Innovative Optical and Electronic Interconnect Printed Circuit Board Manufacturing Research

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Abstract

An overview of the £1.3 million EPSRC and company matched funded Innovative *electronics* Manufacturing Research Centre (I*e*MRC) Flagship project between 3 UK universities and 10 companies entitled "Integrated Optical and Electronic Interconnect PCB Manufacturing". The project aims to develop of optical waveguide design rules, layout software, fabrication methods compatible with commercial production, characterisation techniques and optical connector design to provide a supply chain for Polymer Multimode Optical Waveguide Printed Circuit Boards (OPCB) for 10 Gb/s board-to-board interconnections.

Introduction

Electronic rack based systems often have a central or rear printed circuit board known as the backplane or motherboard into which is plugged multiple smaller printed circuit boards known as line cards, daughter boards, drive cards or mezzanine cards. For the highest reliability and the lowest maintenance costs, the backplane should have only passive interconnects as active components may fail. Conversely, the line cards are highly populated with active components but it is easy to unplug them and to replace them if the active components fail, as they are accessible from the outside of the rack. For highest efficiency, the connectors from the line cards to the backplane must have a high aggregate bandwidth and so data on the line cards is multiplexed to a high bit rate and sent through a multi-channel high bit rate connector onto the backplane. As bit rates increase, the copper tracks or traces on the backplane are now limiting performance.

At high bit rates copper traces have high frequency dependent loss due to the skin depth effect [1] and electromagnetic waves are strongly radiated and received by other traces leading to severe crosstalk. If the system unit is not shielded, then electromagnetic interference (EMI) radiates from the box and likewise traces receive interference from outside the box. Frequency dependent loss and intersymbol interference can be compensated by using transmitter pulse pre-emphasis filters and receiver amplifiers with high gain having either fixed blind or adaptive equalisation filters. However, these techniques consume power and are costly. Electromagnetic crosstalk can be reduced by shielding the traces by burying them in a multilayer board between earth planes; however, there are still high frequency currents in the earth planes which radiate. Differential lines can suppress much radiation but at corners, the asymmetric differential mode can convert to the common mode, which radiates strongly [2]. At high bit rates parasitic impedances also become important so copper vias between traces on different layers must be fabricated to minimise impedance mismatch reflections by back drilling buried vias to remove stubs but this requires additional processing steps requiring additional cost. Therefore, engineers are investigating an alternative technology to copper traces which does not require costly compensations, namely, optical waveguide interconnects.

Optical waveguides have very large bandwidths and so are scalable for use at bandwidth well in excess of 10 Gb/s. The core and the cladding are both polymer for low cost and ease of fabrication but the core has a slightly higher refractive index than the cladding. They are similar to optical fibres in that they operate by total internal reflection but unlike optical fibres, they have a square core rather than a circular core cross section, as they are not fabricated by heating and drawing but instead are formed using techniques compatible with those already used to fabricate printed circuit boards. The waveguides can be formed on one or more layers within or on the surface of a multilayer printed circuit board as part of the usual lamination process.

Copper traces are very good at low bit rates and better than optics for transmitting power so will be preserved for low data rate connections and power connections in the hybrid optical and electronic printed circuit boards (OPCBs). In order to ease the design of optical printed circuit boards by electronic engineers more familiar with the design of conventional PCBs, in this project, optical design rules are being established and incorporated into existing printed circuit board layout programs to layout both copper traces and optical waveguide interconnects together. The design rule checkers and autorouting software will check and layout the optical waveguide interconnects on the optical layers.

If electronic engineers are to use optical waveguides in preference to copper traces, the cost of a full installation must be kept very low. For example, the optical pluggable connector is an important part of the cost of a system using optical waveguides so its cost must be minimised by reducing the part count in the connectors and reducing the fabrication tolerances required in the connector. The connector must be designed to give a low loss connection even if it is

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slightly misaligned. Therefore, the waveguides are made to have large cores of 35 to 75 microns in diameter, which makes them multimode rather than using the small ~5-9 micron cores of single mode waveguides. In multimode waveguides, modal dispersion is the main cause of dispersion but as the lengths of the waveguide are at most 0.5 to 1 metre, this form of dispersion is not a problem. OPCBs will be widely adopted if the cost of fabrication is minimised by slightly adapting PCB manufacturer's existing equipment and processes without adding complex fabrication steps.

