Integrated Optical and Electronic PCB Manufacturing
Invited Plenary Talk

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Outline

- Electrical versus Optical interconnects
- The OPCB project
- Polymer materials
- Waveguide Fabrication
- OPCB Research
  - Heriot Watt
  - Loughborough
  - UCL
  - NPL
- System Demonstrator
Costly high bit rate copper track design procedures

- Impedance control to minimize back reflections
- Inductive and capacitative coupling and parasitics
- Loss due to radiation
- Frequency dependent loss due to shallow skin depth currents*
- Loss due to surface and edge roughness of the copper track
- High power launch to offset losses
- Copper electro-migration at high currents
- Use of low loss tangent dielectric FR-4 laminates
- Active pulse pre-emphasis
- Blind fixed or adaptive equalization

Costly high bit rate copper track design procedures

- Differential signaling
- Balanced differential pair line lengths to minimize common mode propagation causing radiation and dispersion†
- Low clock skew connectors
- Back drilled vias to avoid reflective stubs for impedance control
- Electromagnetic crosstalk between traces
- Electromagnetic interference, EMI outside the enclosure
- EMI a problem for EM transparent composite aircraft skins
- 17 Gb/s demonstrated over 1 metre using such costly techniques

On-board Platform Applications
On-board Platform Applications

Reconfigurable Network Interconnections

Core processor

Aircraft utilities

Signal concentrator

RF/EO Sensors & comms data

High Bandwidth Signals
Optical Waveguide Interconnect Benefits

- Low loss over long distances
- Scalability to ~1 meter length boards
- Scalability to high bit rates well in excess of 10 Gb/s
- Multiplexed transmission path usage using WDM and sub-carrier multiplexing
- Lower power optical drivers
- Low heat generation so reduced system cooling costs
- Improved signal integrity
- Lightweight
- Low electromagnetic crosstalk between waveguides
- Low electromagnetic interference, EMI outside the enclosure
- Low clock skew
Optical Waveguide Interconnect Benefits

- High density since no need for differential lines or signal and ground plane or transmission line geometries, voltage isolation,
- Reduced timing jitter
- No need for costly high dielectric constant or low loss tangent board materials,
- Increases design flexibility
- High reliability
- Higher aggregate bit rates possible in smaller board areas and volumes
- Reduced materials usage as fewer layers are needed
- Reduced board thickness and area for same data rate
- Less waste at end of life
- Simplified routing as waveguide crossings are permitted
- Low cost
The Integrated Optical and Electronic Interconnect PCB Manufacturing (OPCB) project

- The ideal printed circuit board has copper tracks to transmit electrical power and for low data rate control signals with optical waveguides for high bit rate interconnects
- The OPCB project investigates the design and manufacturing procedures for hybrid electronic and optical printed circuit boards
- The OPCB project brings together a supply chain to deliver such boards through a commercial PCB manufacturer
- 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 one of the two Flagship Projects
- 20 months into the 3 year, £1.3 million project
- Mid Term independent review reported excellent progress
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
Integrated Optical and Electronic Interconnect (OPCB) Project Aims

1. Establish waveguide design rules
   - Build into commercial CAD layout software to ease the design of OPCBs and to ensure widespread use.
   - Understand the effect of waveguide wall roughness and cross-sectional shape on loss and bit error rate.

2. Develop low cost, PCB compatible manufacturing techniques for OPCBs including novel polymer formulations
   - Compare the commercial and technological benefits of several high and low risk manufacturing technologies
   - Environmental testing, reproducibility

3. Design an optical-electrical connector
   - Low cost, dismountable, passive, self-aligning, mid-board, multichannel, duplex, long life
End Users

Xyratex
Network storage interconnect

BAE Systems
In-flight interconnect

Renishaw
Precision measurement

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

Exxelis / Dow Corning
Polymer supply

Cadence
PCB design tools and rules

RSOFT
Optical modelling tools

Xaar
Ink-jetting technology
Multimode Waveguide Requirements

- Low optical losses at 850 nm, 1310 nm and 1550 nm wavelengths
  - Absorption
  - Wall roughness
- Good adhesion to substrate
- Able to withstand manufacturing processes e.g. solder reflow, lamination
- Long term reliability
- Easily processed by PCB manufacturers

