# Computers Working at the Speed of Light

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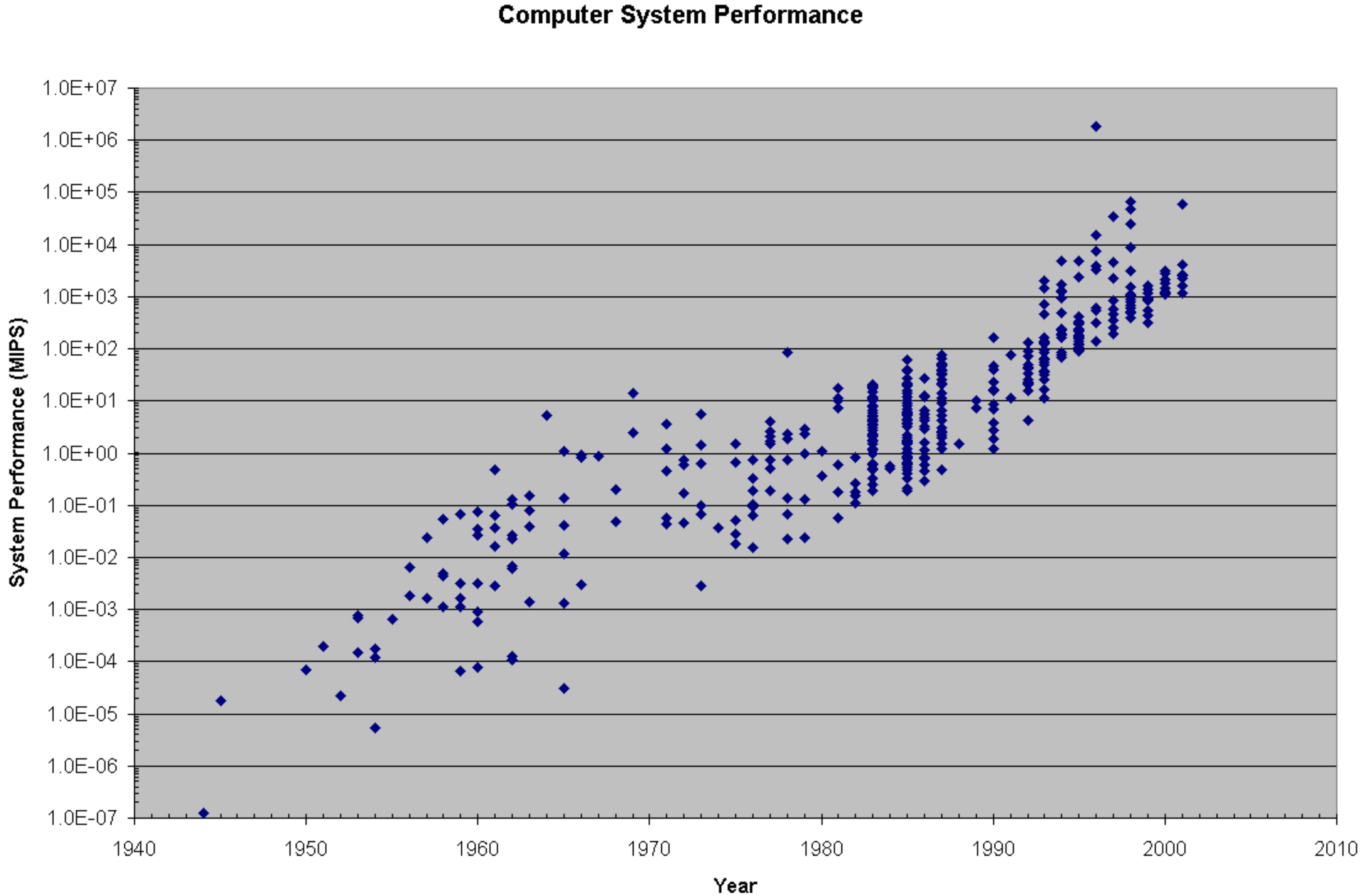
# Moore’s Law

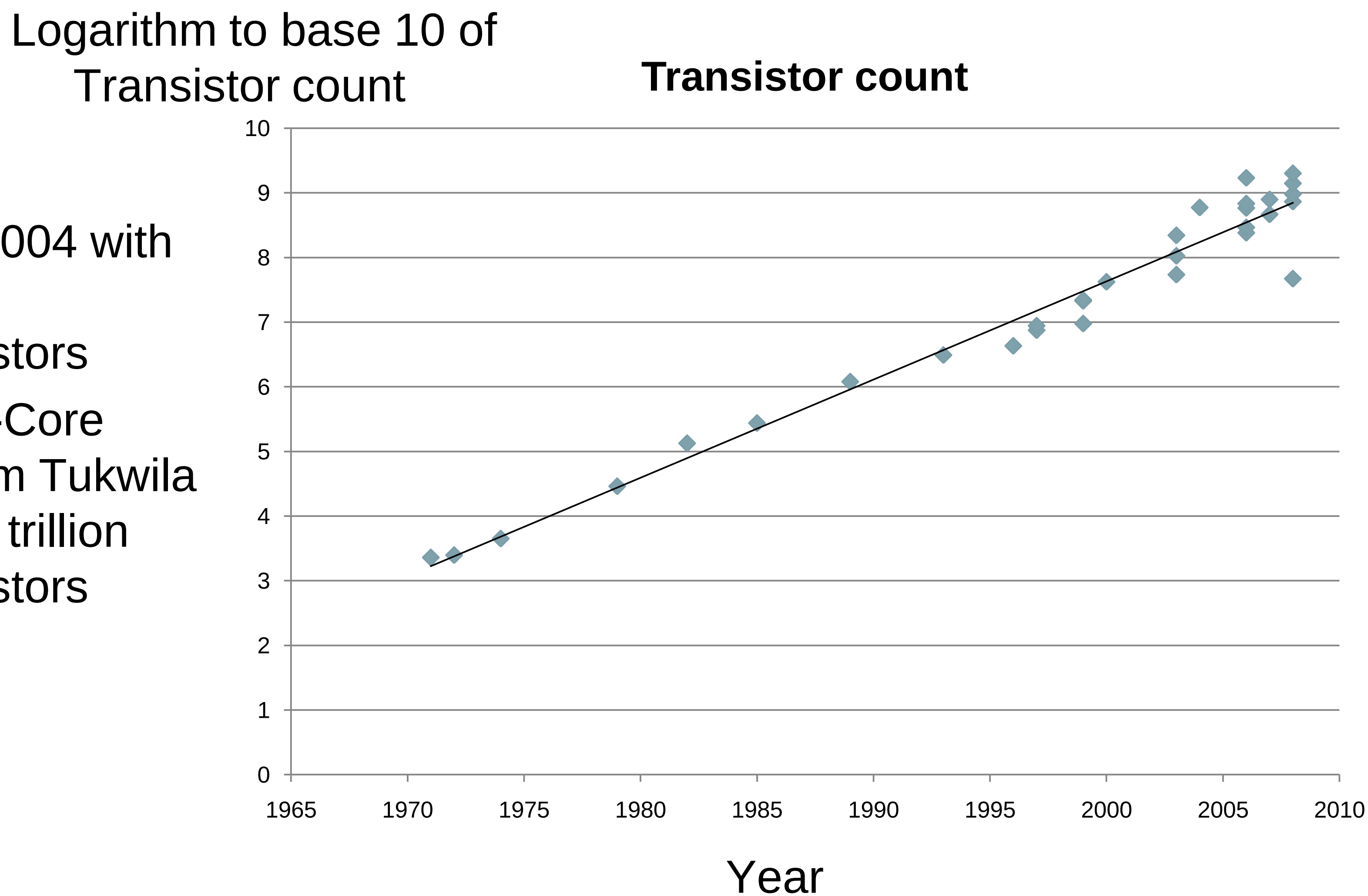
- Gordon Moore was a co-founder of Intel.
- In 1965 he said that the number of transistors in an integrated circuit will increase exponentially, almost doubling every two years in an article in Electronics, Volume 38, Number 8, April 19, 1965
- Moore’s law has been obeyed since the invention of the integrated circuit in 1958 to now
- The smaller the transistor the faster the switching speed can be - giving faster computers.

# Computer CPU Performance Trend




Thanks to John McCallum http://www.jcmit.com/cpu-perf-chart.htm

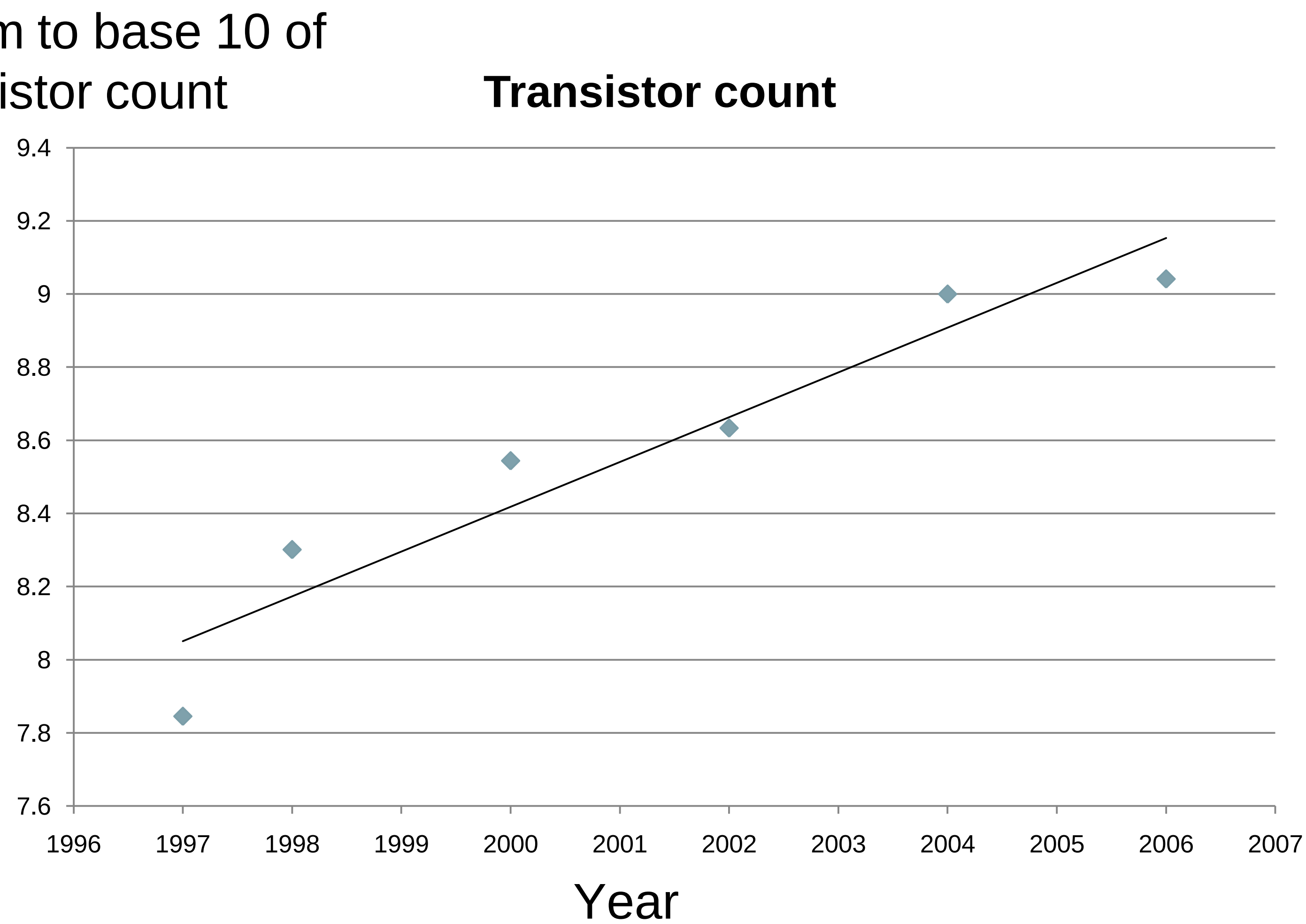
# Computer Processor Transistor Count Trend




- Intel 4004 with 2300 transistors
- Quad-Core Itanium Tukwila with 2 trillion transistors

# Field Programmable Gate Arrays, FPGA
# Transistor count for Xilinx Series

- Virtex with 70 million transistors
- Virtex E
- Virtex II
- Virtex II Pro
- Virtex 4
- Virtex 5 with 1.1 trillion transistors



# Highest Speed Supercomputers

- Used for simulating nuclear tests, weather forecasting ,oil exploration, human genome, human brain, astronomy

- 1 Flop/s – Floating point operations per second = $10^0$
- 10 Flop/s – Speed of a simple calculator = $10^1$
- 1,000 Flop/s = kFlop/s = 1 thousand = $10^3$
- 1,000,000 Flop/s = 1 MegaFlop/s = 1 million = $10^6$
- 1,000,000,000 Flop/s = 1 GigaFlop/s = 1 US billion = $10^9$
- 1,000,000,000,000 Flop/s = 1 TeraFlop/s = 1 US trillion = $10^{12}$
- 1,000,000,000,000,000 Flop/s = 1 PetaFlop/s = 1 US quadrillion = $10^{15}$

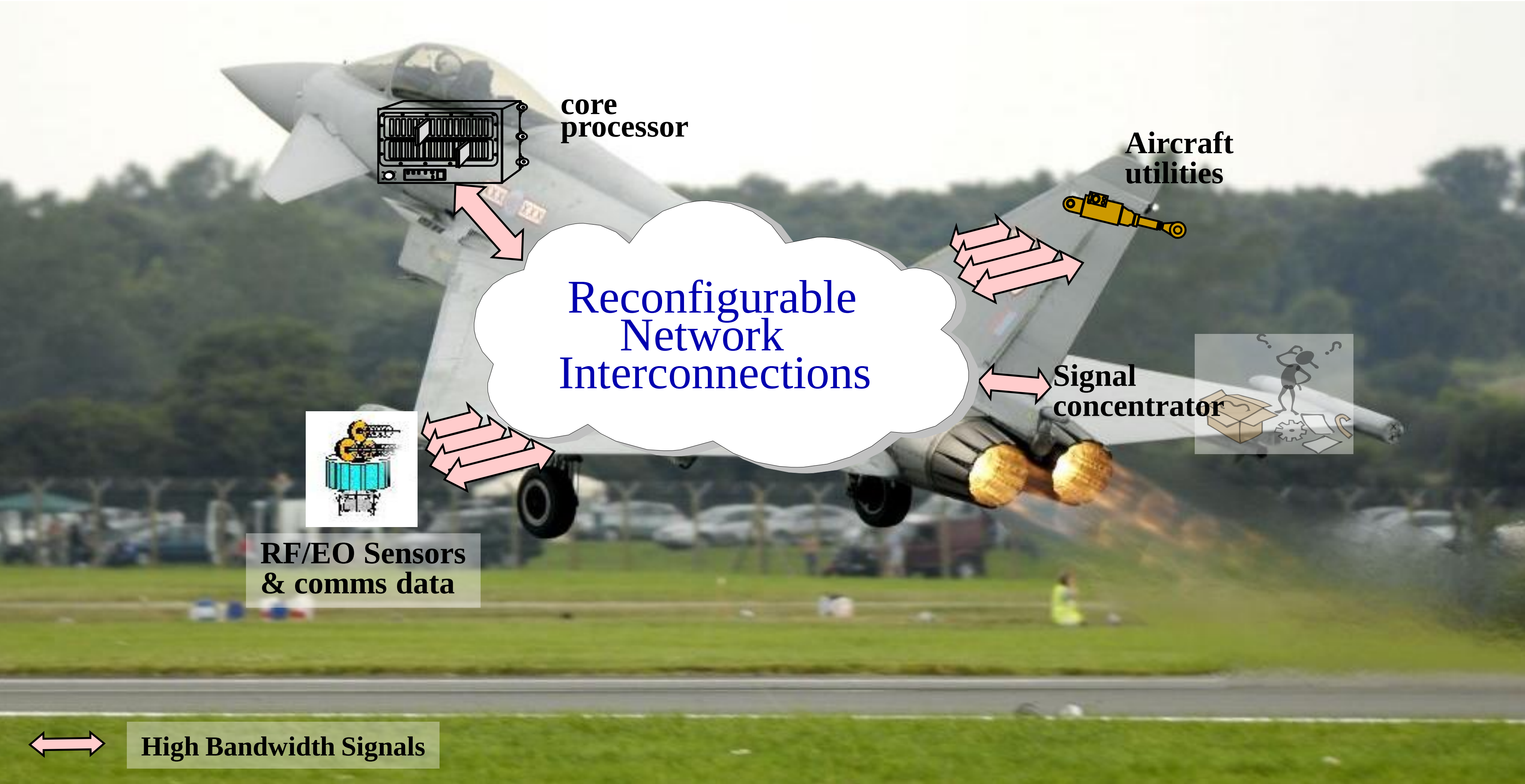
# Two Types of High Speed

1. Bandwidth
   – Large number of bits transmitted per second
   – Large data throughput
   – Measured in Hz or Bits/s
2. Latency
   – High travel velocity for data
   – Short Delays
   – Important for real time control of vehicles and robots, gaming
   – Measured in seconds

# On-board Platform Applications

# On-board Platform Applications

BAE SYSTEMS



# Cray-1

- Based at Los Alamos National Laboratory
- Fastest in 1976
- Speed of 160 million floating-point operations per second
- Weighed 5.5 tons.