In an earlier project, "Storlite" also funded by EPSRC together with DTI, three partners of the current consortium UCL, Xyratex and Exxelis began research on optical waveguides. Storlite resulted in [3-17] the establishment of some design rules and several patents including the design of a novel, low cost, high precision alignment technique which is being used in the first commercial optical backplane waveguide connector being made by US connector manufacturer Samtec.

Project Aims

1) To establish waveguide design rules for each of several waveguide manufacturing techniques – photolithography, laser-writing, laser ablation, extrusion and printing – and to incorporate them into commercial design rule checker and constraint manager layout software for printed circuit boards so that PCB designers can easily incorporate optical connection layers without detailed knowledge of the optics involved. To investigate and understand the effect of waveguide wall roughness and cross sectional shape on the behaviour of light and the effect on waveguide loss.
2) To develop low cost manufacturing techniques, including polymer formulation, for integrated Optical and Electronic interconnected Printed Circuit Boards, OPCBs. To develop and to compare the commercial and technological benefits of optical printed circuit board manufacturing technologies – photolithography, laser-writing, laser ablation, extrusion and printing – for high data rate, small and large 19", printed circuit boards so that it will be clear which technology is best for each type of PCB. To characterise the behaviour of optical waveguide backplane systems in real world conditions, including cycling temperature, high humidity and vibration.

The results of the research are being disseminated through a range of public conference presentations and proceedings [18-29], private talks to other polymer waveguide researchers at IMEC, Ghent University and IBM Zurich, circuit engineering publications for PCB manufacturers, [30-31] and through peer reviewed academic journals [32-35].

The Consortium Partners

Department of Electronic and Electrical Engineering, University College London, UCL, (Lead), School of Engineering and Physical Sciences, Heriot-Watt University, UK, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, UK, Xyratex Technology Ltd., BAE Systems Advanced Technology Centre (Photonics Group), Renishaw, Exxelis Ltd, Dow Corning, Stevenage Circuits, Cadence Design Systems and National Physical Laboratory (NPL) plus two associated corporators: RSoft and Xaar.

University College London (UCL) Research

UCL is establishing design rules for optical multimode acrylate polymer waveguides by optical measurement and computer modelling. UCL have initially concentrated on waveguides fabricated photolithographically from Truemode® acrylate formulation at the partner company Exxelis.

Loss Design Rules

The loss of individual waveguide components, such as straight sections, 90° bends, crossings, tapers and tapered bends must be known across a range of design parameters, such as bend radii or waveguide widths, so that the combined loss of a cascade of such elements can be found to determine whether the interconnection's optical power budget is sufficient to achieve a good bit error rate. UCL characterized the cross-talk between adjacent and neighbouring waveguides by laterally moving an input VCSEL to scan an array of waveguides [35]. When the light source is misaligned to a waveguide core, it emits into the cladding and its transmitted power drops almost linearly at a rate of 0.011 dBm/μm.