- Refractive index of core, $n \sim 1.50$
- For total internal reflection, cladding refractive index lower than core $\Delta n \sim 1\%$
## Optical Materials

<table>
<thead>
<tr>
<th>Manufacturer/ commercial name</th>
<th>Polymer class</th>
<th>Deposition/ Patterning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microresist/ ORMOCER</td>
<td>Inorganic-organic hybrid</td>
<td>Spin-coat, UV lithography</td>
</tr>
<tr>
<td>Wacker Chemie</td>
<td>Liquid polysiloxane</td>
<td>Moulding, doctor blading,</td>
</tr>
<tr>
<td>Exxelis/ Truemode</td>
<td>Acrylates</td>
<td>UV lithography, laser ablation</td>
</tr>
<tr>
<td>Rohm and Haas/ Lightlink</td>
<td>Liquid polysiloxane</td>
<td>Spin-coat, photo-patterning</td>
</tr>
<tr>
<td>Ticona/ Topas</td>
<td>Cyclic olefin copolymer</td>
<td>Spin-coat, RIE</td>
</tr>
<tr>
<td>Asahi/ Cytop</td>
<td>Fluorinated polyether</td>
<td>Spin-coat, RIE</td>
</tr>
<tr>
<td>Dow Corning</td>
<td>Polysiloxane</td>
<td>UV lithography</td>
</tr>
<tr>
<td>Norland/ NOA series</td>
<td>Liquid photopolymer</td>
<td>Dispense, UV light cure</td>
</tr>
</tbody>
</table>

Courtesy of Tze Yang Hin, Loughborough University
**Waveguide Material**
UV-curable polymeric acrylate (Truemode®)
Propagation loss @ 850 nm: 0.04 dB/cm
Heat degradation resilience: up to 350 °C

**Waveguide properties**
Size: 70 µm x 70 µm
Core index: 1.556
Cladding index: 1.526
Numerical aperture: 0.302

**Waveguide Array**
Centre to centre pitch: 250 µm
Polymer Waveguides

Waveguide losses

The measured attenuation spectrum for the multifunctional acrylate polymer waveguides.

Waveguide loss measured by Terahertz Photonics using the cutback method: 0.05 dB/cm at 850 nm

Environmental Stability

Guide unaffected by:

- Board lamination: 1 hour at 180°C
- Solder reflow: 160 seconds at 288°C
- Damp heat: 85% RH @ 85°C
- Temperature cycling: -40 to 85°C (2 wks)
- High degradation temperature: ~ 400°C
OPCB Waveguide Manufacturing Methods

- Development of a range of waveguide fabrication processes both high and low risk:
  - UV Photolithography from e-beam mask – Exxelis, Dow Corning
  - UV Laser Direct Write – Heriot Watt
  - Excimer Laser ablation – Loughborough
  - Ink Jet Printing – Loughborough
  - UV embossing/stamping – Exxelis/EPIGEM
  - Polymer Extrusion – BAE Systems

- Manufacturing at Stevenage Circuits Ltd
- Existing commercial PCB manufacturing facilities available include polymer deposition, mask fabrication, photolithography, Laser Direct write Imaging (LDI), laser ablation, ink jet printing
ELECTRO-OPTICAL PRINTED CIRCUIT BOARD MANUFACTURING TECHNIQUES

Source: Excelis Ltd

Source: Fraunhofer IZM

Source: Varioprint AG

Source: IBM Zürich
• **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\textsubscript{00}

60 \textmu m square aperture

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

OPTICAL INPUT
Photo-polymer & Processing

- 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
Laser writing parameters

• 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
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)
Intensity Profiles

Gaussian beam diameter = 1.2 mm
Spot size = ~40 μm

f = 80 mm

Gaussian beam diameter = 1.1 mm
60 μm square aperture

Imaging system / lenses

Gaussian beam diameter = 1.1 mm

f = 250 mm
f = 80 mm
f = 50 mm

100 μm circular aperture
Direct laser written waveguides using imaged circular aperture

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

8 mm/s
63 x 74µm

4 mm/s
69 x 78µm

2 mm/s
76 x 84µm
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.
Large Board Processing: Polymer Dispensing / Developing

**Key challenge:** Dispensing / applying a uniform layer of liquid photo polymer over a large area 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
Laser Ablation for Waveguide Fabrication

