Integrated Optical & Electronic Interconnect PCB Manufacturing
Tuesday, March 16, 2010 | David R. Selviah, Dept. of Electronic and Electrical Engineering, UCL

Digital information, encoded onto light signals, is regularly sent along optical fibres over distances varying from a few metres to thousands of kilometres. Fibres have largely replaced traditional copper cables for high performance broadband communication over distances exceeding a metre, as they offer advantages such as lower cost, immunity to electrical interference and weight savings. Printed circuit board (PCB) backplanes are widely used in the electronic cabinets, or racks, that form the heart of a variety of IT systems and incorporate connectors to allow other PCBs to be attached and detached at right angles (Figure 1). In the highest speed computers, for communication between the central processor arrays, hard disc storage arrays, and through data routing switches, there is now considerable interest in incorporating high speed "optical wiring," by means of plastic light-guides, within large, metre-scale, electrical PCBs combining optical and electrical interconnections (OPCBs).

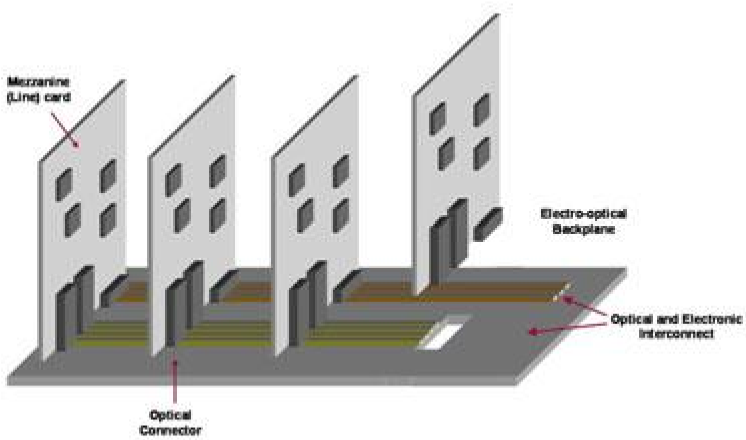

Figure 1: Schematic view of system backplane architecture.

Optical interconnections were investigated in this I*e*MRC "Integrated Optical and Electronic Interconnect PCB Manufacturing" flagship project for short distance, high-speed, data communication applications on PCBs to replace high data rate copper tracks which suffer severe cross-talk and increased loss and increased cost at data rates above 10 Gb/s. This three-year research project explored methods for the manufacture of optical waveguides within an optical layer laminated into the board and investigated their compatibility with techniques already in use in commercial PCB manufacturers.

Four different polymer waveguide manufacturing techniques were investigated and compared: Photolithography, direct laser writing, laser ablation and inkjet printing. Some of these techniques were very new, while others were more established, although in all cases their extension to larger areas and adaptation for use by PCB manufacturers remained a significant challenge. As the photolithographic fabrication technique was better established, so waveguides fabricated by this method at two companies in two polymers, were measured and used as a benchmark to compare with those fabricated by the other methods as they were developed during this project.

Another aim of the research was to take the findings and use them to adapt existing computer programmes, used for laying out patterns of copper tracks, so that they incorporated new rules suitable for designing optical waveguide layouts in OPCBs. By working with materials suppliers within the consortium, new polymer formulations were developed suitable for rapid production of waveguides on large area boards and characterised. In addition, research considered low cost methods for polishing the waveguide end facets to increase light throughput and waveguides were tested under severe conditions of high temperature and humidity to determine these effects on their losses.

The large team of university and industrial collaborators comprised: The Electronic and Electrical Engineering Department, University College London, UCL (Instigator, Principal Investigator and Technical Project Leader); the School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh; and the Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University--together with eight companies: Xyratex Technology (Project Manager and manufacturer of petabyte data storage systems), BAE Systems (global aerospace, security and defence company), Renishaw, Dow Corning USA (polymer supplier), Exxelis (polymer supplier), Stevenage Circuits Ltd. (PCB manufacturer), Cadence Design Systems (PCB layout software supplier) and National Physical Laboratory (national standards laboratory).

Figure 2: The project sponsors and the consortium.