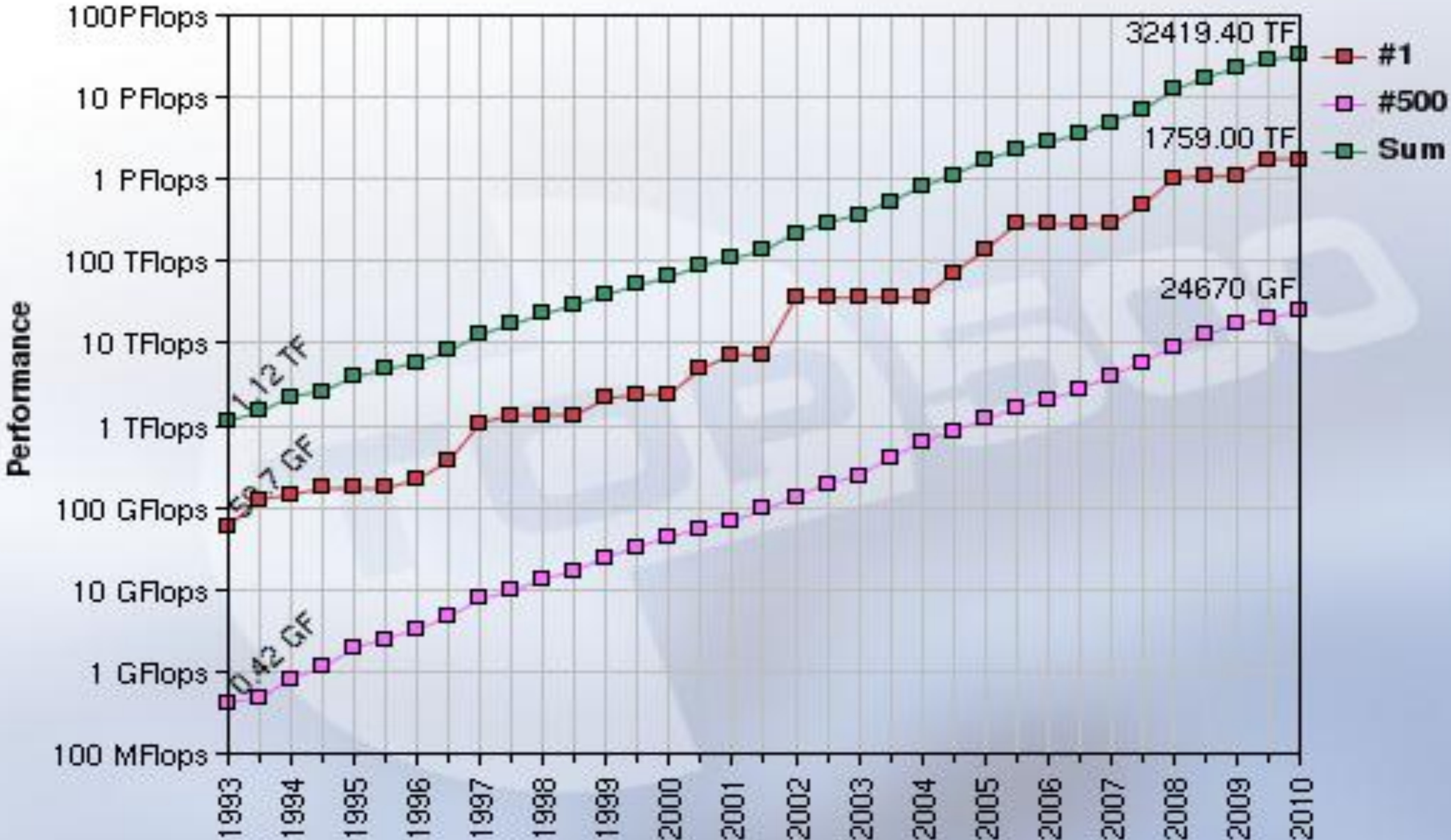
  Read more: http://realitypod.com/2010/04/top-super-computers/#ixzz0unV5k3nv

# Cray-2

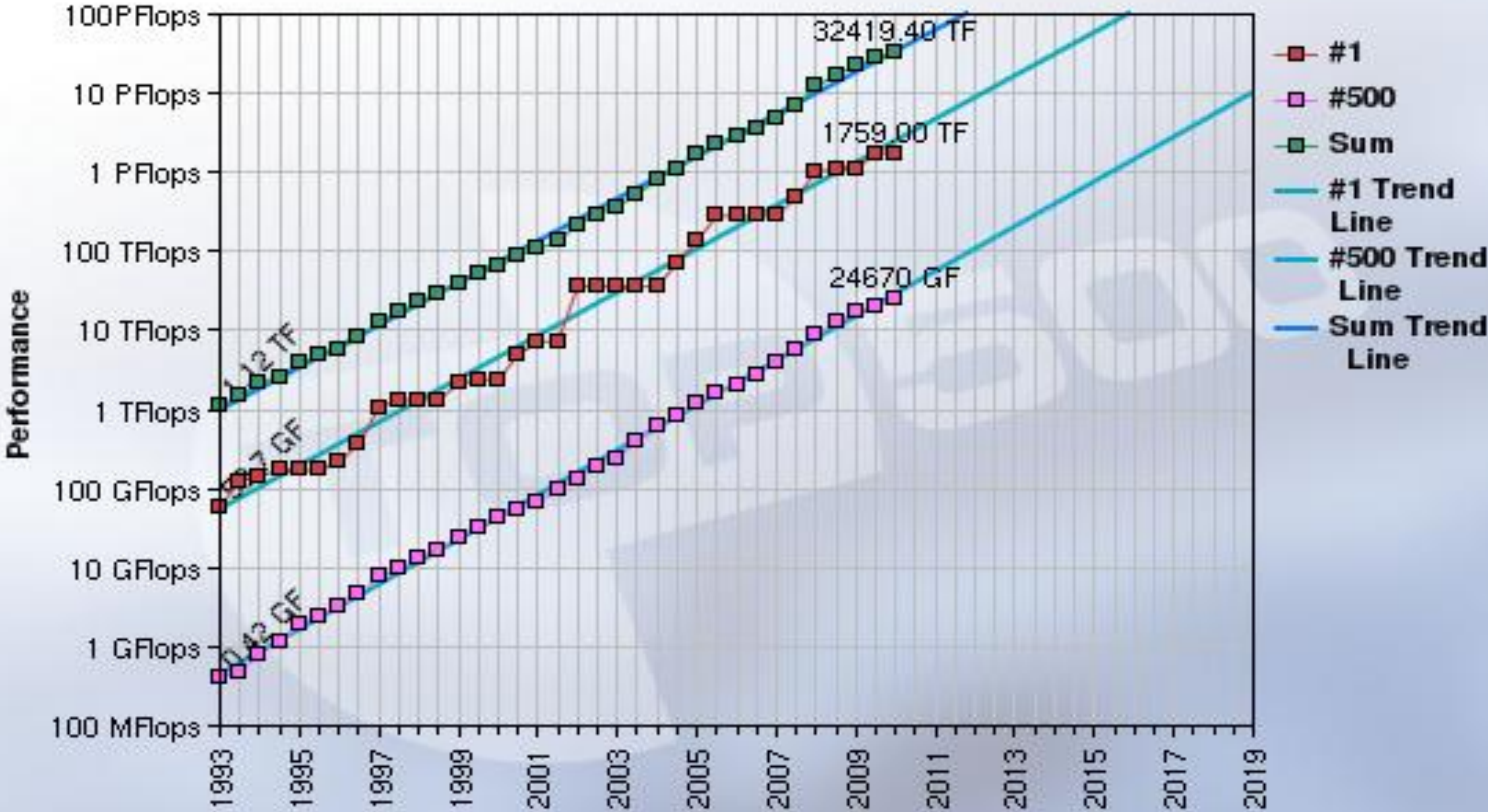
- Based at United States Departments of Defense and Energy
- Worlds fastest computer 1985-1989
- Speed 1.9 gigaflops
- Liquid cooling, it was nicknamed `Bubbles'.

http://realitypod.com/2010/04/top-super-computers/#ixzz0unVup2zZ

# Performance Development



# Projected Performance Development



# Top 10 Fastest Computers in July 2010

| | |
|---|---|
| 1 | Jaguar - Cray XT5-HE Opteron Six Core 2.6 GHz |
| 2 | Nebulae - Dawning TC3600 Blade, Intel X5650, NVidia Tesla C2050 GPU |
| 3 | Roadrunner - BladeCenter QS22/LS21 Cluster, PowerXCell 8i 3.2 GHz / Opteron DC 1.8 GHz, Voltaire Infiniband |
| 4 | Kraken XT5 - Cray XT5-HE Opteron Six Core 2.6 GHz |
| 5 | JUGENE - Blue Gene/P Solution |
| 6 | Pleiades - SGI Altix ICE 8200EX/8400EX, Xeon HT QC 3.0/Xeon Westmere 2.93 GHz, Infiniband |
| 7 | Tianhe-1 - NUDT TH-1 Cluster, Xeon E5540/E5450, ATI Radeon HD 4870 2, Infiniband |
| 8 | BlueGene/L - eServer Blue Gene Solution |
| 9 | Intrepid - Blue Gene/P Solution |
| 10 | Red Sky - Sun Blade x6275, Xeon X55xx 2.93 GHz, Infiniband |
| | http://www.top500.org/ |

# Jaguar

- Based at Department of Energy, Oak Ridge Leadership Computing Facility, Tennessee, USA
- Demonstrated 1.75 petaflop/s
- Theoretical peak capability of 2.3 petaflop/s.

# Nebulae

- Based at National Supercomputing Centre, Shenzhen, China
- Demonstrated 1.271 PFlop/s
- Theoretical peak capability of 2.98 petaflop/s, which is the highest ever on the TOP500.

# IBM Roadrunner

- The first system to record a performance greater than a petaflop/s was Roadrunner, Based at Los Alamos, New Mexico, USA
- First system to demonstrate more than 1 petaflop/s at 1.04 petaflop/s

# IBM BlueGene/P

- Based in Forschungszentrum Juelich in Germany
- Demonstrated 825.5 teraflop/s

# Tianhe-1


- China's second fastest computer
- 4× faster than the previous top computer in the country
- 563 teraflops
- Tianhe, means "river in the sky“
- Based at the National Super Computer Center, Tianjin
- 6144 Intel processors + 5120 AMD graphics processing units

# IBM's Blue Gene/L: world's fastest supercomputer in 2005

- 65,536 processors
- Speed 280.6 teraflops or 280.6 trillion calculations per second

# IBM's Blue Gene/L supercomputer simulated half a mouse brain 2007

- University of Nevada with IBM Almaden Research Lab, ran a "cortical simulator that was as big and as complex as half of a mouse's brain on the BlueGene L,"
- It had 8,000 neurons and 63,000 synapses
- It ran for 10 seconds at a speed "ten times slower than real-time"

# IBM BlueGene/L

- Based at Lawrence Livermore National Laboratory
- Demonstrated 478.2 trillion floating operations per second.

  http://realitypod.com/2010/04/top-super-computers/4/#ixzz0unTZLwt4

# Worldwide

- China now runs 24 of the top 500 computers in the world
- But America's Jaguar machine still has the fastest actual performance
- The UK has 38 computers in the top 500, making it the most powerful supercomputing nation in Europe, with the University of Edinburgh's Hector machine placed sixteenth

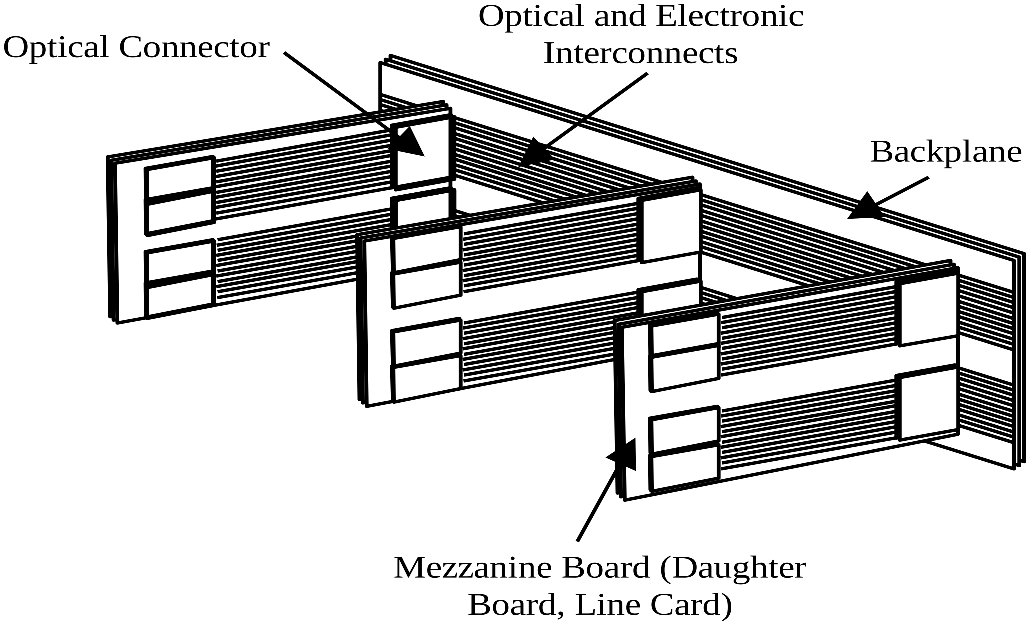
- A third of the computers on the list are made by IBM, and 20 per cent by Hewlett Packard

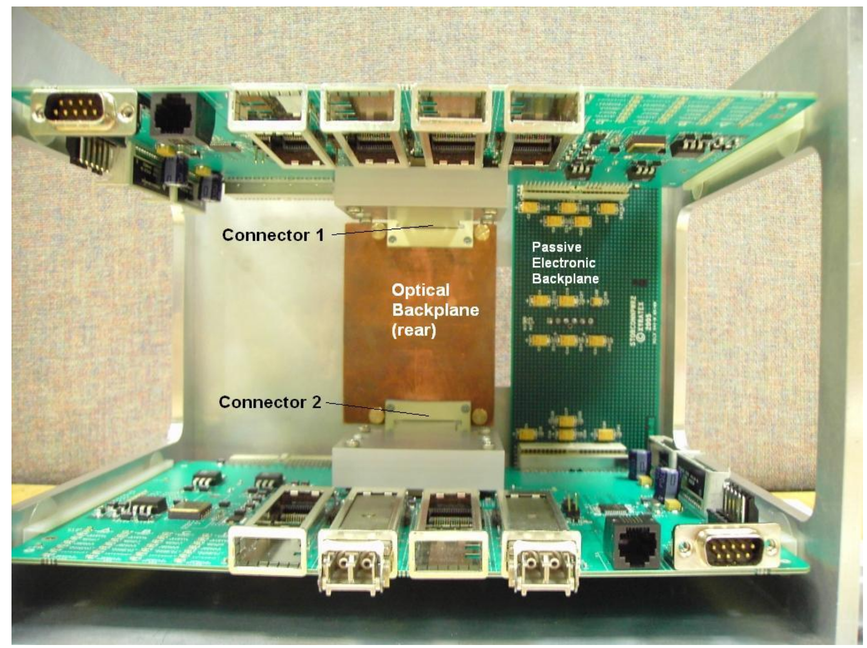
- Thanks to Matt Warman, Consumer Technology Editor, The Telegraph Newspaper, 1 Jun 2010

# Sequoia

- Being constructed by IBM for completion in 2011
- To be based at Lawrence Livermore National Laboratory, Department of Energy, USA
- Operating speed expected 20 petaflops per second
- It will occupy 96 refrigerator size racks in an area the size of a large house
- It will have the processing power of 1.6 million laptops
- Cost more than $100 million
- 6 megawatts energy consumption per year ~ same as 500 USA homes

# Backplane Motherboards



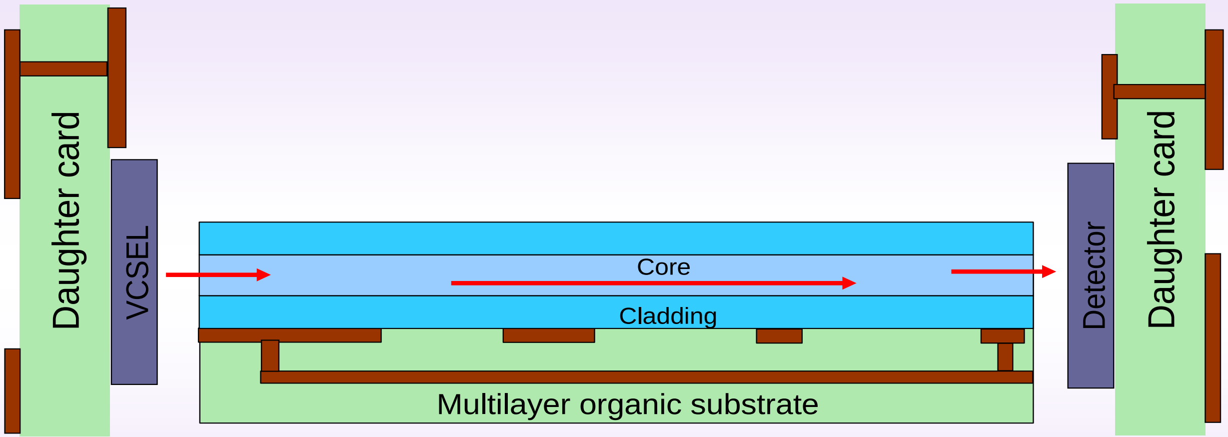
# Electromagnetic Carrier Waves

- Information is transmitted by encoding it onto a high speed carrier wave
- The highest speed waves are electromagnetic waves
- This includes radio waves, microwaves, VHF, UHF, gamma rays, X-rays, light
- Speed $3 \times 10^8$ metres per second in a vacuum
- A little slower in wires or optical fibres
- Radio and microwaves are guided along copper tracks or traces
- Light is guided through a transparent optical fibre or optical waveguides

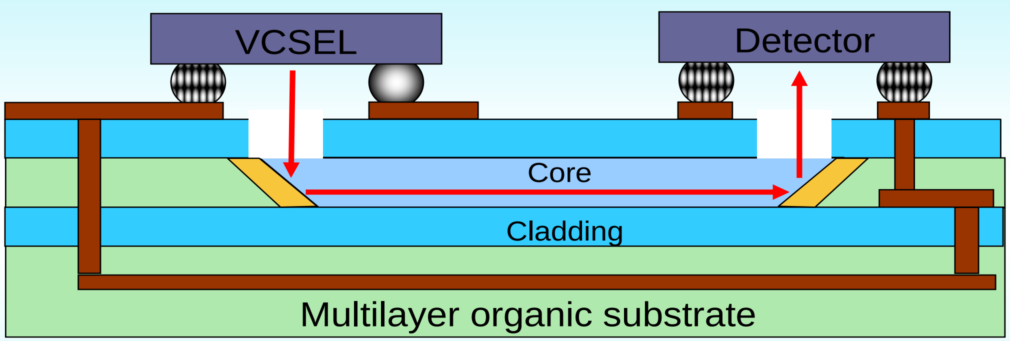
# Copper Tracks versus Optical Waveguides for High Bit Rate Interconnects