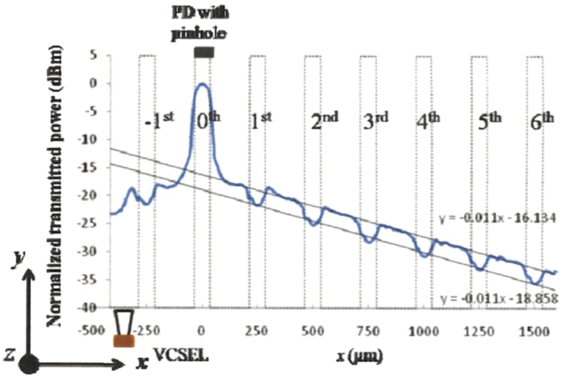

Fig. 1. Cross talk in straight waveguides

UCL used a combination of crossings at straight sections and a curved waveguide to measure loss per crossing and achieving a consistent result with that of other workers [37,38] for the 90° crossing case. 0.023 dB per crossing was achieved at a 90° crossing which means output power dropped down 0.5% at each 90° crossing. The mean loss of each point was found by averaging 50 measurements at each designed crossing angle. The loss of multimode polymer waveguide bends was measured for a range of radii of curvature and for several waveguide widths to establish design curves to aid optical waveguide interconnect backplane designers to minimise transmission and radiation loss [36]. The experimental results were obtained for waveguides having a refractive index difference of Δn =1.9% of core index and having unpolished end faces which are commonly used in OPCB backplane applications. The optimum bend radius for polymer waveguide backplanes is 13.5 mm for 50 µm × 50 µm, is 15.3 mm for 75 µm × 50 µm and is 17.7 mm for 100 µm × 50 µm waveguide cores as these provide a balance of transition and radiation loss versus propagation loss.

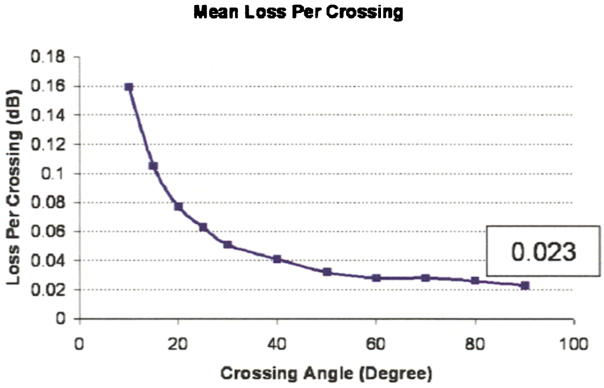

Fig. 2. Transmitted mean power per crossing as a function of crossing angles

Tapered bends can increase misalignment tolerance at the input facet. However, there is a trade-off between insertion loss and misalignment tolerance [34]. UCL found that the product of these two factors is a constant which increases linearly with taper ratio (TR = w_{in}/w_{out}).

$$\text{Product} = 0.650TR - 0.09$$

independent of bend radii. Based on these measurement, UCL suggest that taper ratios TR ≥ 0.4 may be best for a backplane system.

Misalignment Design Rules

Translation and rotation misalignment is investigated by modelling and experiment. A VCSEL is chosen as the light source and offsets between VCSEL-waveguide and waveguide-receiver are studied to find the translation and rotation tolerance. Beam proprapagation method (BPM) is used for modelling and the waveguides are multimode with a channel structure made of Truemode® acrylate polymer. UCL have measured the translation and rotation misalignment for several waveguides with deferent widths. Values along the *x* axis represent lateral misalignment between optical source and waveguide core centre. Values along the z axis represent axial misalignment between the optical source and the waveguide. The modelled result fig (3.a) and experimental result fig (3.b) is shown for the waveguide width used in this figure is 50×50 µm.

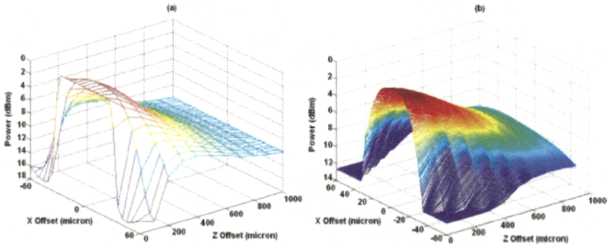

Fig. 3. Output power with related to lateral and axial misalignment between VCSEL and waveguide. (a) Modelling result. (b) Experimental result.

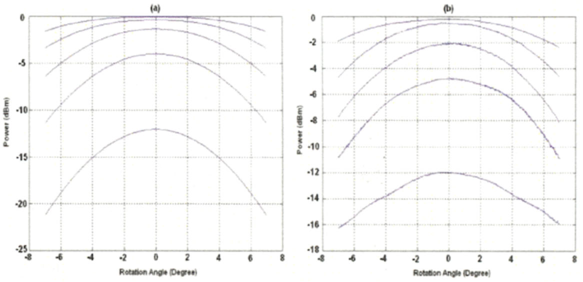

Fig. 4. Comparison of (a) modeling result and (b) experimental result of rotation tolerance of different guide width.