Consortium partners Xyratex, BAE Systems and Renishaw formed the end user system partner group. The end users provided specifications for the types of optically and electrically interconnected PCB that are required for practical exploitation of this novel technology. In addition, Xyratex was, in parallel, carrying out an internal research and development project called "Candeo" to develop active pluggable in-plane connectors for optical backplanes and a demonstration assembly, which incorporated a fully operational electro-optical backplane, high speed switch test cards and the prototype connectors.

Xyratex was able to provide precise specifications for prototype OPCB backplanes required for use in their system demonstrator. UCL, having established waveguide design rules from comprehensive waveguide measurements and modelling, collaborated with Cadence to use their PCB layout software to design complex waveguide interconnection patterns and test waveguide component structures, The waveguide design files were supplied directly or after fabrication of photomasks to all fabrication partners for waveguide fabrication.

Consortium polymer partners, Dow Corning supplied their OE4140 and OE4141 photopatternable polysiloxane and Exxelis supplied their Truemode™ photosensitive polyacrylate formulation to fabrication partners: Heriot Watt University for direct laser writing fabrication, Loughborough University in collaboration with Stevenage Circuits for laser ablation, to Loughborough University for ink jet printing fabrication and to Stevenage Circuits for photolithographic, laser direct imaging and laser ablation fabrication in order to develop their different manufacturing processes.

In addition, Dow Corning and Exxelis themselves fabricated waveguides in their own polymers, in house, using photolithographic techniques. Heriot Watt University developed their own photosensitive polyacrylate formulations to increase the speed of their direct laser write process. All of the fabricated waveguides were sent to UCL for development of measurement techniques and use of them to characterise and compare the waveguide performance, as the fabrication processes were themselves developed.

NPL developed an alternative measurement technique and some waveguides measured at UCL were remeasured at NPL giving the same results to within experimental measurement accuracy so validating both techniques. UCL also sent measured waveguides to BAE Systems and Stevenage Circuits for accelerated aging being returned them to UCL at regular intervals for remeasurement to assess any deterioration of performance.

Further research interactions between the partners are also indicated below in the more detailed descriptions of the research performed.

Computer Aided Design (CAD) and Test and Measurement of Waveguide Structures

UCL was technical leader of the entire project and their research included:

- Establishment of waveguide design rules from comprehensive measurements and modelling of waveguide components, including bends and crossings.
- Modification of widely-used commercial computer aided design layout tool software, Cadence Allegro/OrCAD, to enable it to design the novel optically and electronically interconnected PCBs (OPCBs).
- Measurement of waveguide insertion loss of each of the four waveguide manufacturing techniques and comparison with National Physical Laboratory's measurements.
- Investigation and analysis of the effect of waveguide wall roughness, end facet roughness and cross sectional shape on the behaviour of light and the effect on waveguide loss.
- Comparison of the benefits of different methods of milling and polishing waveguide end facets (in collaboration with Xyratex and Stevenage Circuits

Ltd.).

- Characterisation of the behaviour of optical waveguides in aging tests at high temperature and humidity (in collaboration with BAE Systems and Stevenage Circuits Ltd.).
- Development of novel connector designs suited for interfacing flip chip lasers and photodiodes to OPCBs (in collaboration with Loughborough University and Stevenage Circuits Ltd.).
- Development of low cost novel manufacturing techniques compatible with commercial PCB manufacturing processes (in collaboration with Stevenage Circuits Ltd.).
- Sourcing of suitable waveguide manufacturing techniques and material and transfer of technology to Stevenage Circuits Ltd.

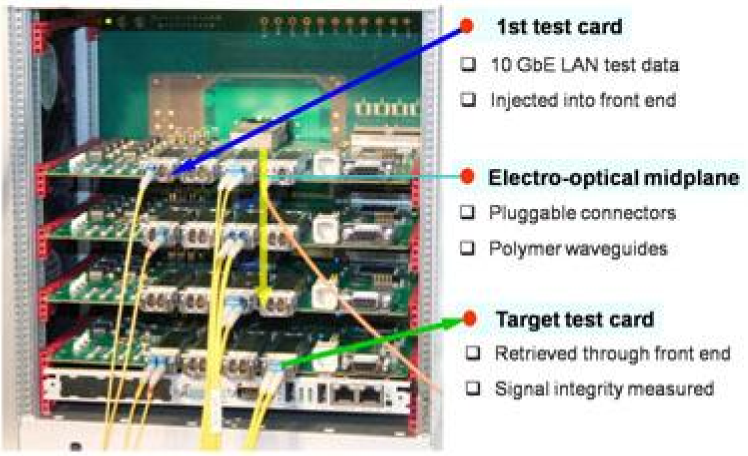

Figure 3: 10 Gb/s Ethernet system demonstrator with an integrated optical waveguide and multilayer copper track interconnected printed circuit board backplane fully interconnecting 3 daughter (line) cards via novel 80 Gb/s aggregate self aligning optical pluggable connectors.