- 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

# Integration of Optics and Electronics

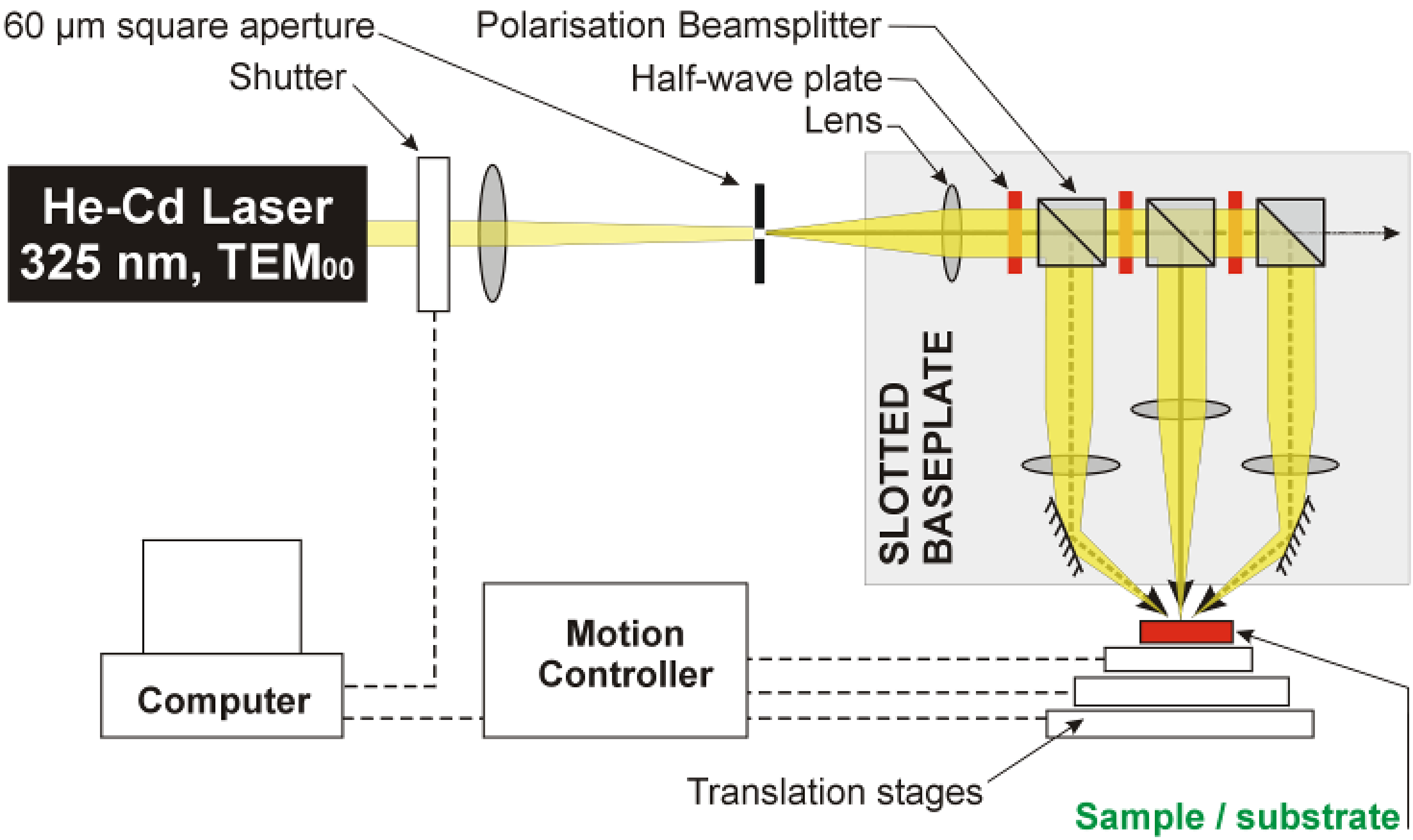


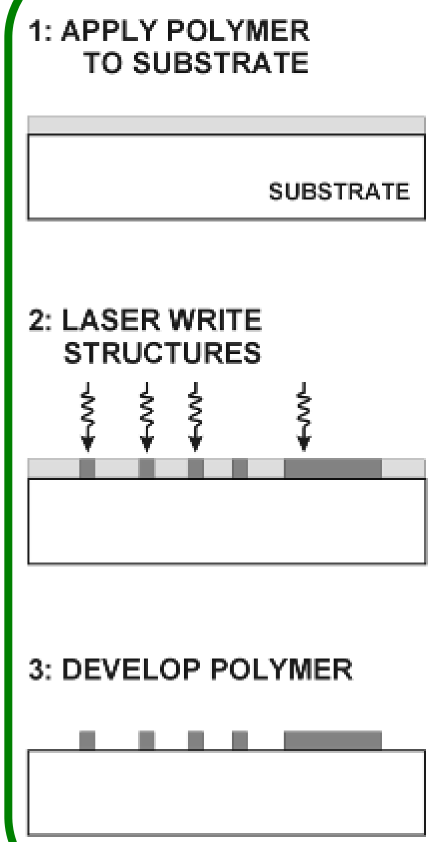

- Backplanes
  - Butt connection of "plug-in" daughter cards
  - In-plane interconnection
- Focus of OPCB project




- Out-of-plane connection
  - 45 mirrors
  - Chip to chip connection possible

# Direct Laser-writing Setup: Schematic



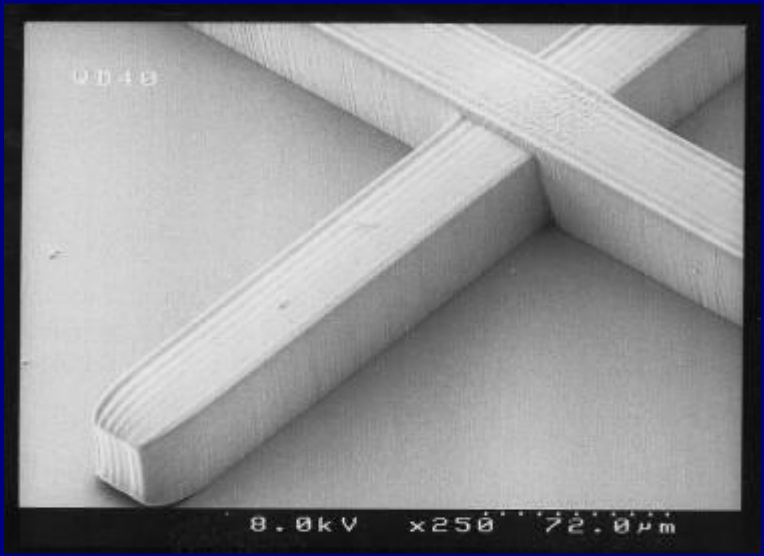



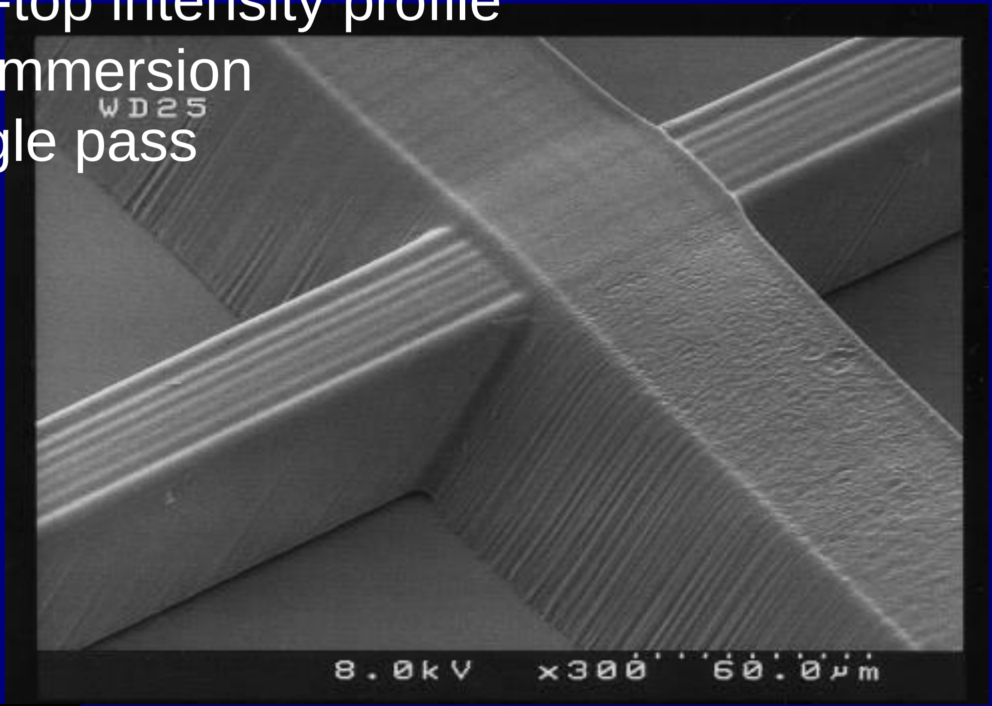

- **Slotted baseplate** mounted vertically over translation, rotation & vertical stages; components held in place with magnets
- By using two opposing 45º beams we minimise the amount of substrate rotation needed

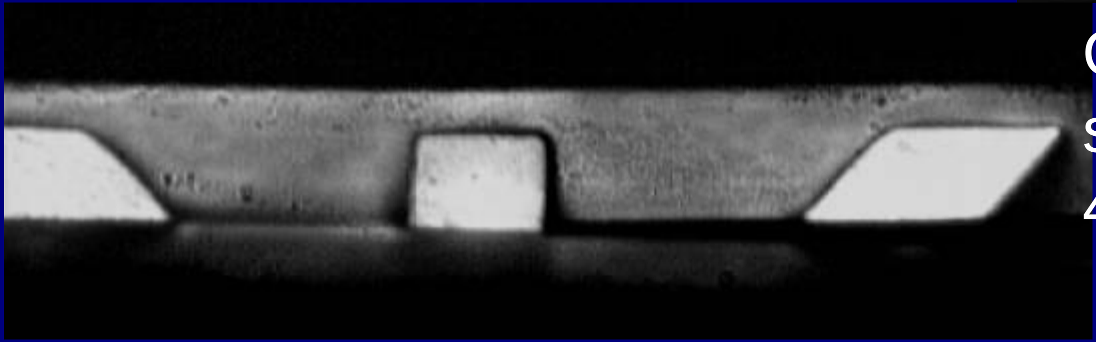
# Laser written polymer structures

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 45º surfaces

# Current Results

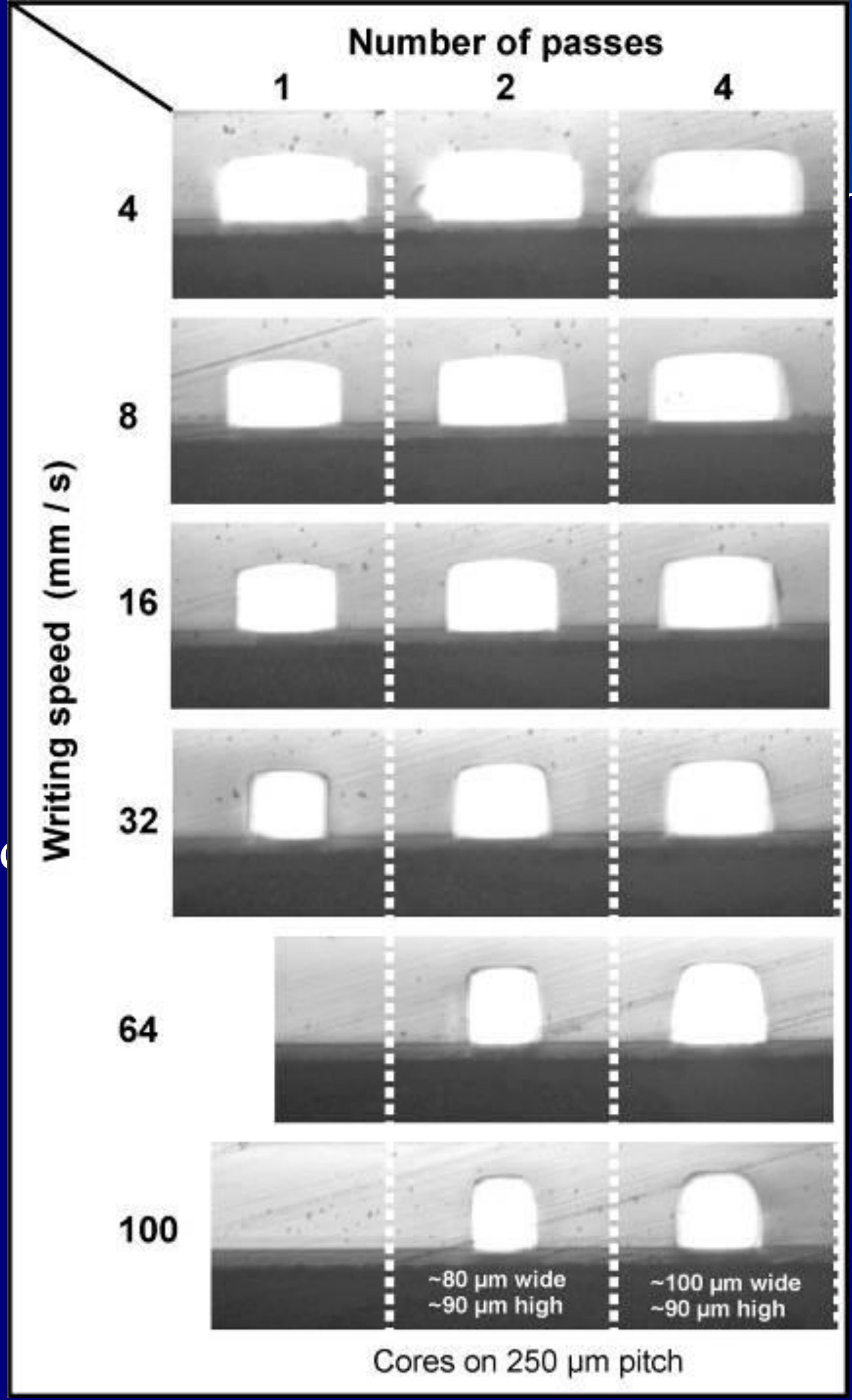
**Laser-writing Parameters:**

- 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)*

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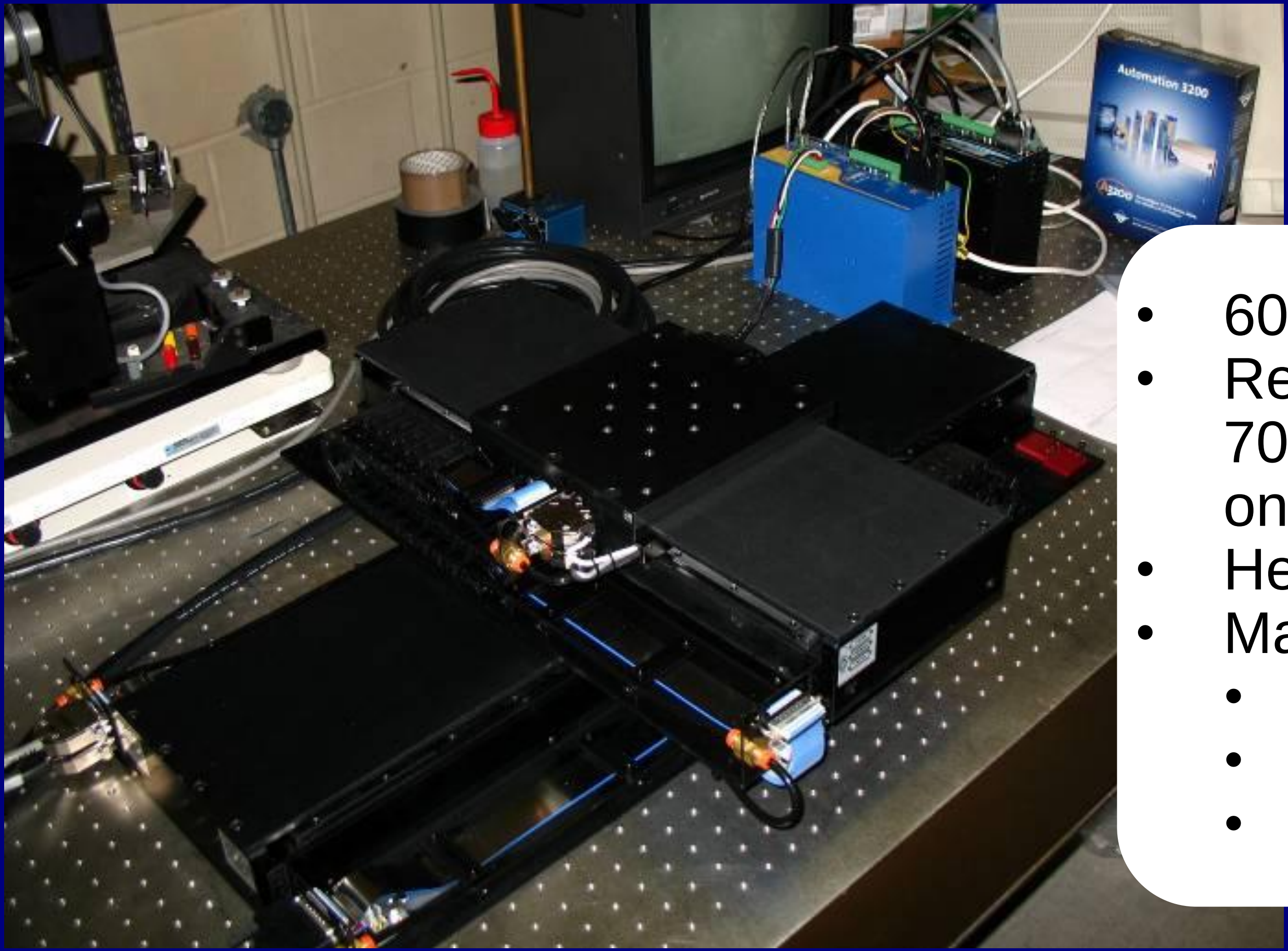
OPCB