- Ablation to leave waveguides
- Excimer laser – Loughborough
- Nd:YAG – Stevenage Circuits

Deposit cladding and core layers on substrate

Laser ablate polymer

Deposit cladding layer
Nd:YAG Ablation

- Nd:YAG laser based at Stevenage Circuits
- Grooves machined in polymer
- Ablation depth characterised for machining parameters
Excimer Laser Ablation

- Straight waveguide structures machined in polymer
- Future work to investigate preparation of curved mirrors for out of plane interconnection
Ink Jet Deposition of Polymer Waveguides

- Localised deposition of cladding and/or core materials
  - More materials efficient
  - Active response to local features

- Printing UV cure material
  - Deposit liquid, then cure
Ink Jet Printing Challenges

- Ink formulation
  - Viscosity, surface tension
- Waveform development
- Drying effects
  - Coffee stain

Waveguide material with solvent addition - viscosity as a function of temperature

PMMA on glass. Deposited by pipette from solution.
Line Stability

Increasing volume of fluid deposited

- Ink / substrate interactions affect droplet spread
- Waveform for jetting still to be optimised. Initial observations:
  - Increasing volume of fluid leads to greater line stability
  - Solvent selection aids line stability

Same droplet size, different solvent

1mm
Control of Surface Wetting

- Need to control contact angle of polymer droplet on surface
  - Wetting angle is an important factor in determining droplet cross-section / printing resolution
  - Control of surface chemistry (balance of wetting and adhesion)

Droplets on wettable and non-wettable surfaces

Increased contact angle leads to unstable features

Modified glass substrate enables 75µm wide features, 15µm high to be printed
UCL Research

- Layout of waveguide test patterns
- Design and layout of system demonstrator patterns
- Measurement of fabricated waveguides
  - End facet roughness, sidewall roughness, optical power loss, misalignment tolerance, bit error rate, eye diagram, jitter
- Reliability Assessment
  - Humidity, temperature cycling, vibration, aging
- Modelling and Experimental comparison
  → Design rules embedded in layout tools
Waveguide components and measurements

- 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
Characteristics of waveguide measurements reported

- Photolithographically fabricated by Exxelis using e-beam mask
- Truemode® acrylate polymer formulation
- Core refractive index 1.556
- Cladding refractive index 1.5264
- NA = 0.302
- Cross sections typically 50, 70, 75, 100 μm wide  50, 70 μm thick
Waveguide Output Face Photographs

- Photolithographicly fabricated by Exxelis
- Cut with a dicing saw, unpolished
- VCSEL illuminated
Surface roughness

- RMS side wall roughness: 9 nm to 74 nm
- RMS polished end surface roughness: 26 nm to 192 nm.
Optical Loss Measurement

850 nm VCSEL

50/125 μm step index fibre

mode scrambler

Index matching fluid

150 μm pinhole

Integrating sphere photodetector

nW Power Meter

-15 dBm

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Far Field from 50/125 µm fibre with and without mode scrambling
Waveguide 90 bend test pattern
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 $R = 5.5\,\text{mm} – 34.5\,\text{mm}$
Loss of Waveguide Bends as a Function of Bend Radius

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

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

(left picture) in the first segment (first 10°).  
(right picture) in the 30° to 40° degree segment.

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Theory versus experiment for bend loss

BPM modeled loss for launched fully filled 50/125 μm MM fiber modes and for fully filled waveguide modes compared to normalized experimental loss as a function of bend radius for 50 μm × 50 μm waveguides.
Power as a function of angle propagated by cascading the results

nine $10^\circ$ segments and its derivative for $w = 75 \, \mu m$, $R = 5 \, mm$. 
Design Rules for tapered bends

- 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 $40 \ \mu m$
Excess taper loss in a tapered bend

- Defined as the power measured at the end of one of the tapered bends minus the power measured at the end of the waveguide bend of the same input width $w_{in}$.
- This removes the coupling, transition, radiation, and propagation loss of a bend.
- Taper ratios $TR \geq 0.4$ have lower losses.
Misalignment tolerance of a tapered bend compared to a straight bend

- 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
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
The product of transmission and misalignment tolerance is a constant which increases linearly with TR such that the product = 0.650 TR - 0.09