The waveguide design rules were used to design a novel complex optical backplane layout. The end user system industrial partners specified two main requirements for demonstration of a practically viable system: First, the line-cards had to be directly interchangeable (without rotation); so all optical interfaces were designed to face in the same direction and to be identical to each other; second, the line-cards were required to be closely spaced. An interconnection pattern was designed (Figure 5(c)) to allow each of several daughter cards to have bi-directional low loss communications to each of the others.

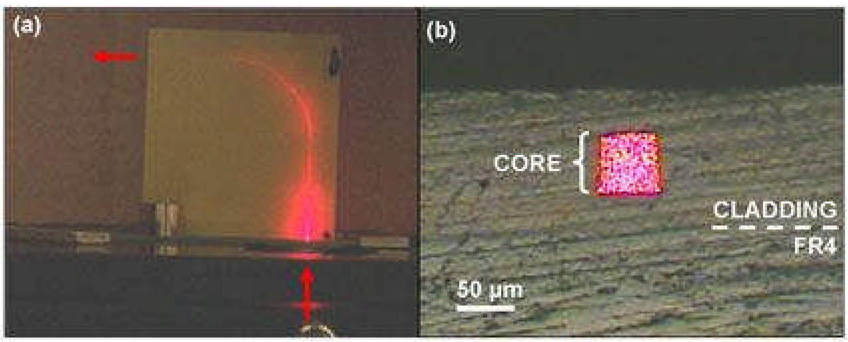

Figure 4: Sample waveguide (FR4/cladding/core/cladding) manufactured using dry film: (a) photograph of a curved waveguide transmitting red laser light, sample size ca. 50 mm x 50 mm; (b) microscope image acquired in reflection mode: cross-section of a waveguide transmitting red laser light, core size is 50 mm x 50 µm.

Using an optical PCB, to this design, sourced from IBM Zürich/Varioprint, Xyratex and UCL constructed a system demonstrator (Figure 3) fully inter-linking bi-directionally three daughter cards via self-aligning pluggable optical connectors, developed by Xyratex and Samtec, containing 4 VCSELs and 4 photodiodes. The optical interconnections were tested by UCL and Xyratex and it was demonstrated that 10 Gb/s Ethernet traffic could be passed error free through each of the waveguides, obtaining open eye-diagrams. This is, to our knowledge, the world's most highly-integrated demonstrator built to date, incorporating connectors to allow daughter cards to be attached and detached at right angles and to be interchanged. Later in the project, Heriot-Watt University also manufactured the UCL waveguide interconnection design using laser direct writing (Figure 5(c)).

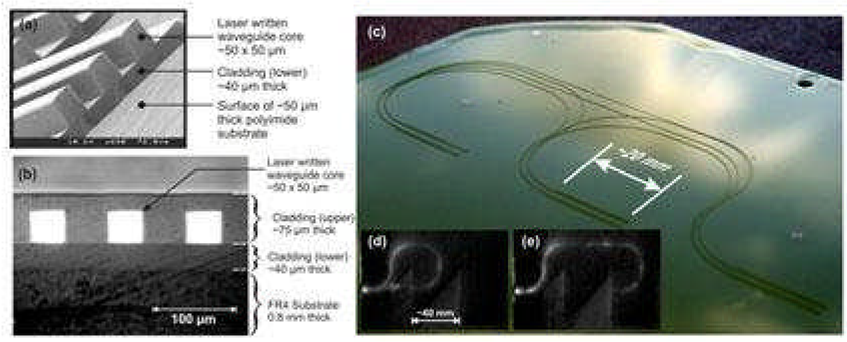

Figure 5: The SEM image in (a) shows direct laser-written, unclad polysiloxane waveguide cores (~50 x 50 µm, on a 100 µm pitch) with lower cladding, on a ~50 µm thick polyimide sheet. The optical microscope image in (b) shows an end-on view of back illuminated, clad, laser-written multimode polysiloxane waveguide cores on a 100 µm pitch, on an FR4 substrate. The cores shown in this figure were laser-written using a flat-top intensity profile and an optical power of 3 mW. The photograph in (c) is of direct laser written waveguide cores and cladding on FR4, to UCL's design, for use as an optical backplane interconnect board in the Xyratex demonstrator system. The CCD images in (d) and (e) show an 850 nm laser coupled into the 120 mm and 170 mm long waveguides on this board.