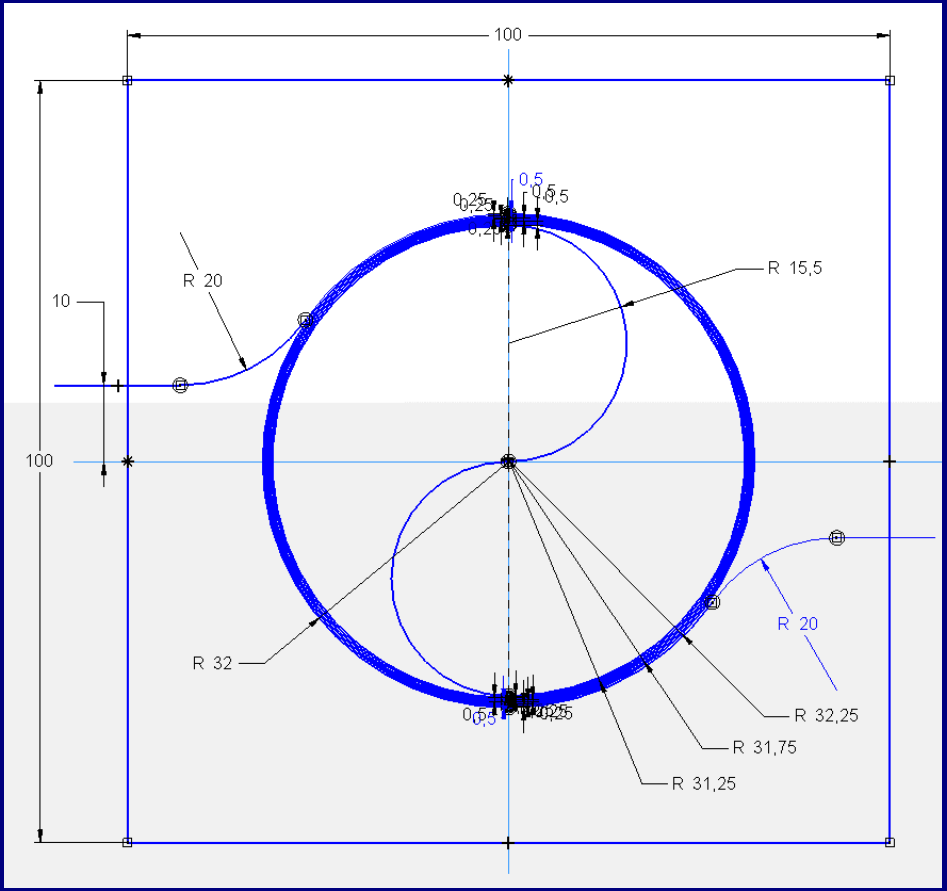
# Large Board Processing: Writing

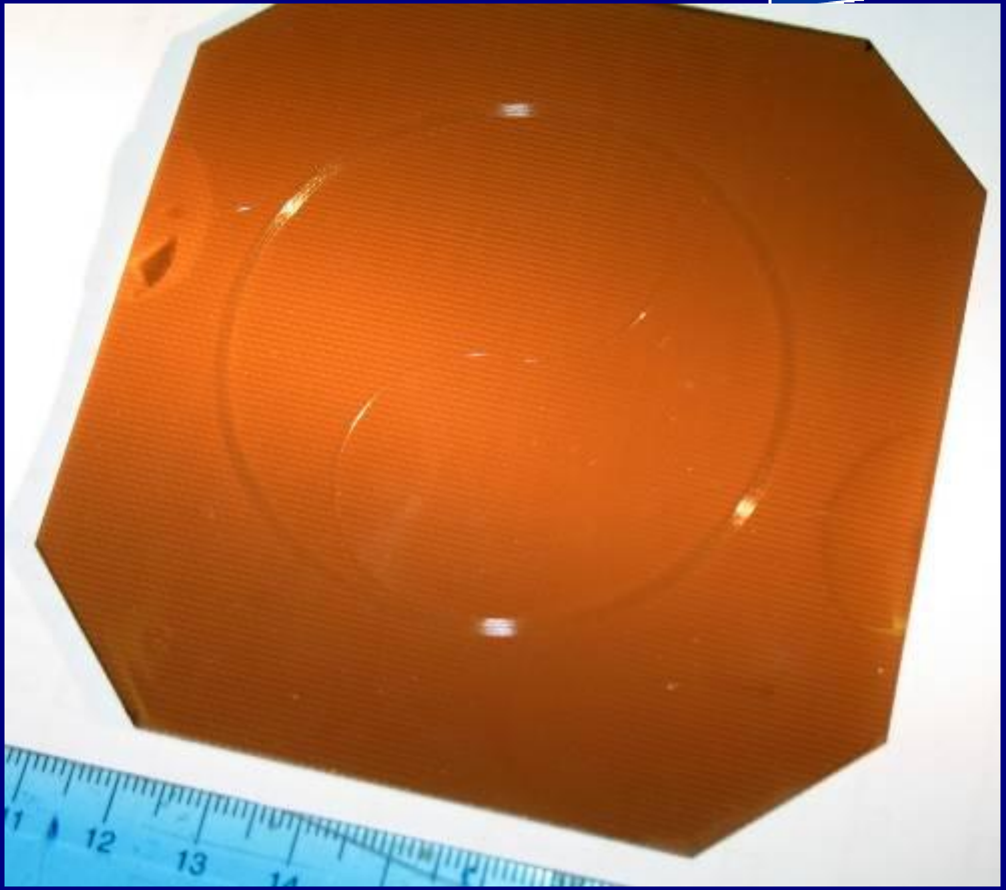
- Stationary “writing head” with board moved using Aerotech sub-µm precision stages
- Waveguide trajectories produced using CAD program




- 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

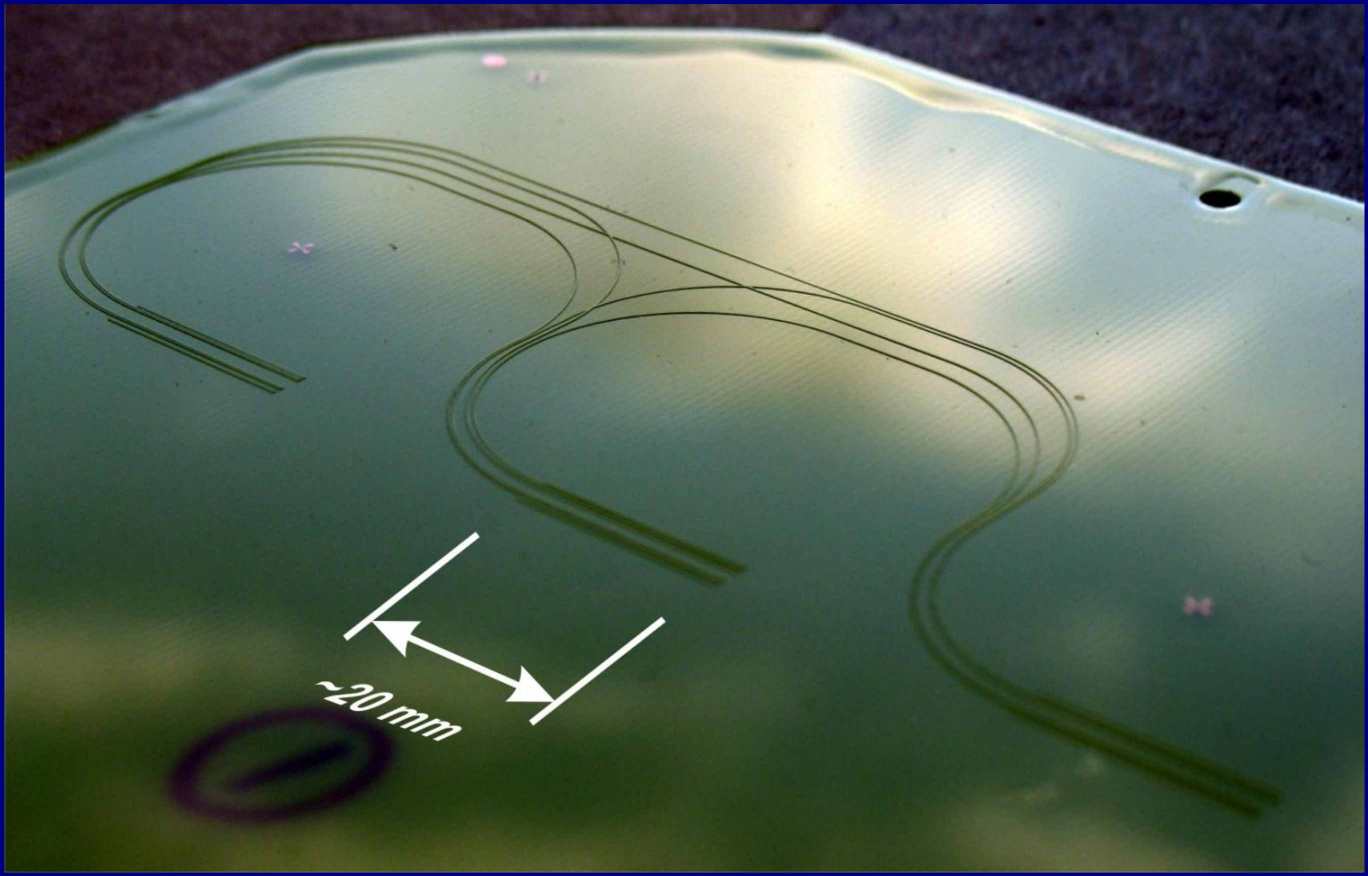
# Large Board Processing: Writing




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.

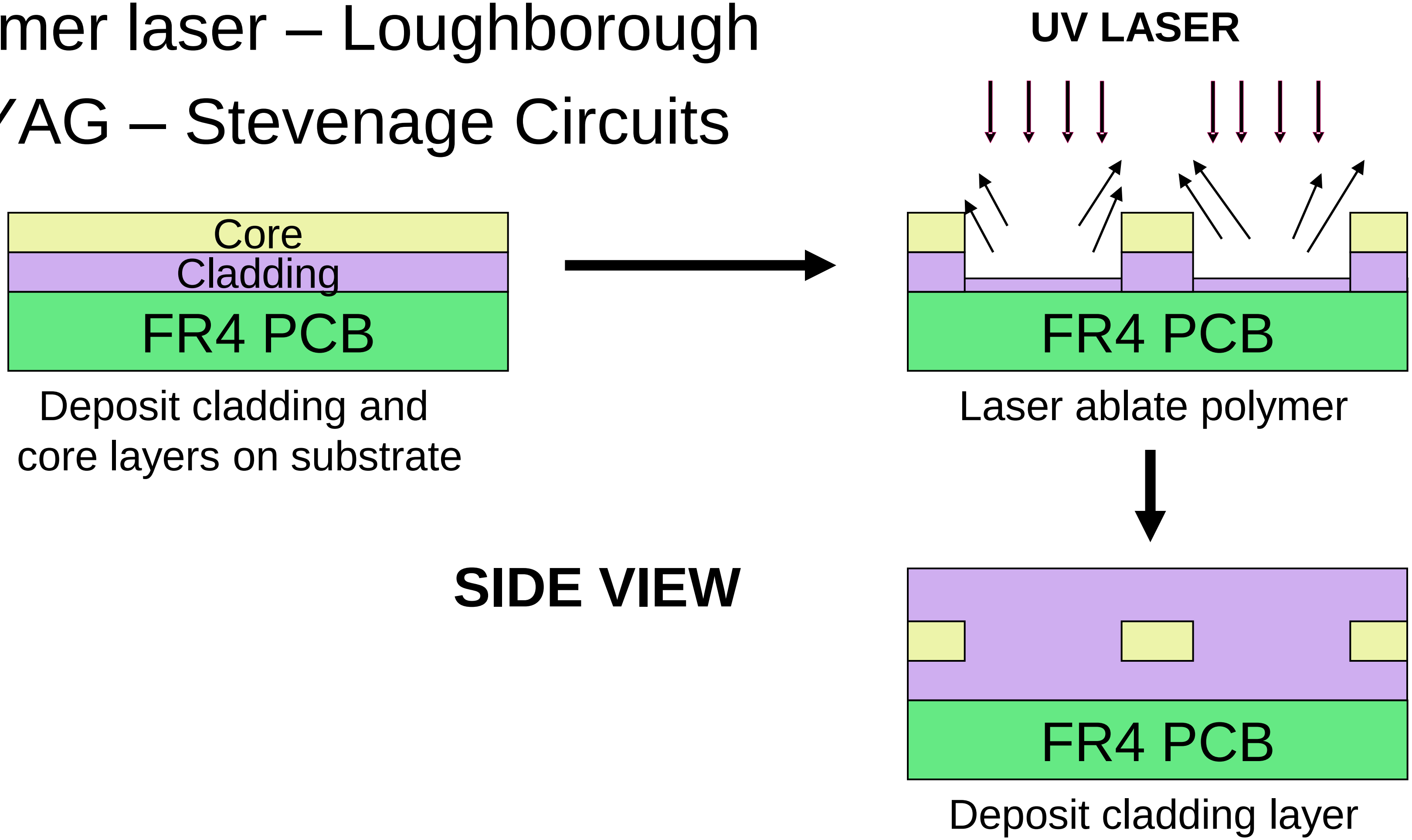
# Laser direct written backplane



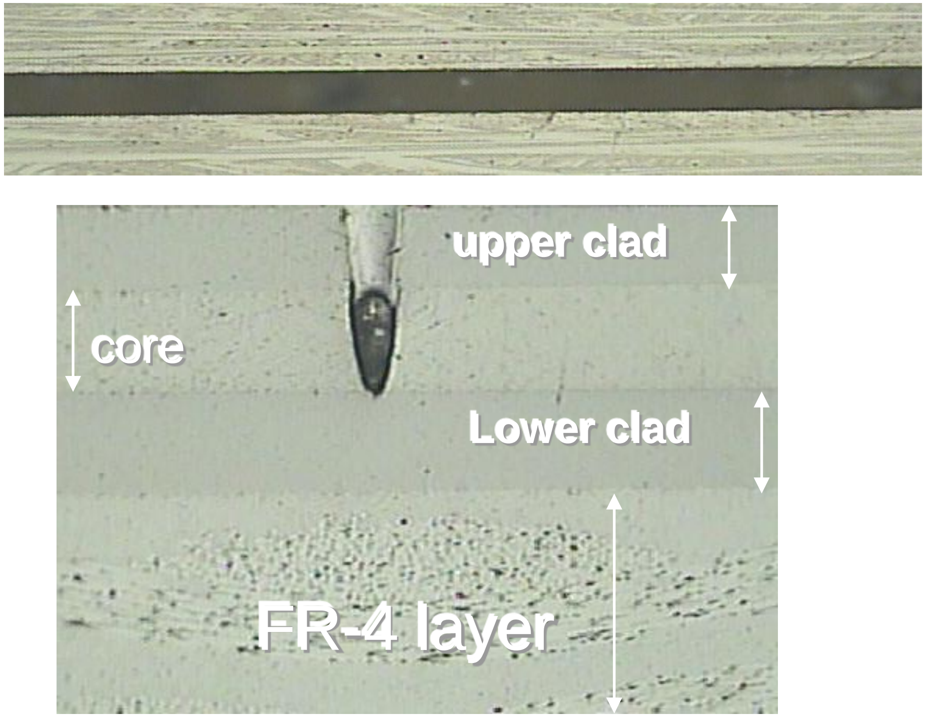

- HWU Direct laser written waveguide cores and cladding backplane layout designed by UCL fabricated on FR4

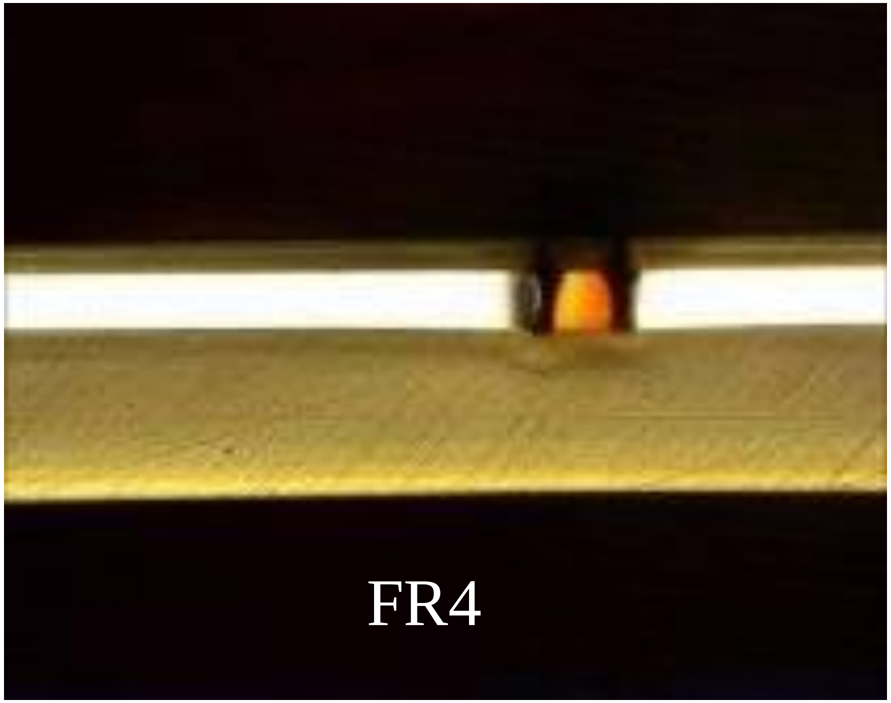
# Laser Ablation for Waveguide Fabrication

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



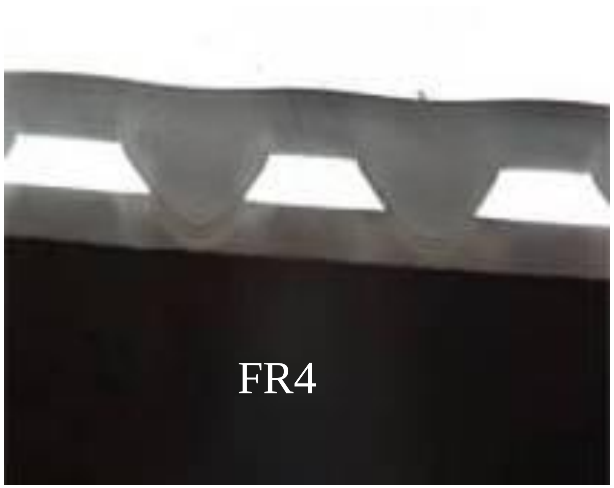
# Nd:YAG Ablation




- Nd:YAG laser based at Stevenage Circuits
- Grooves machined in optical polymer and ablation depth characterised for machining parameters
- Initial waveguide structures prepared

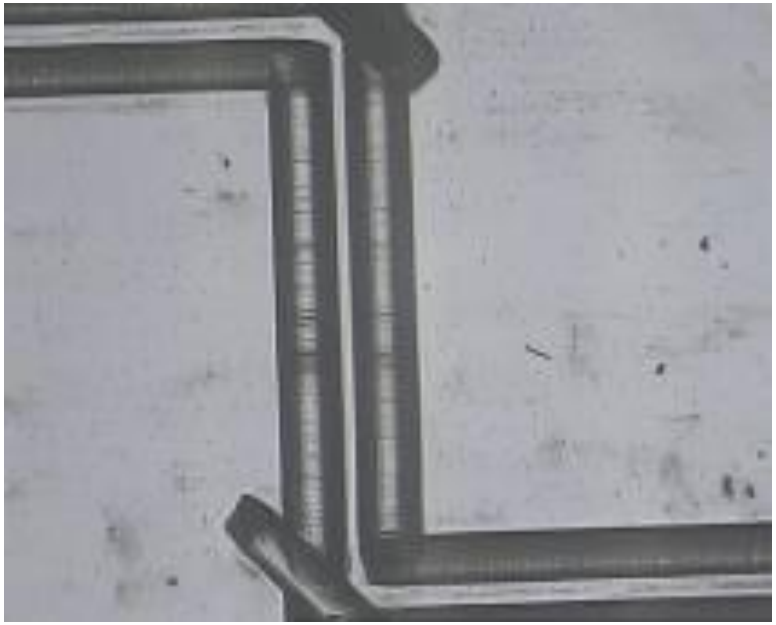
# CO2 Laser Ablation of Polyacrylate Waveguides




A cross-section through an array of waveguides fabricated in polyacrylate using $CO_2$ laser ablation

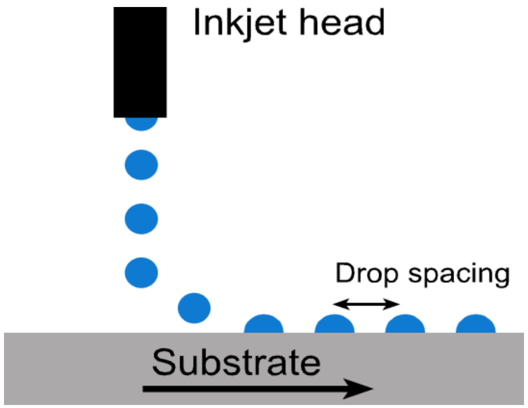
# Excimer Laser Ablation of Polyacrylate Waveguides

Cross-section through a waveguide (approx. 50 μm x 35 μm) formed in polyacrylate by excimer laser machining.

