user applications
PARTICIPANTS

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PARTICIPANTS
Integrated Optical and Electronic Interconnect PCB Manufacturing
Research Objectives

- Investigate optical PCB technology
- Identify technology challenges
- Develop optical PCB and connector technology
- Integrate OPCB backplanes into storage systems
- Aid commercial proliferation
Data storage systems increasing in complexity, density and speed

**Storage demand increasing**
- Manage more storage
- Increased complexity

**Disk sizes decreasing**
- Increased system density

**Data rates increasing**
- Data access speeds:
  - 3 Gb/s SAS -> 6 Gb/s SAS
  - 10 Gb/s Gigabit Ethernet
  - 12 Gb/s SAS
**End User Requirements**

**Deployment by end-users of OPCB technology into various applications**

<table>
<thead>
<tr>
<th>Data Storage / processing</th>
<th>Sensors</th>
<th>Military</th>
</tr>
</thead>
<tbody>
<tr>
<td>High density, fast</td>
<td>Flexible optical</td>
<td>Robust, low EMI, high</td>
</tr>
<tr>
<td>communication within storage</td>
<td>sensors for biomedical</td>
<td>speed communication within</td>
</tr>
<tr>
<td>backplanes</td>
<td>applications</td>
<td>military vehicles</td>
</tr>
</tbody>
</table>

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**INGEMAC**

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**Integrated Optical and Electronic Interconnect PCB Manufacturing**
**Cost Implications of High Speed Copper**

**High frequency copper issues**

- Crosstalk
- Reflections
- Electromagnetic Interference (EMI)
- Dielectric Loss / Skin effect
- Skew

![Diagram showing signal frequency and costs](Diagram)

- Low Skew Connector
- Low loss PCB materials
- Equalisation Pre-emphasis
- Via Control Processes
- Number of layers per board

![Diagram of copper transmission line](Diagram)

- Skin effect
- Capacitive coupling
- Inductive coupling
- Impedance mismatch

Output signal

**Integrated Optical and Electronic Interconnect PCB Manufacturing**
- Optical signal pipelines possible
- Send optical data further
- Fit more optical channels
- Send data faster
- No EMI outside the waveguide
- Send multiple signals (WDM)
Integrated Optical and Electronic Interconnect PCB Manufacturing

Material Supply and Development

Two different classes of optical polymer evaluated and compared for waveguide production

**Polyacrylates**
- Truemode® polymer - Exxelis
- New polymer formulations - Heriot Watt U

**Polysiloxane**
- Polysiloxane formulations – Dow Corning
Four techniques for fabricating optical waveguides investigated and characterised

**Photolithography**

**Laser Writing**

**Laser Ablation**

**Ink Jet Printing**

Integrated Optical and Electronic Interconnect PCB Manufacturing
Design services for optical waveguide layout developed

**Design Rules and Characterisation**
- PCB layout constraints for waveguides:
  - *Minimum bend radius*
  - *Separation*
  - *Crossing angle*

**OPCB CAD Design**
- Cadence software adapted to layout optical tracks
- Software used to design optical backplane
PCB Manufacturer to adapt fabrication techniques toward commercial production of electro-optical PCBs
POLYMER WAVEGUIDE TECHNOLOGY EXISTS

Source: Exxelis

Source: Fraunhofer Institute

Source: IBM Zürich

Source: Fraunhofer Institute

Source: Fraunhofer IBM

Source: Variprint AG

Source: IBM Zürich

Source: Exxelis
**Optical Layout Advantages**

**Splitters**
- 1 – many power splitters possible
- Depends on loss budget

**Crossings**
- Signal crossings on same layer without shorts

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**Source:** IBM Zürich

**Source:** Exxelis

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**Source:** Exxelis

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Integrated Optical and Electronic Interconnect PCB Manufacturing
Right Angled Bends (In-plane)

- Overcomes bend radius restrictions
- Allows higher density routing

Right Angled Bends (Out-of-plane)

- Eases optical signal insertion
- Basis for optical vias
**Environmental Benefits**

**Reduction in PCB Waste Material**

- All electronic PCB
- Electro-optical PCB

- Reduce layers by 40%
- Reduce area by 25%
- Total size reduction: 65%

**Reduced Power Consumption**

- 10 Gb/s data stream
- 10 Gb/s data stream
- Drive power reduction: 30%
**Parallel Optical Transceiver**
- Small form factor
- 10 Gb/s per channel
- Microcontroller with I²C interface