Waveguide Fabrication in a PCB Manufacturing Environment

Stevenage Circuits Ltd., in cooperation with the universities, identified technology processes required for manufacture of optical waveguides using standard PCB technologies. Trials involved making waveguides using: Photolithography with liquid polymers supplied by Dow Corning and Exxelis; using dry film with photolithography and evaluation of Nd:YAG laser ablation of the aforementioned polymers in cooperation with Loughborough University. The dry film approach was identified as the best means for mass production, because the same technology is used to manufacture standard PCBs.

Using this method, Stevenage Circuits Ltd. successfully manufactured waveguides for characterization (Figure 4). The adhesion of the liquid polymers to the substrate FR4 could be improved by engineering the polymer formulation or laminate surface properties. The deposition of the liquid polymers by screen printing was considered and it was found that there was a need to develop new polymer formulations with different density and viscosity. In addition to waveguide manufacturing, Stevenage Circuits Ltd. provided its facility resources for various waveguide testing purposes (polishing, inspection and environmental testing) and, in cooperation with UCL, carried out research on improvement of micromachining of the waveguide end facets to minimise their scattering.

Laser Direct Writing of Waveguides

Heriot-Watt University studied the viability of direct UV-laser writing as a manufacturing technology capable of forming multi-mode polymer waveguides over large metre-scale backplanes. An optimum intensity profile for the writing beam was identified, compatible with producing both straight and curved guides. Following up earlier work with acrylate-based polymers, excellent results have been obtained using OE4140 and OE4141 photopatternable polysiloxane, supplied by consortium partner--Dow Corning.

Studies focused on the optimisation of optical power and writing speed and led to the production of well-defined, low-loss waveguides written at speeds in excess of 20 mm/s. The waveguide writing system permits production of guides over boards as large as 300 mm x 600 mm, at potential speeds of up to 2 m/s, with sub micron resolution. The waveguide writing system has been used to produce an optical-interconnect insert board, compatible with the Xyratex system demonstrator.

Laser Ablation of Waveguides

Loughborough University investigated laser ablation (in cooperation with Stevenage Circuits Ltd) of optical polymer materials (OE4140 and OE4141 photopatternable polysiloxane from Dow Corning and Truemode™ from Exxelis) to form waveguides (Fig. 6a) and examined the preparation of in-plane mirrors. Excimer, UV Nd:YAG and CO_2 laser systems were trialled and waveguide structures fabricated (Figure 6b and c). Transmission measurements of straight waveguides prepared in this way were carried out at UCL and showed that while signals could be transmitted, the losses were significant, which was thought to be due to the wall roughness. Further work is needed to fully characterise the ablation process and investigate the different process parameters, such that the transmission efficiency can be improved.