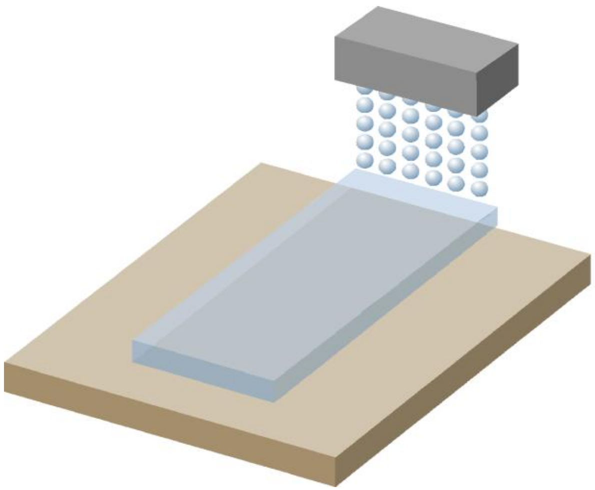


A plan view image of two 45 degree in-plane mirror structures formed in an optical waveguide by excimer laser ablation in polyacrylate.

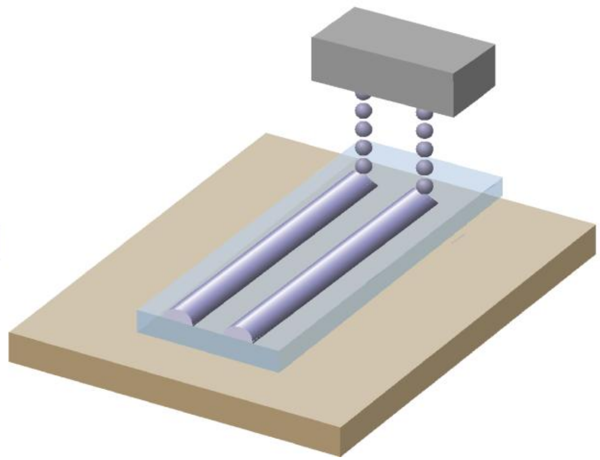
# Inkjetting as a Route to Waveguide Deposition



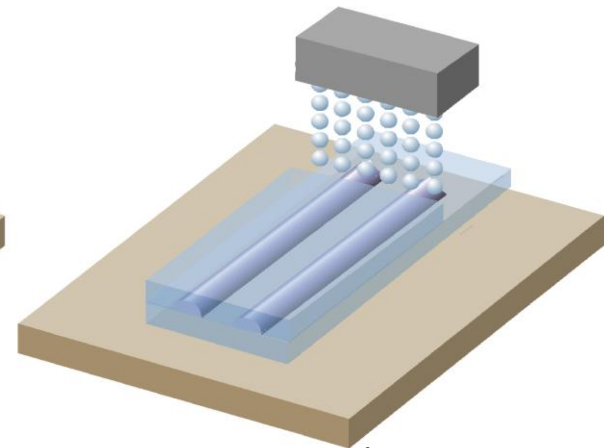

- Print polymer then UV cure
- Advantages:
  - controlled, selective deposition of core and clad
  - less wastage: picolitre volumes
  - large area printing
  - low cost



**Deposit Lower Cladding**



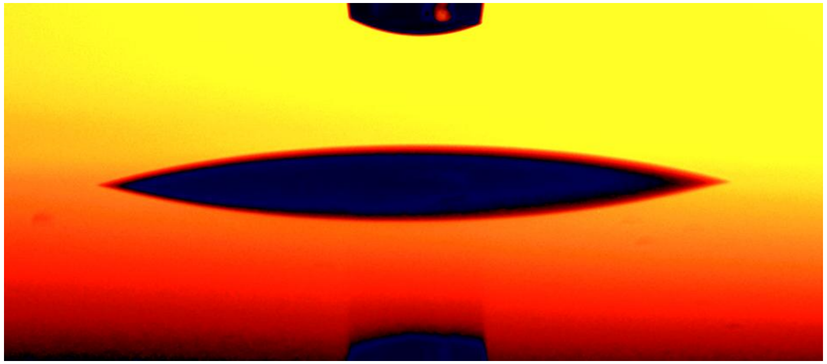
**Deposit Core**



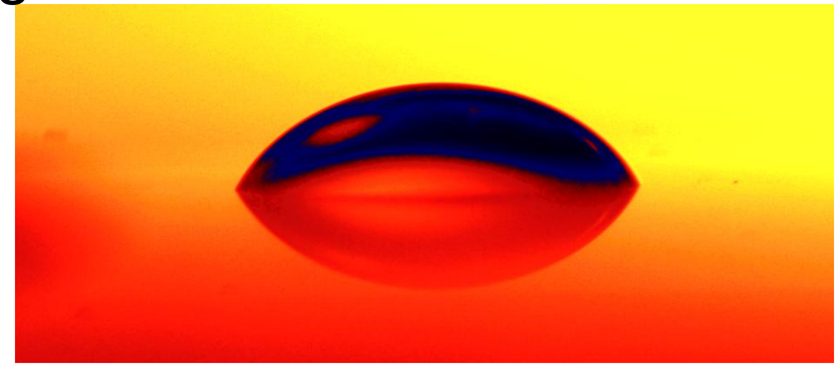
**Deposit Upper Cladding**

# Changing Surface Wettability

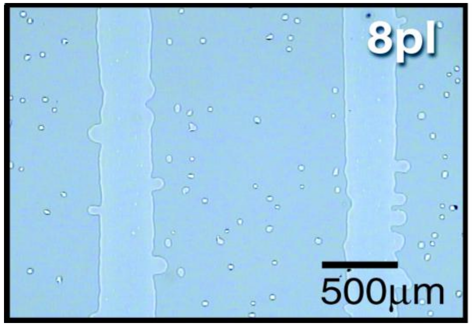
Contact Angles

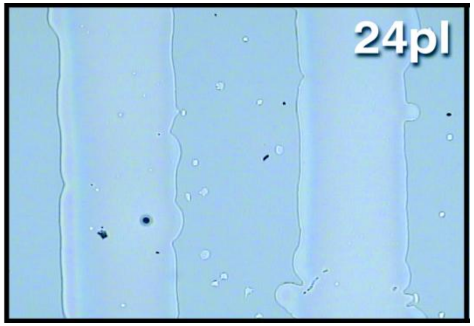


Core material on cladding

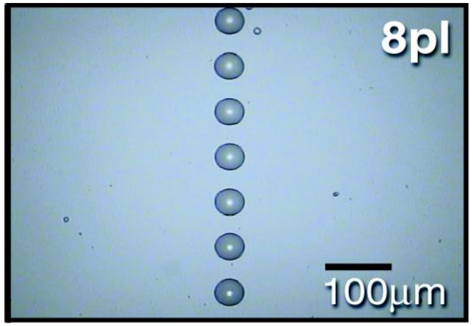


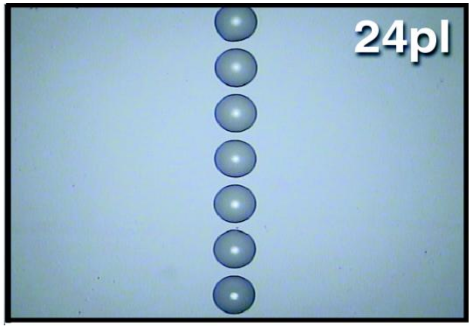
Core material on modified glass surface (hydrophobic)




Large wetting - broad inkjetted lines

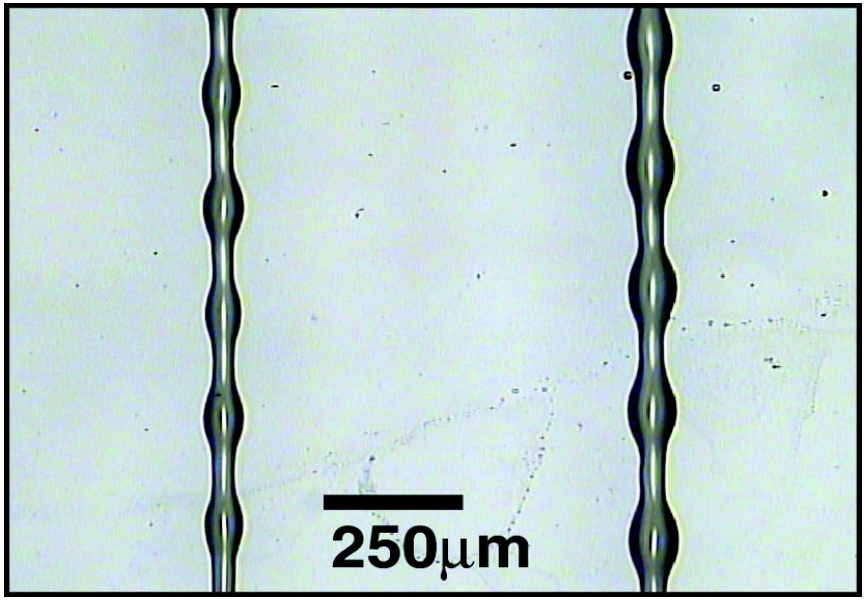


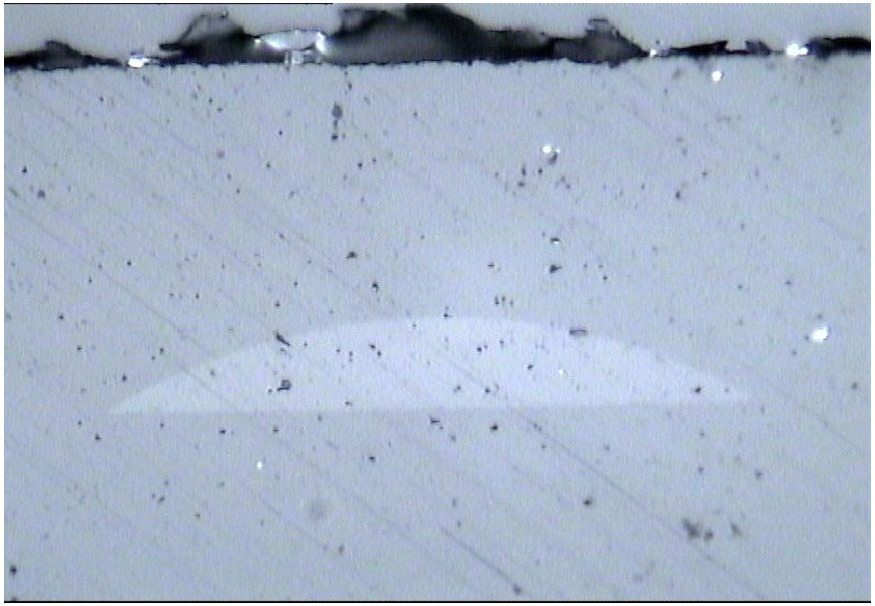

Reduced wetting – discrete droplets

Identical inkjetting conditions - spreading inhibited on modified surface

# Towards Stable Structures



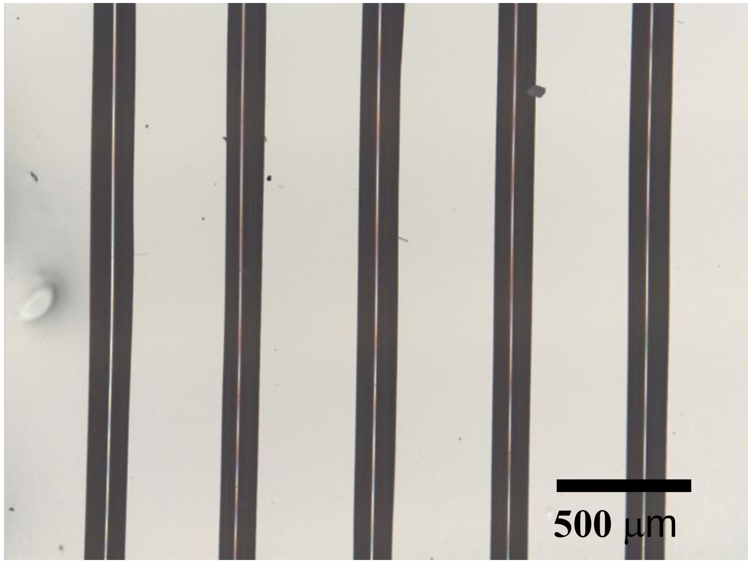

Stable line structures with periodic features



Cross section of inkjetted core material surrounded by cladding (width 80 microns)

A balance between wettability, line stability and adhesion

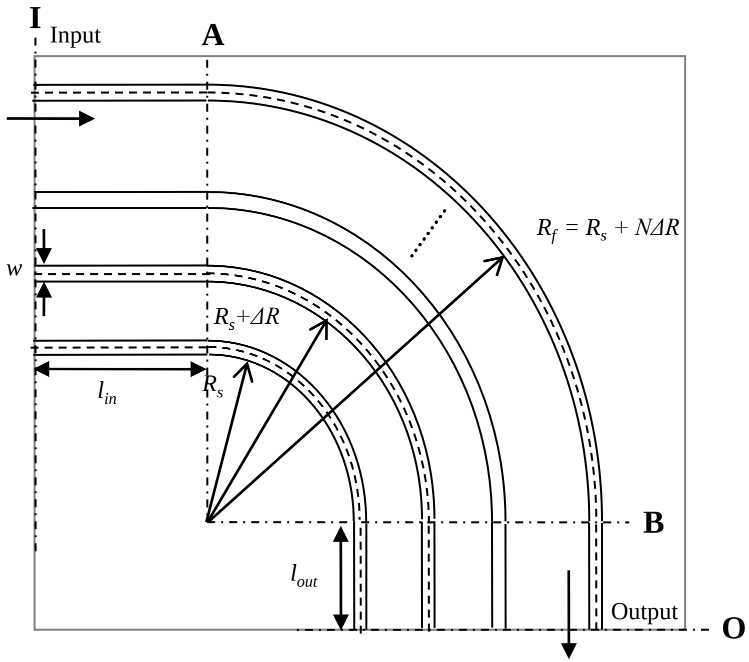
# Final Ink Jet Printed Waveguides



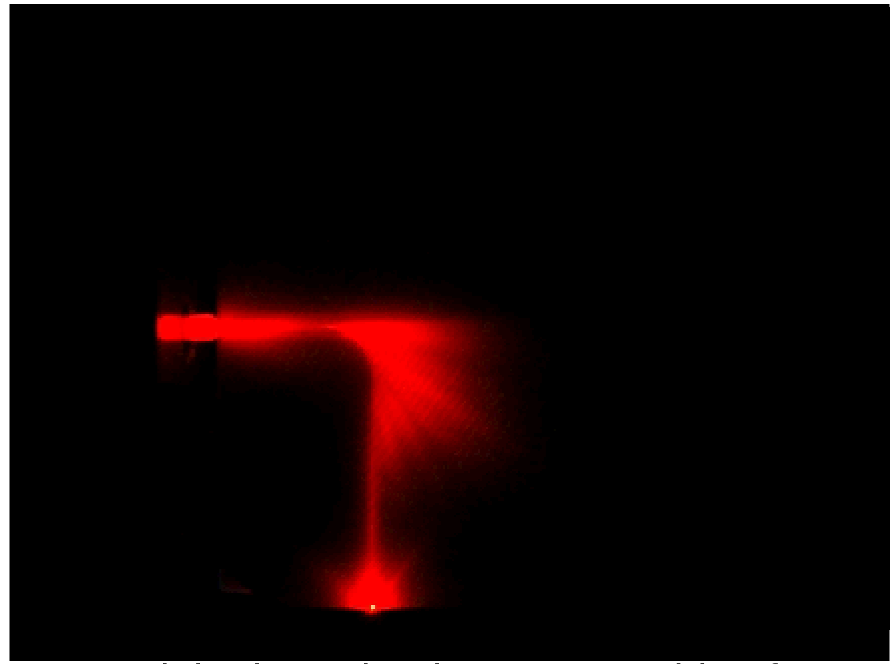

Waveguides of OE4140 optical polymer inkjet printed onto OE4141 cladding using multiple print and cure passes.

A cross-section through an inkjet printed waveguide of OE4140 core on cladding prepared using multiple print and cure cycles.