This product is independent of the bend radius as experimental points almost coincide.
Design rules for Waveguide Crossings

• Loss of 0.023 dB per 90° crossing consistent with other reports
• The loss per crossing ($L_c$) depends on crossing angle ($\theta$), $L_c = 1.0779 \cdot \theta^{-0.8727}$.
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
Design rules for Inter-waveguide Cross Talk

- 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
Design rules for waveguide width depending on insertion loss and cross-talk

6~7 dB for a 70 μm width waveguide

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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

Insertion Loss (dB)

axial distance $z$ (μm)

VCSEL

Photo Detector

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Bit Error Rate Measurement System – Fibre to fibre version

50/125 μm fibre mode scrambler

Programmable optical attenuator

Electrical to optical conversion

2.5 Gbit/s, PRBS 2^{33}-1

62.5/125 μm graded index fibre

Optical to electrical conversion

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Bit error rate for laterally misaligned 1550 nm 2.5 Gb/s DFB laser
System Demonstrator fully connected waveguide layout using design rules
Optical Coherence Tomography ‘OCT’
Refractive Index Profiling

![Diagram](image)

- Power vs Wavelength
- Power vs Wavelength
- Signal (dB) vs Distance (um)

NPL National Physical Laboratory
Optical Coherence Tomography Initial Results

- The XY reflected intensity from the end surface of the OPCB
Optical Coherence Tomography Initial Results

Apparent optical thickness

- Core-Cladding
- \( \Delta = 1.7\% \)

Dimensions:
- 1937 \( \mu m \)
- 1969 \( \mu m \)
- 2024 \( \mu m \)
Optical Coherence Tomography

• OCT measures the reflected light intensity as a function of optical depth
• The waveguide end facet is scanned in XY
• The two cross sections show a section through the waveguides A to A’ in the X direction and B to B’ in the y direction through the centre of the central waveguide.
• The bright intensities occur due to reflections at the upper and lower surfaces of the sample, the upper surface is at the very top of the images.
• The optical path to the lower surface depends on the refractive index, hence, the waveguide core is deeper than the cladding and the weave is the deepest.
Group Index by Optical Coherence Tomography

- OCT measures the apparent thickness
- Apparent thickness = group refractive index × actual thickness
- Actual thickness by laying waveguides flat using OCT as travelling microscope
- By substitution the group refractive index can be found

- Ellipsometry is used to find the cladding phase index versus wavelength
- From which the group refractive index can also be found at 850 nm

- The group refractive index is 1% higher than the phase refractive index
- Currently comparing the group indices measured by the two measurement techniques
**Research Objectives**
- Design and system integration of optical PCB technology
- Commercial proliferation of optical PCB technology
- Commercial development of optical backplane connection technology

**Electro-optical PCB Technologies**
- High speed parallel optical interface (80 Gb/s aggregate)
- Pluggable optical PCB connector modules
- C-PCI backplane with embedded multimode polymer waveguides

**Meeting Storage System Trends**
- Increasing data bandwidth
- Decreasing disk drive form factors
- Higher system integration

Eventual incorporation of Optical PCB technology into high bandwidth storage systems
**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
CHARACTERISATION SETUP

- Test traffic: **10 GbE LAN (10.3 Gbps)**
- VCSEL bias current: **11.91 mA**
- VCSEL modulation current: **9.8 mA**
- Divergence: **25**
- Output optical power: **0.43 mW**
- Average optical jitter: **31.2 ps (Pk – Pk)**
**Optical Coupling Characterisation**

**Test traffic:** 10 GbE LAN (10.3 Gbps)

**Wavelength:** 850 nm

### Arrangement:
Active connector – waveguide - patchcord

#### Reference Signal – No Waveguide
- Jitter: 0.34 UI
- Relative Loss: 0 dB

#### 10 cm Waveguide with Isopropanol
- Jitter: 0.36 UI
- Relative Loss: 4.5 dB

#### 10 cm Waveguide – Diced and Polished
- Jitter: 0.56 UI
- Relative Loss: 6.9 dB

#### 10 cm Waveguide – Diced Only
- Jitter: 0.89 UI
- Relative Loss: 7.9 dB
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
**ELECTRO-OPTICAL BACKPLANE**

**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

![Diagram of Compact PCI slot for single board computer and Compact PCI slots for line cards]
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