**Backplane Connector Module**
- Automated connector mechanism
- High precision alignment
**Electro-Optical Backplane**

- Compact PCI architecture
- Electrical layers for power
- Electrical layers for low speed
- Optical layer for 10 Gb/s traffic
- 4 optical PCB connector sites
- Connector slots for line cards
Demonstration Platform for ECOC 2008

Integrated Optical and Electronic Interconnect PCB Manufacturing
Demonstration Platform

Signal Analyser (supplied by UCL) showing eye diagrams

Bit Error Rate tester (supplied by UCL)

10 GbE pattern generator and traffic capture analysis

Single Board Computer monitor and interface to run control GUI

Integrated Optical and Electronic Interconnect PCB Manufacturing
• **Direct Laser-writing of waveguides**
  • Increase writing speeds and manufacturability

• **Photo-polymer Formulation**
  • Optimise for faster writing; alternative polymer systems; possible dry formulation

• **Writing over a large areas (400 – 500 mm long)**
  • Stationary “writing head” with board moved on long translation stage

• **Connectors**
  • Possible use of 45-deg out-of-plane mirrors

• **Advanced Optoelectronic Integration**
• **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

Gaussian Beam Imaged aperture

Images of the resulting waveguide core cross-sections

Integrated Optical and Electronic Interconnect PCB Manufacturing
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 45º surfaces
Out-of-plane coupling, using 45-deg mirror (silver)

Microscope image looking down on mirror coupling light towards camera
• Polymer Types: Acrylate (HWU custom & Exxelis) & polysiloxane systems (Dow Corning)
• Tuning of refractive index and viscosity is possible
• Equivalent to negative photoresist processing
• Compatible with a wide range of substrates
• Mechanical and thermal properties compatible with PCB processing
• “Wet” format processing; Possibility of a dry film format formulation
• Low optical loss at 850 nm (>0.1 dB/cm typical)
• Polymer deposition techniques include: Spinning, doctor-blading, casting, spray coating and ink-jet printing
Polymer system / formulation

Writing speed
- New Aerotech stages capable of speeds of up to 2 m/s

Intensity profile
- Gaussian
- Flat top (imaged aperture)

Optical power
- Gaussian beam: up to ~10 mW
- Imaged aperture: up to ~1.5 mW

Oil immersion
- Permits writing of 45° surfaces
- Excludes oxygen, which inhibits polymerisation process

Number of passes
- Exposure process is non-reciprocal
- Can obtain better results with multiple fast passes than single slow pass
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)
**Intensity Profiles**

Gaussian beam diameter = 1.2 mm

Spot size = ~40 μm

f = 80 mm

Gaussian beam diameter = 1.1 mm

Imaging system / lenses

60 μm square aperture

Gaussian beam diameter = 1.1 mm

100 μm circular aperture

f = 250 mm

f = 80 mm

f = 50 mm
- 100 µm aperture was de-magnified
- Optical power at sample ~0.5 mW
- HWU custom photo-polymer

8 mm/s
63 x 74 µm

4 mm/s
69 x 78 µm

2 mm/s
76 x 84 µm
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 \( \sim 1.4 \text{ m} \). The spiral was upper cladded at both ends for cutting.
**Key challenge:** Dispensing / applying a uniform layer of liquid photo polymer over a large are FR4 boards.

We plan to experiment with a number of techniques including the use of a roller system (as shown in the CAD drawing on right)
- Shims along edge
- Mylar sheet

Board Developing: Appropriate container for developing large FR4 boards after UV exposure
Inkjet Fabrication of Optical Waveguides
IeMRC, 4th July 2008

John Chappell, David Hutt, Paul Conway

Wolfson School of Mechanical and Manufacturing Engineering,
Loughborough University
Advantages
- selective deposition of core and clad - less wastage: picolitre volumes
- large area printing
- low cost

Target core dimensions of 50-100 microns height/width
- Material properties tailored to inkjet head
- Optimising ‘waveform’ for each fluid - fluid dynamics
- Interaction of material with substrate: wetting, adhesion
- Control and stability of liquid structures
- Truemode (Exxelis) suitable material core/clad
- Solvent needed to tailor viscosity
- Controlled spreading
  - drop spacing of 17.5 microns
    (4x jetting frequency)
- (a) low BP solvent
  (b) high BP solvent
- rate of solvent evaporation affecting line shape