# Optical Power Loss in 90  Waveguide Bends



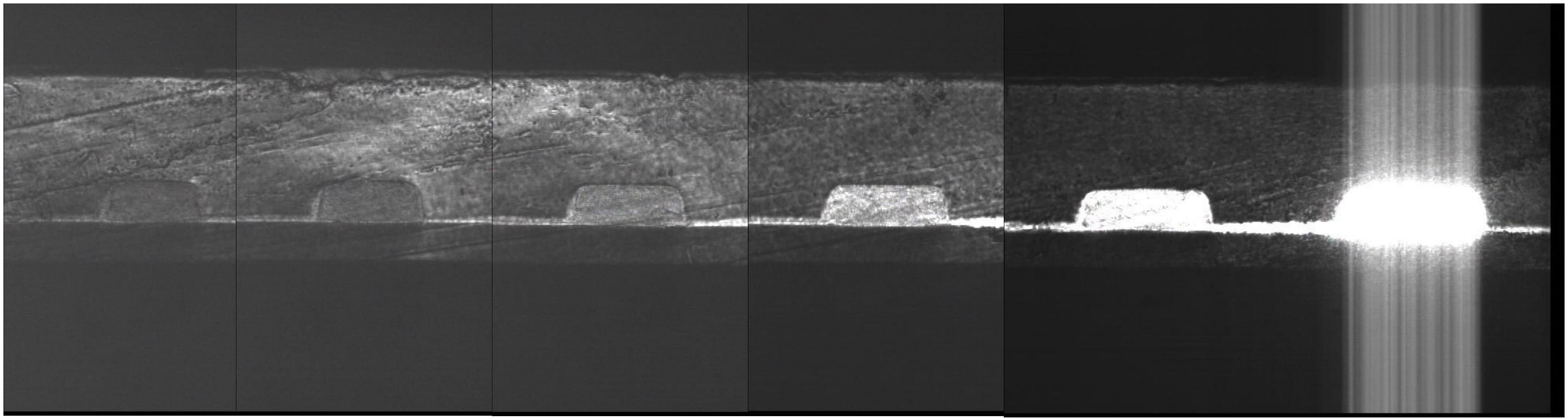

Schematic diagram of one set of curved waveguides.



Light through a bent waveguide of *R* = 5.5 mm – 34.5 mm

- Radius *R*, varied between 5.5 mm < *R* < 35 mm, *ΔR* = 1 mm
- Light lost due to scattering, transition loss, bend loss, reflection and back-scattering
- Illuminated by a MM fiber with a red-laser.

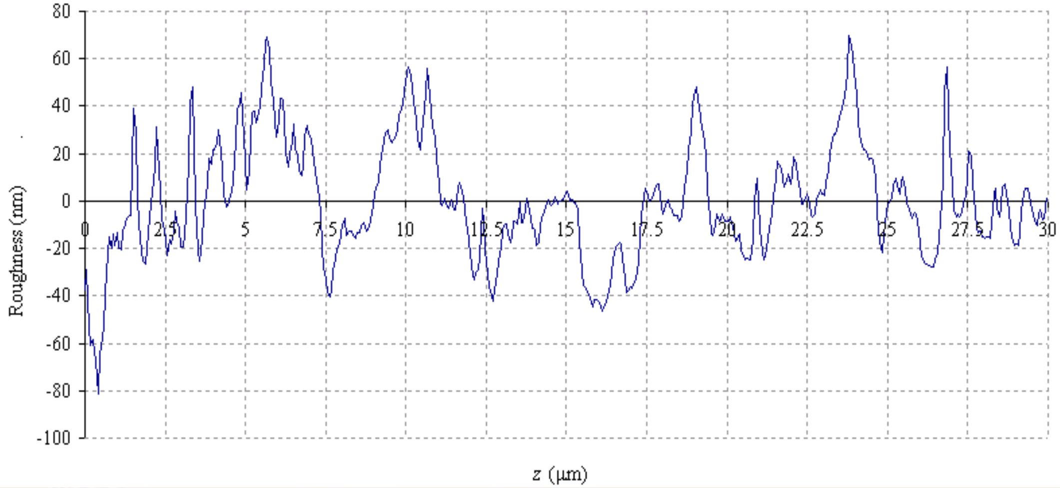
# Crosstalk in Chirped Width Waveguide Array



100 µm 110 µm 120 µm 130 µm 140 µm 150 µm

- 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

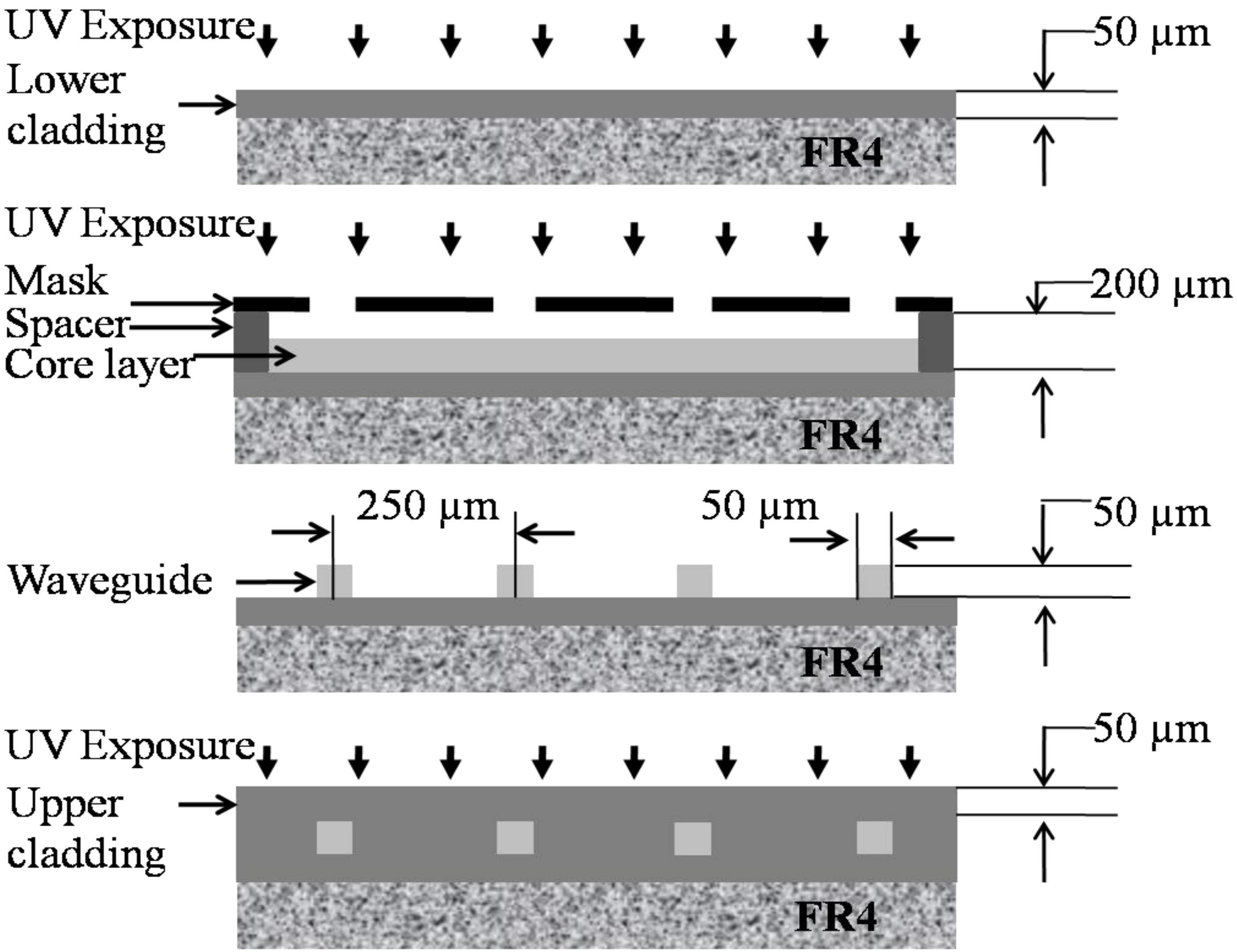




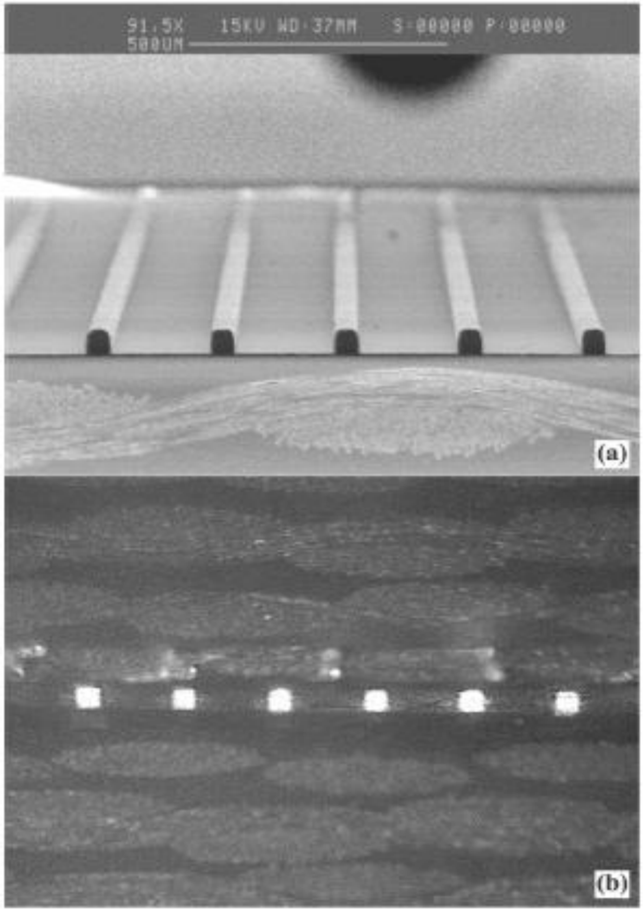
- RMS side wall roughness: 9 nm to 74 nm

- RMS polished end surface roughness: 26 nm to 192 nm.

# Photolithographic Fabrication of Waveguides

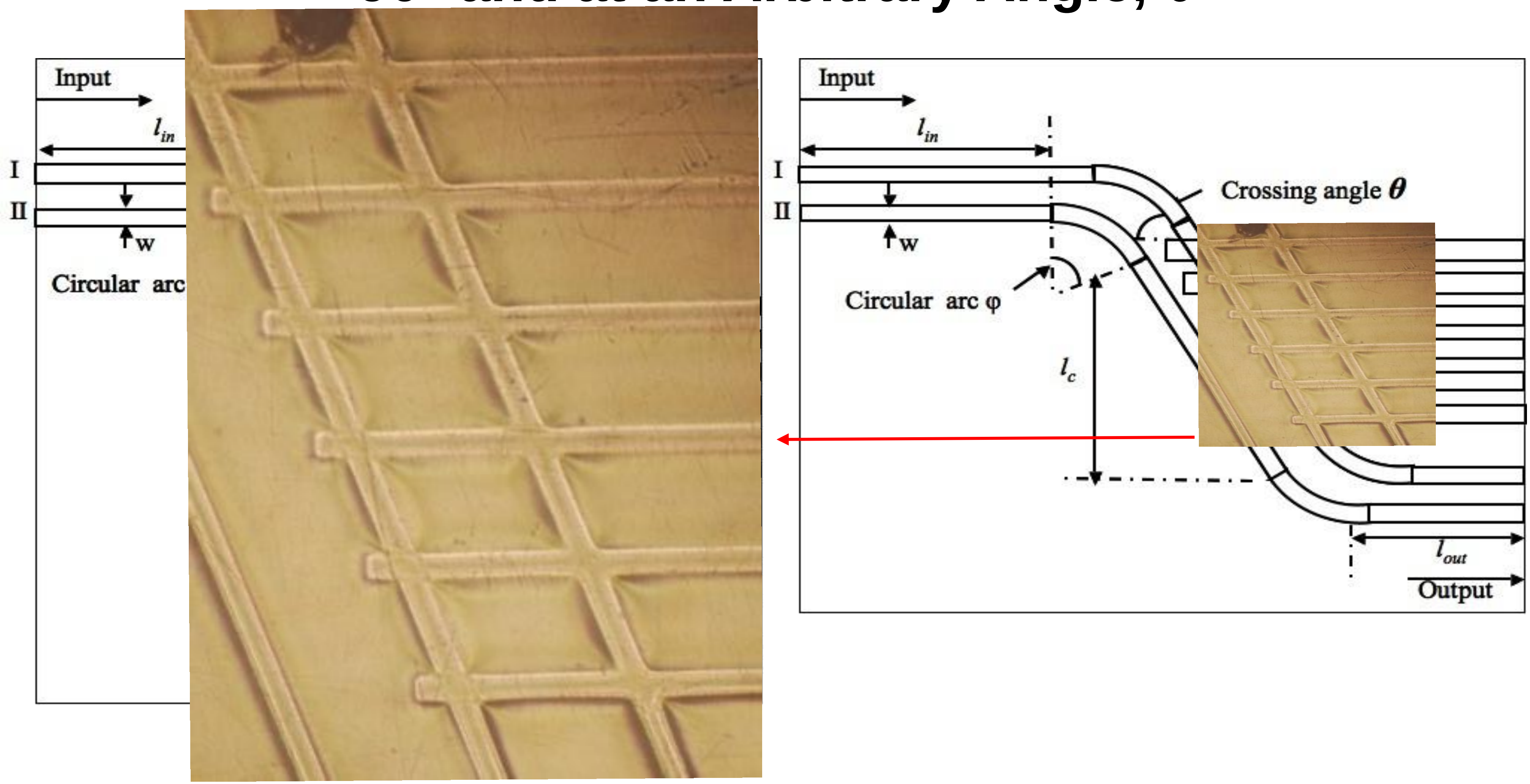


# Polymer waveguides formed by Photolithography in Truemode® polymer

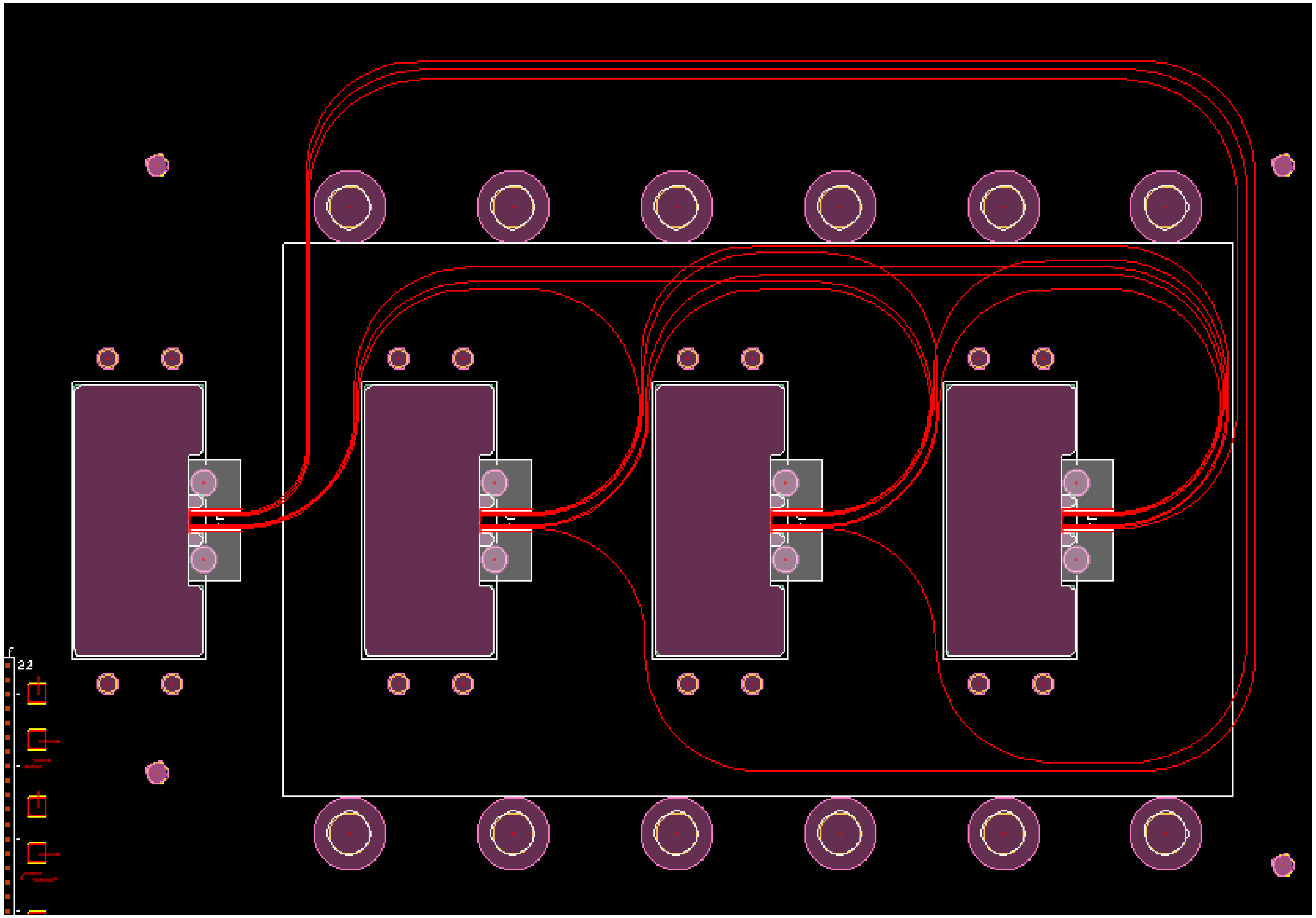



Happy T. Holden
*The developing technologies of integrated optical waveguides in printed circuits*
Circuit World
29/4 [2003] 42–50