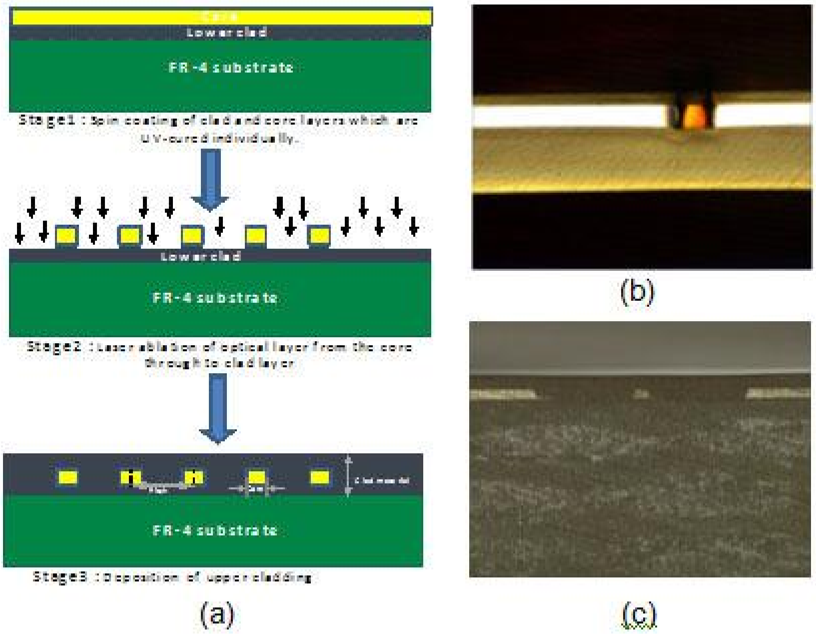

Figure 6: (a) The laser ablation process to create optical waveguides; (b) a cross-section through a waveguide machined in Truemode™ using a Nd:YAG laser; (c) a cross-section through an optical waveguide prepared using Excimer laser ablation of Truemode™ polymer.

Inkjet Printing of Waveguides

A significant part of the research considered the inkjet deposition of polymer waveguide structures focussing principally on the structuring of the core layer on top of the lower cladding. It was found that the UV cure optical polymer materials, OE4140 and OE4141 photopatternable polysiloxane from Dow Corning and Truemode™ from Exxelis, could be inkjet printed by controlling the viscosity and developing correct inkjet print-head waveforms. Using this technique, initially lines of optical polymer were deposited and then cured in a separate UV exposure unit. However, a key issue was preventing the spread of the material before curing, such that structures with a good height to width ratio (aspect ratio) were formed.

An aspect of the work investigated the control of the substrate wettability (Figure 7a, b) to increase the contact angle of the printed core droplets, whilst maintaining a stable parallel line structure before UV curing, but it was found that this alone did not create suitable structures. Better aspect ratio features, such as those shown in Figure 7c, d, were obtained using different methods of UV cure that enabled multiple print and cure cycles to be carried out to build up the thickness of the deposit. Measurements of the losses of these structures were carried out at UCL and showed encouraging results, but further work is needed to reduce the width of these features to dimensions closer to that required for the application.

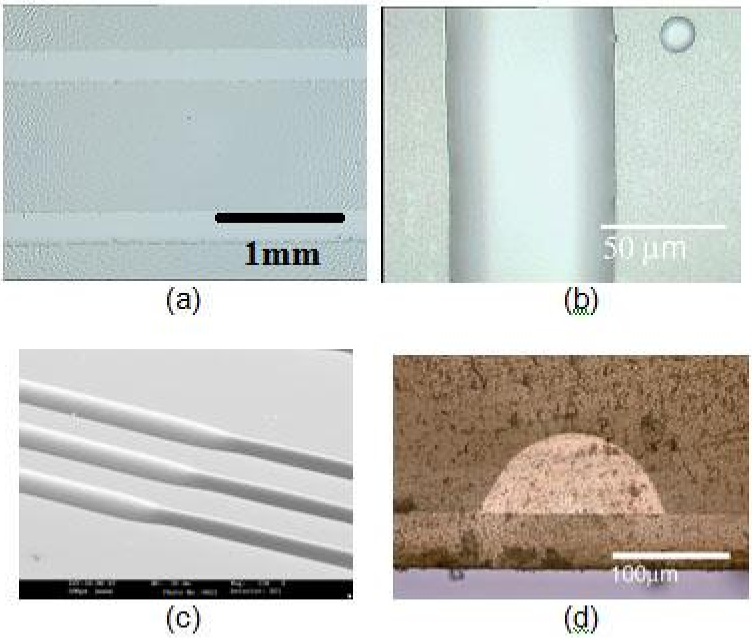

Figure 7: Inkjet printed lines showing: (a) extensive wetting leading to broad features; (b) reduced spreading of an inkjet printed line of core material on a modified hydrophobic glass surface; (c) parallel lines of polysiloxane showing the effect of different cure regimes; (d) cross-section through an inkjet printed polysiloxane waveguide, built up from multiple print and cure cycles.

Acknowledgements

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Further details of the research reported here can be found at the following links:

- **IeMRC Flagship Project**
- **The IEMRC Opto-PCB Manufacturing Project**
- **Integrated Optical and Electronic Interconnect PCB Manufacturing (OPCB)**
- **IeMRC Conference, September 5, 2007**.
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