- Extensive spreading
  - drop spacing of 70 microns

Substrate temperature ~-20°C
- Young’s Equation
  \[ \sigma_{AS} = \sigma_{SW} + \sigma_{AW} \cos \Theta \]
- Balance of surface tensions acting at the contact lines
- Differences in material properties will affect the contact angle of the drop with the surface
- Surface tension (and viscosity) are temperature related - lowering the temperature increases surface tension (and viscosity)
Increase contact angle of liquid on substrate to reduce the wetting of liquid core

Change the surface energy

Choose a model hydrophobic surface - octadecyltrichlorosilane (OTS) on glass

Cladding substrate shows water contact angles of ~73°

OTS on glass gives water droplet contact angles >100°

Creates adhesion problems
- Drop spacing of 70 microns
- Room temperature (left) and cold substrate (right)
- Discrete droplets – no splashing: material tailored well to inkjet system
- Temperature not the dominant factor in controlling feature shapes
- Possible demixing of solvent and core material at lower temperature
- Increasing the material deposited causes periodic features in the line shape - due to a combination of contact angles, viscosity and surface tension
- Surface roughness of ‘tracks’ is very low - investigating optical properties of these structures
- Poor adhesion between treated glass and inkjetted material
- Aspect ratio of 5:1 - aiming towards 1:1
- Investigating ways to confine the line width, increase aspect ratio and increase adhesion
Characterisation of Optical Waveguides
IeMRC, 4th July 2008


Department of Electronics and Electrical Engineering, UCL
- 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

- Surface Roughness
- Loss
- Crosstalk
- Misalignment tolerance
- Bit Error Rate, Eye Diagram
50 μm × 50 μm waveguide

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

50 μm × 140 μm waveguide
- RMS side wall roughness: 9 nm to 74 nm
- RMS polished end surface roughness: 26 nm to 192 nm.
Schematic diagram of one set of curved waveguides.

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

- 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 fibre with a red-laser.
### LOSS OF WAVEGUIDE BENDS

#### Power transmission (dB)

<table>
<thead>
<tr>
<th>Width (μm)</th>
<th>Minimum Radius (mm)</th>
<th>Minimum Loss (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>

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**Integrated Optical and Electronic Interconnect PCB Manufacturing**
The input section $w_{in} = 50 \, \mu m$, and its length $l_{in} = 11.5 \, mm$

The tapered bend transforms the waveguide width from $w_{in}$ to $w_{out}$

The width of the tapered bends varies linearly along its length

Output straight waveguide length $l_{out} = 24.5 \, mm$.

Output widths $w_{out} = 10 \, \mu m, 20 \, \mu m, 25 \, \mu m, 30 \, \mu m$ and $40 \, \mu m$
Dashed lines correspond to the boundaries of the $w_{in} = 50 \, \mu m$ tapered bend
Dotted lines correspond to the boundaries of the $20 \, \mu m$ bend
Tapered bend has more misalignment tolerance for a slight loss penalty
Loss of 0.023 dB per 90° crossing consistent with other reports.

The loss per crossing ($L_c$) depends on crossing angle ($\theta$),
$$L_c = 1.0779 \cdot \theta^{-0.8727}.$$
Light launched from VCSEL imaged via a GRIN lens into 50 µm x 150 µm waveguide.

- Photo-lithographically fabricated chirped with waveguide array.
- Photomosaic with increased camera gain towards left.
70 μm × 70 μm waveguide cross sections
- Waveguide end facets diced but unpolished scatters light into cladding
- In the cladding power drops linearly at a rate of 0.011 dB/μm
- Crosstalk reduced to -30 dB for waveguides 1 mm apart
Fully connected waveguide layout using design rules
We have

- Created basic waveguide design rules
- Input waveguide designs into Cadence tool
- Established measurement techniques
THANK YOU FOR YOUR ATTENTION

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Integrated Optical and Electronic Interconnect PCB Manufacturing
Supplemental Slides


Selviah, D.R. (2008), *UK Displays and Lighting, Korean Trade Visit, Department of Business, Enterprise and Regulatory Reform, 1.*


Selviah, D.R. (2008). 19th IEEE LEOS Workshop on High Speed Interconnections within Digital System, HSD '08, May 18th-21st, Santa Fe, New Mexico, USA


Integrated Optical and Electronic Interconnect PCB Manufacturing
HOW TO MAKE AN OPTICAL PCB

1. Deposit lower cladding
2. Cure
3. Deposit core
4. Align mask
5. Cure waveguides
6. Remove uncured material
7. Deposit upper cladding
8. Cure

Photolithographic mask

UV Exposure

Upper cladding
Core layer
Lower cladding

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