# Schematic Diagram Of Waveguide Crossings at 90° and at an Arbitrary Angle, *θ*

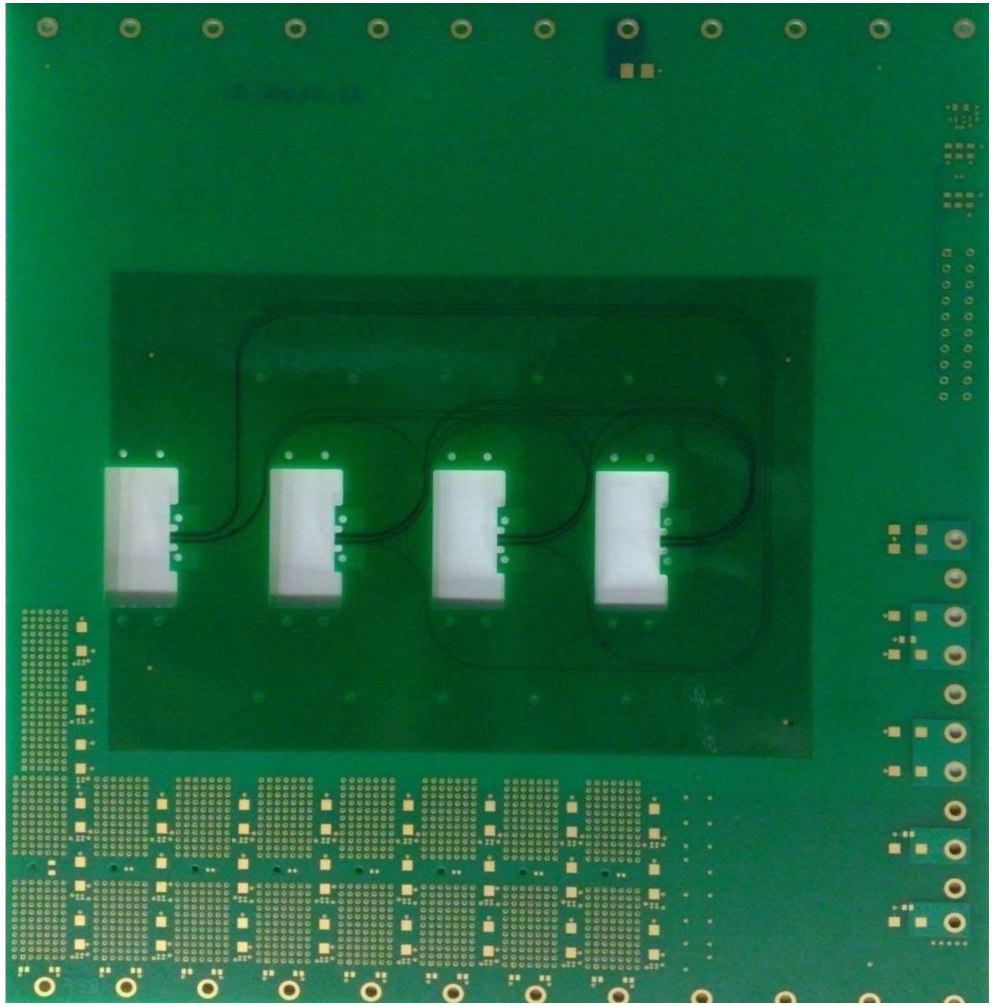


# System Demonstrator

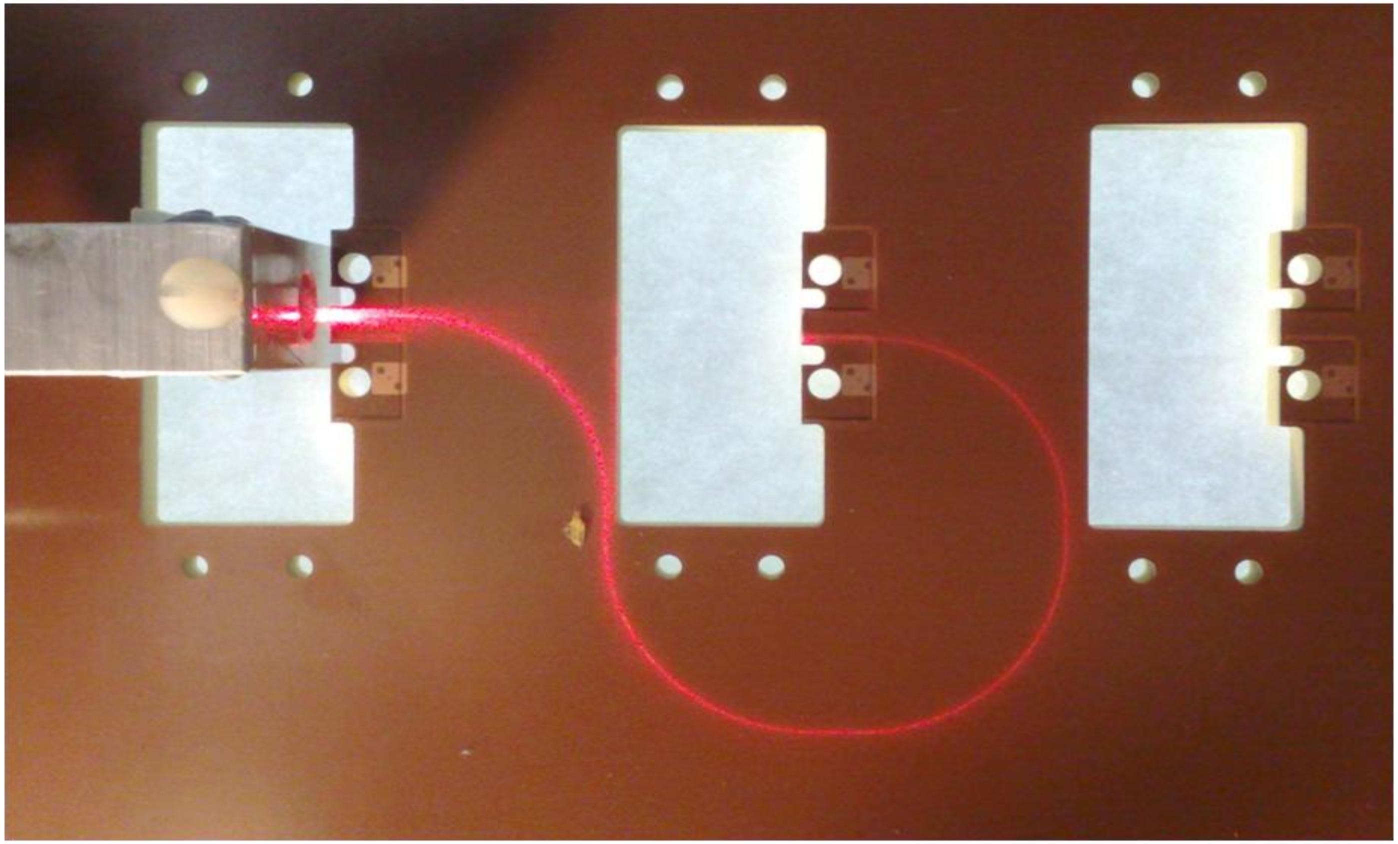


**Fully connected waveguide layout using design rules**

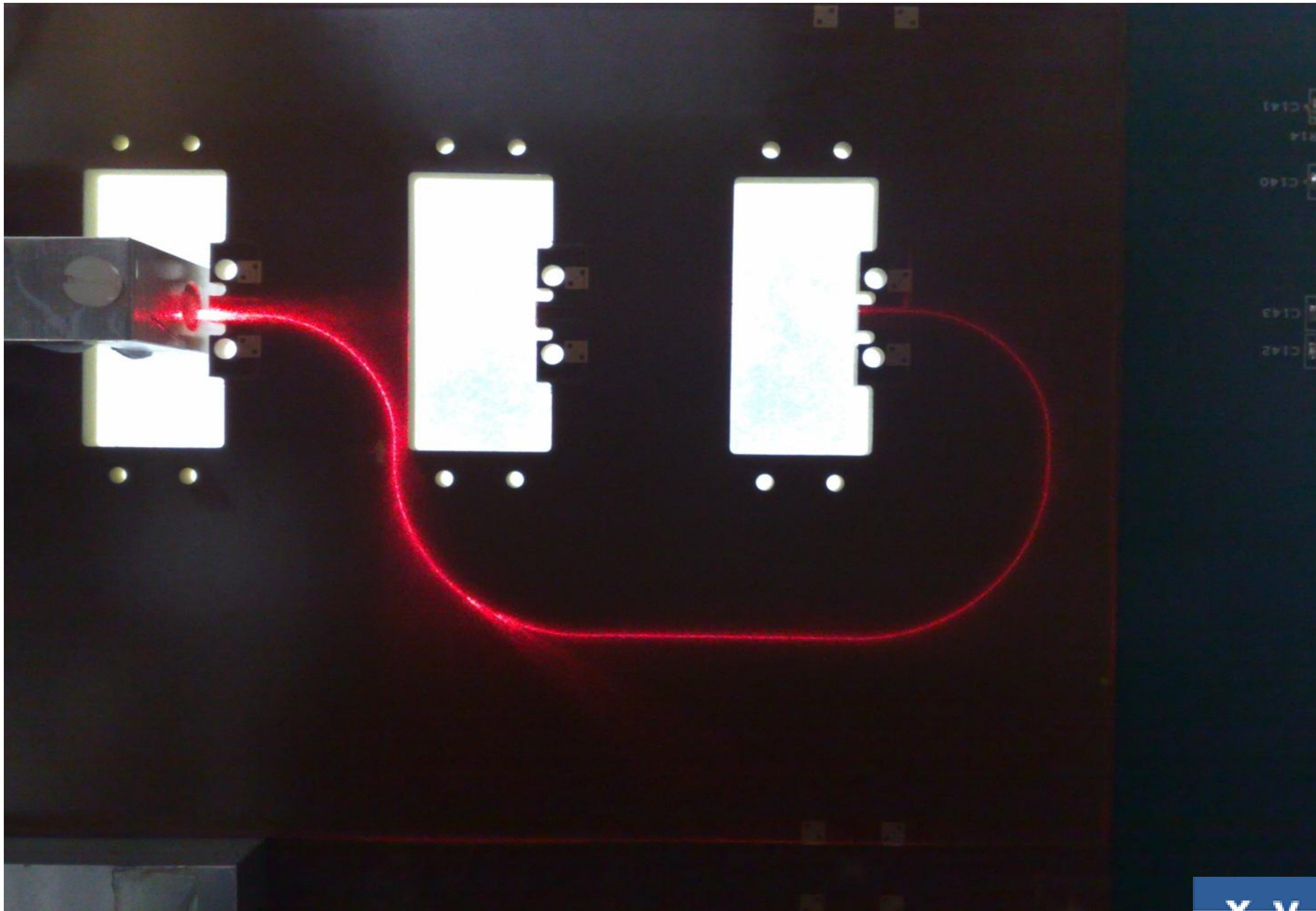
# Demonstrator Dummy Board



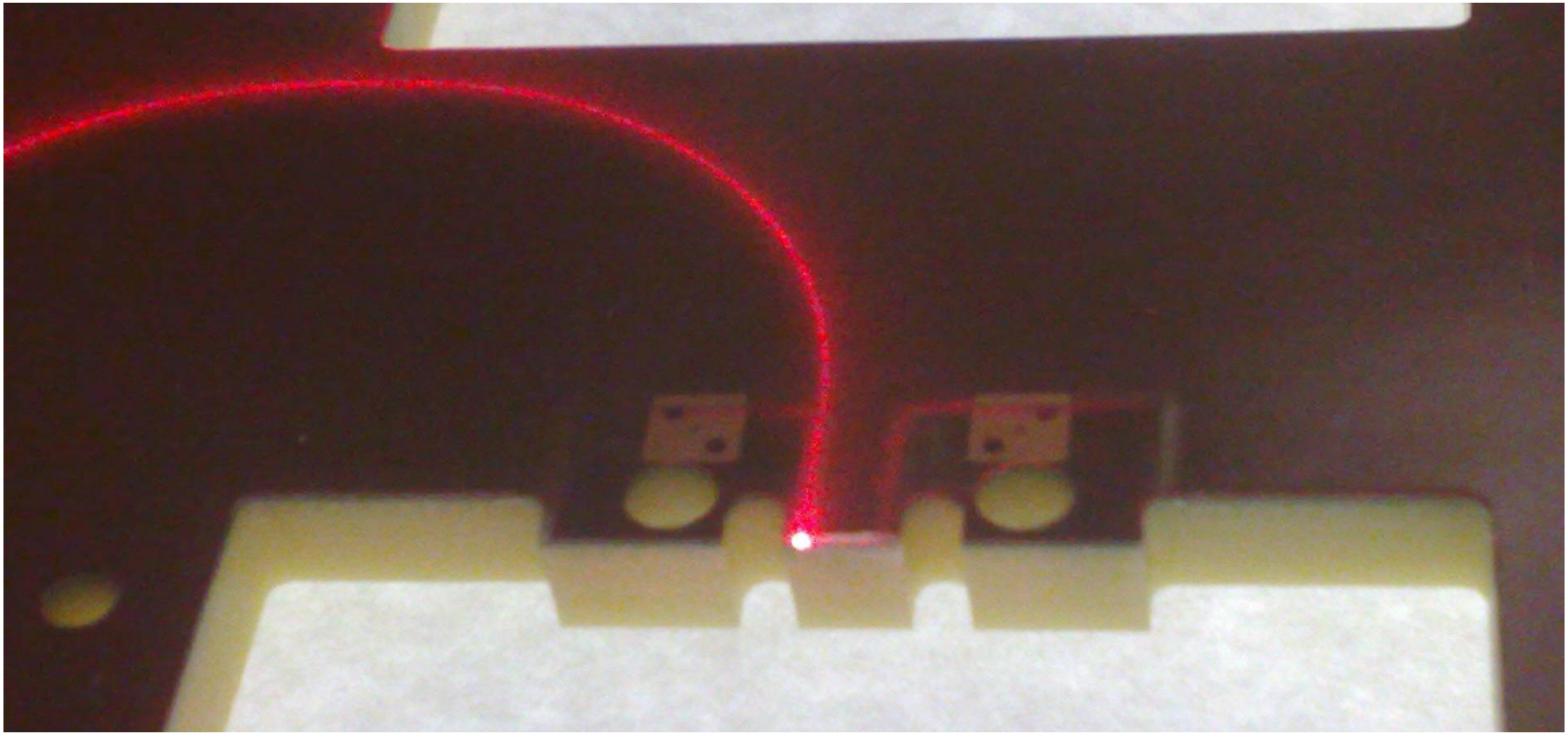
# The Shortest Waveguide Illuminated by Red Laser



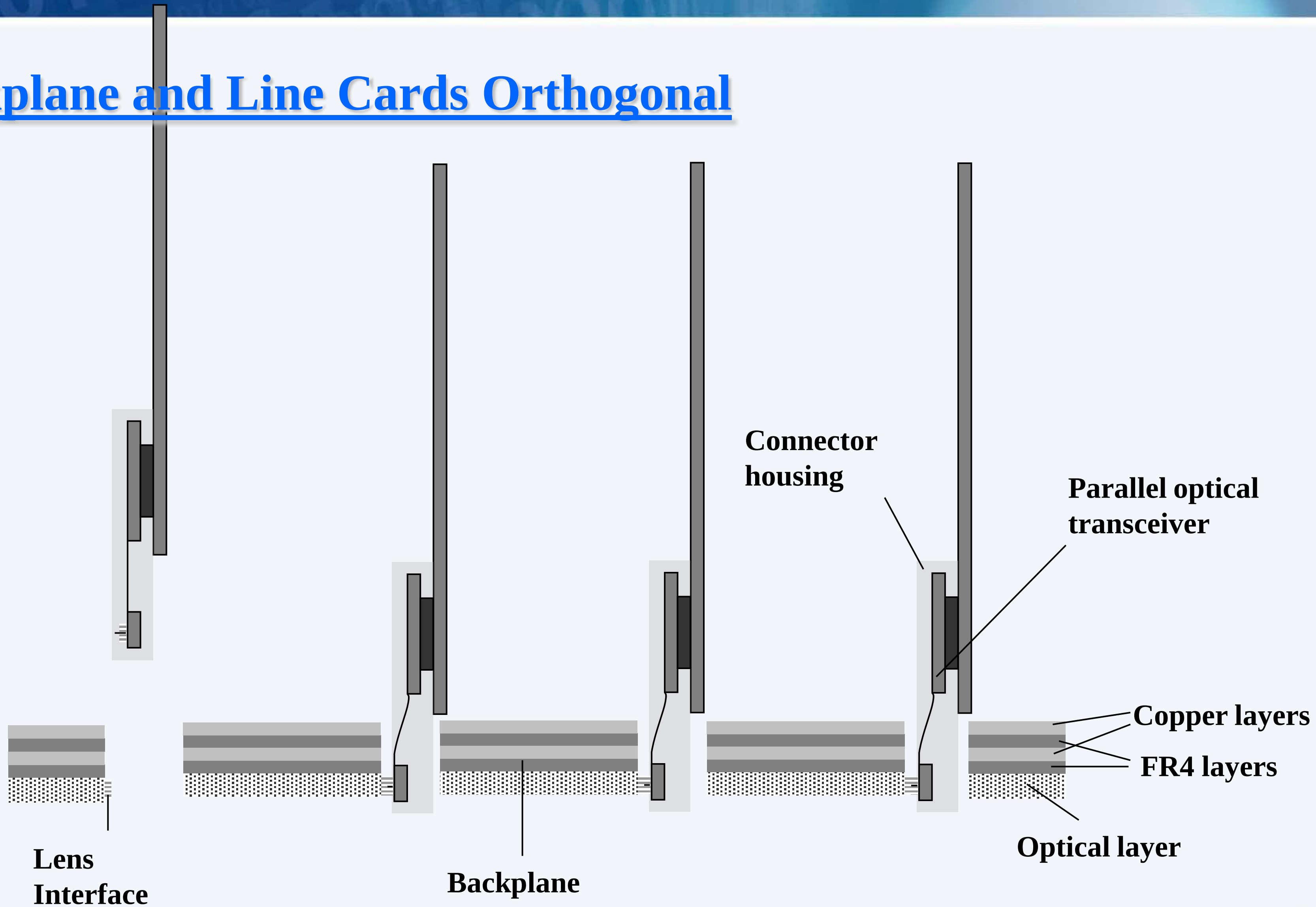
# Waveguide with 2 Crossings Connected 1$^{st}$ to 3$^{rd}$ Linecard Interconnect



# Output Facet of the Waveguide Interconnection



# Backplane and Line Cards Orthogonal



# VCSEL Array for Crosstalk Measurement

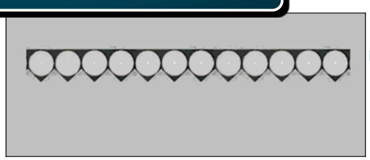
**PIN Array**

**Source:** **Microsemi Corporation**

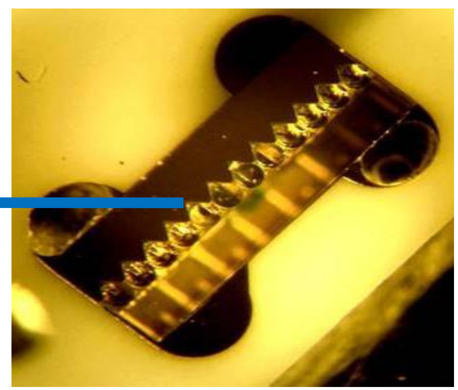
**VCSEL Array**

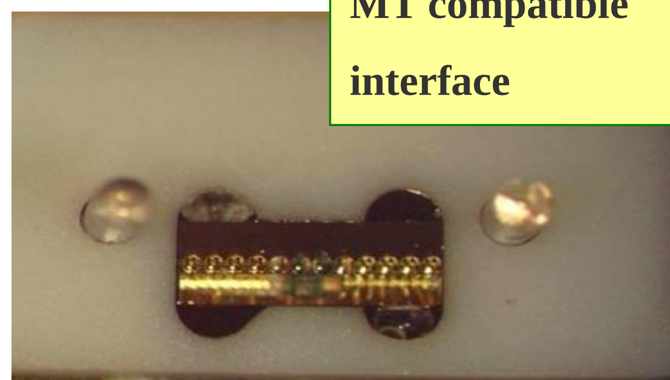
**Source: ULM Photonics GmbH**

**GRIN Lens Array**



**Source:** **GRINTech GmbH**





**MT compatible interface**

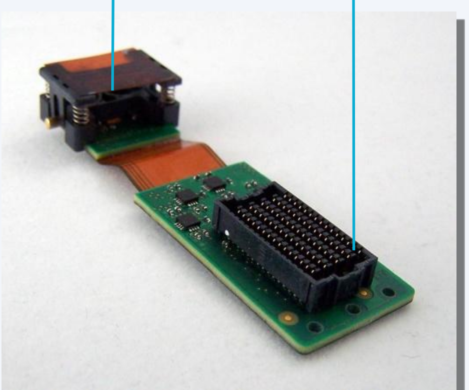
# PARALLEL OPTICAL PCB CONNECTOR MODULE

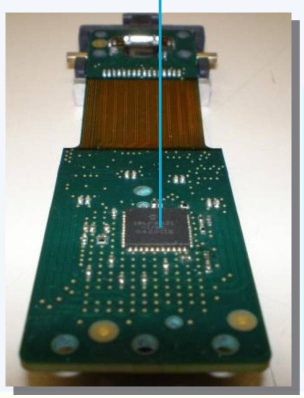
## Parallel optical transceiver circuit

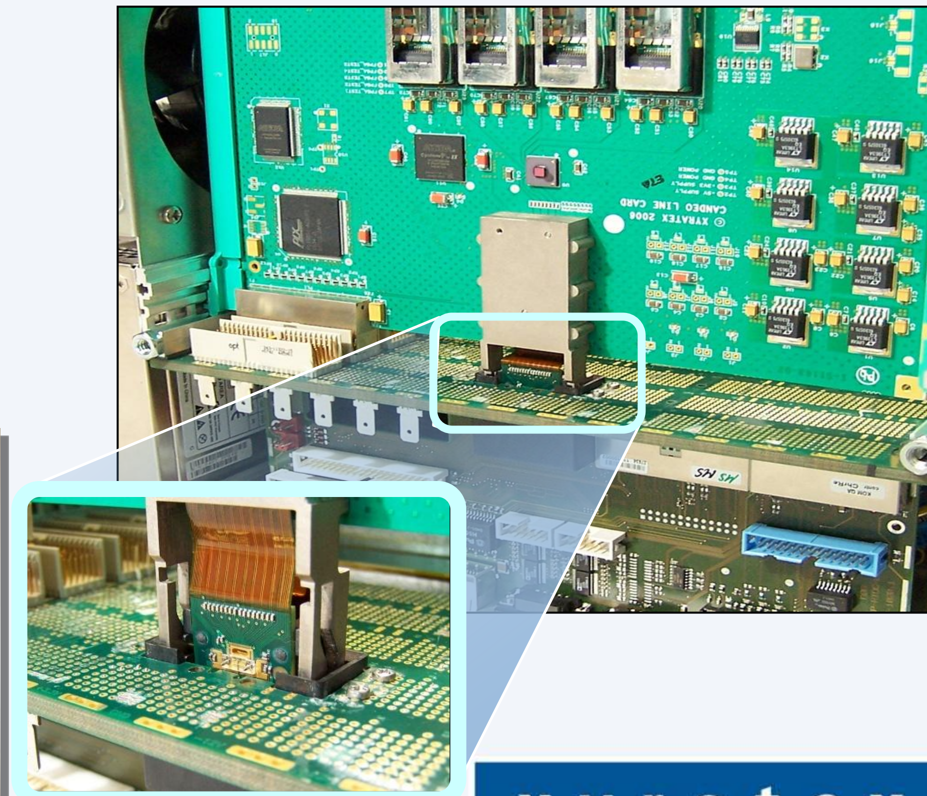
- ❑ Small form factor quad parallel optical transceiver
- ❑ Microcontroller supporting I²C interface
- ❑ Samtec "*SEARAY™*" open pin field array connector
- ❑ Spring loaded platform for optical engagement mechanism
- ❑ Custom heatsink for photonic drivers

## Backplane connector module

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



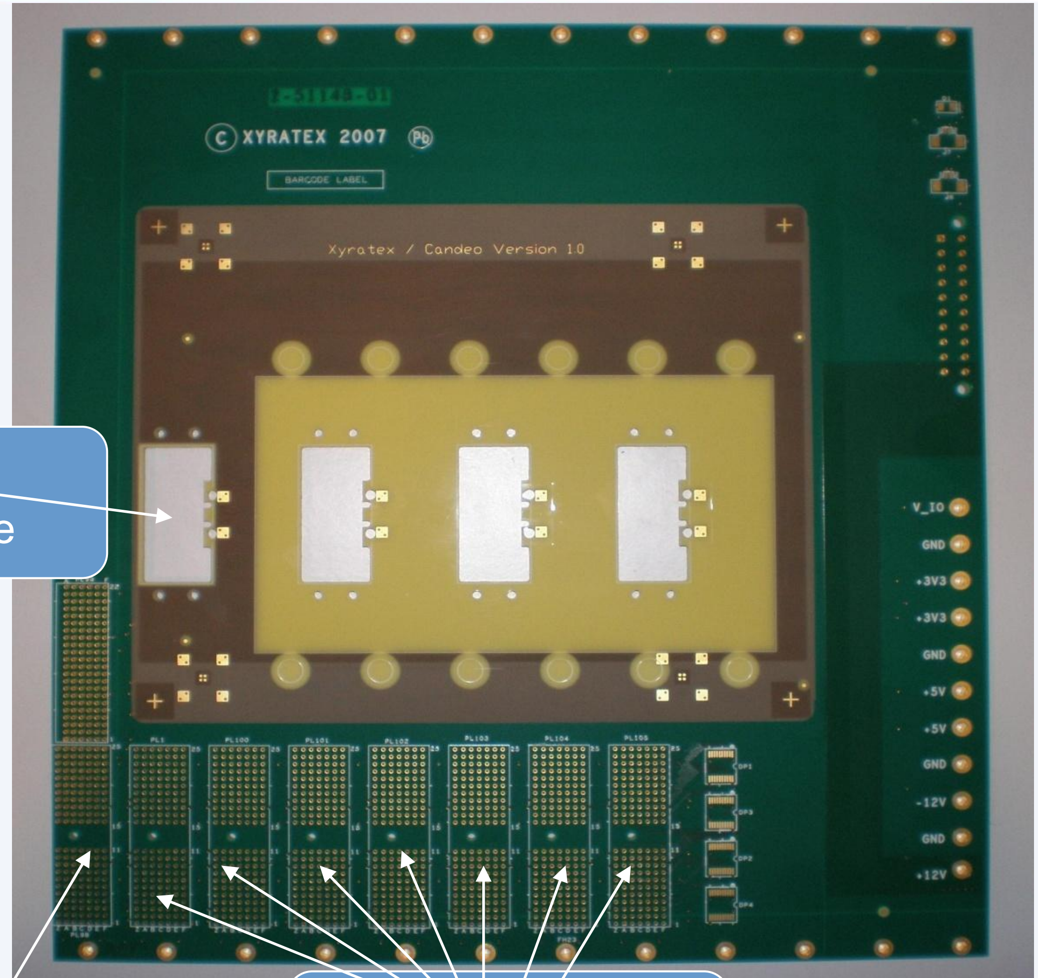



xyratex

## 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




Optical connector site

Compact PCI slot for single board computer

Compact PCI slots for line cards

# ELECTRO-OPTICAL BACKPLANE

<u>Hybrid Electro-Optical Printed Circuit Board</u>

- ❑ 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
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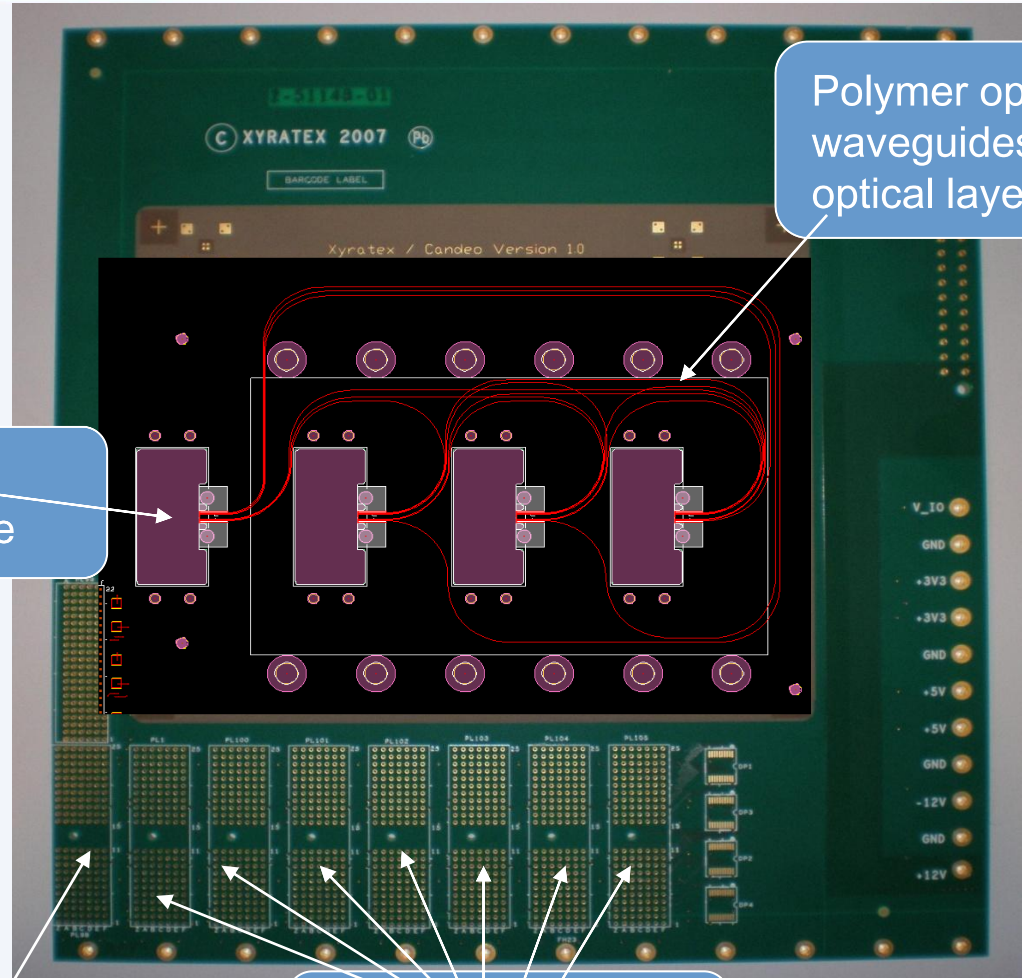
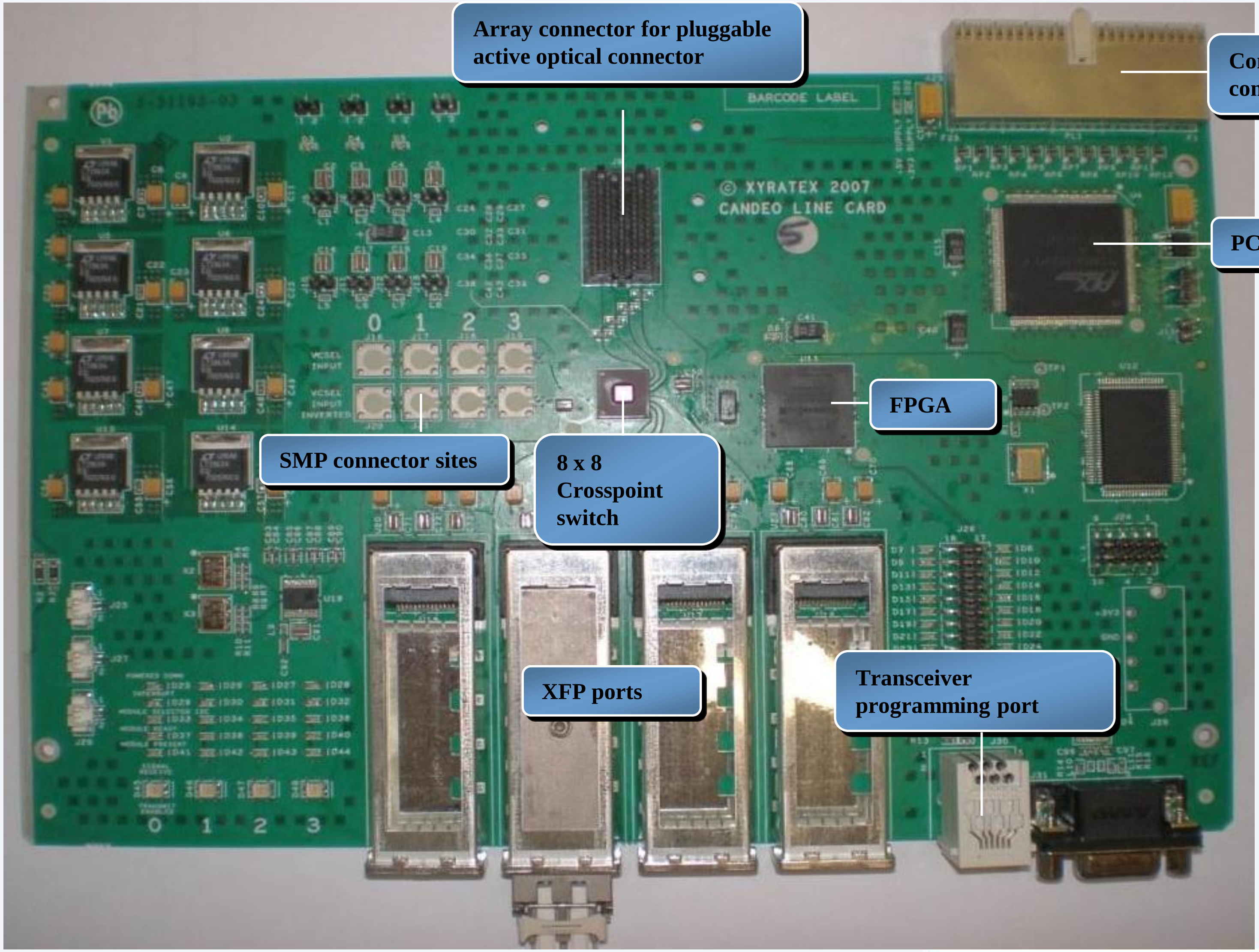
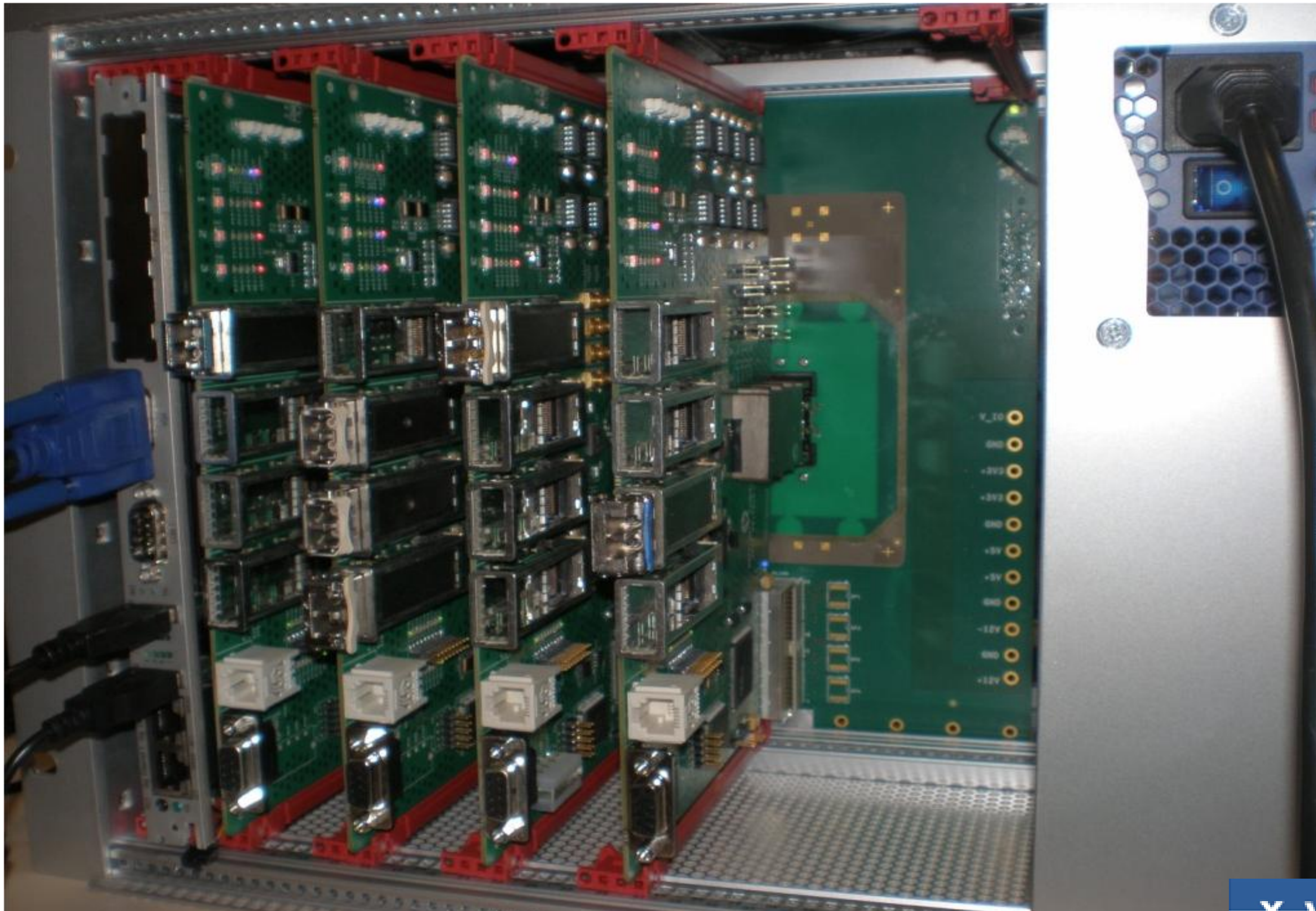


# High Speed Switching Line Card



# Demonstrator with Optical Interconnects



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