The results are compared in fig. 4. ; (a) shows modelling result of rotation tolerance when axial distance is 200 µm between source and waveguide. (b) Represents experimental measurement corresponding to the modelling.

Loughborough University Research

Laser ablation to create waveguide structures

Laser ablation is another technique that is being investigated for the fabrication of waveguides as shown schematically in fig 5.

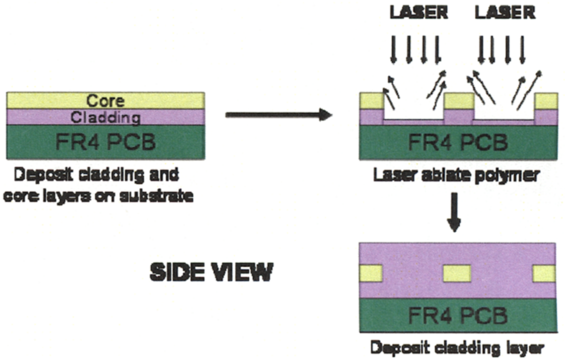

Fig. 5 Schematic diagram of the laser ablation process route for the fabrication of waveguides.

The process involves depositing a layer of cladding polymer onto the substrate, followed by a layer of core material, typically using spin coating. Laser ablation is then used to remove tracks of material to leave a standing structure of core and cladding. While it is not necessary to ablate into the cladding layer, in general, a little of it is intentionally machined away to ensure complete removal of the core that, if left behind, could otherwise lead to cross-talk. After machining, a final layer of cladding is applied to complete the structure. In this work, ablation using two different laser systems is underway: KrF excimer (248nm) and Nd:YAG (355nm). The Nd:YAG system used here is a commercial device for via drilling in PCB manufacture and, therefore, offers the opportunity to utilise existing infrastructure to enable the rapid integration of this technique into conventional PCB manufacture. Trials with this system have already been conducted to establish machining rates and some waveguides have been fabricated for subsequent characterisation.

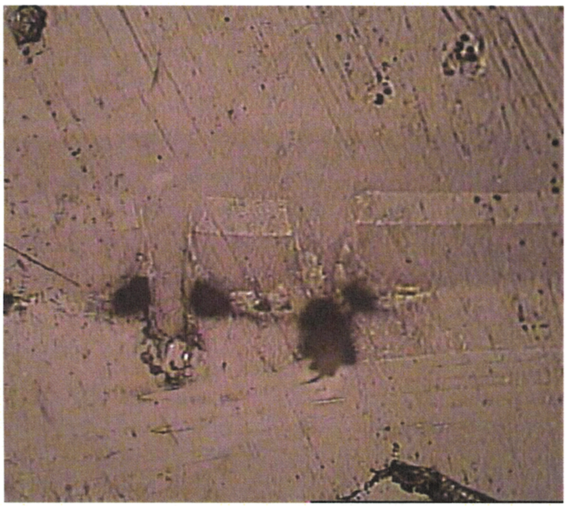

Fig.6 Cross-section through an optical waveguide on FR4 prepared using Nd:YAG laser ablation.

Fig 6 shows a cross-section of a trial waveguide structure on FR4: in this case the ablation rate was too high and even some of the FR4 substrate was removed. Waveguide fabrication is also underway using the excimer laser which uses a mask projection technique to shape the beam spot such that complex profiles can be achieved. A key aim of this work, is to use the higher machining precision available, to form two and three dimensional structures such as curved mirrors for in-plane and out-of-plane interconnection.

Inkjet printing of polymer waveguide materials

Inkjet deposition offers the potential to selectively deposit waveguide materials where they are required, reducing the amount of material used and enabling substrates with a variety of geometries to be processed. However, there are numerous challenges to be overcome before core waveguide structures can be printed directly onto cladding layers. The formulation of the "ink" such that it has the required viscosity for successful printing needs consideration and in this work the optical polymer has been partially diluted with two candidate solvents in order to meet this requirement. However, it is the control of the spread of the droplets once they have impinged on the surface that is potentially the most significant issue if structures with aspect ratios approaching the typical 1:1 height : width of optical waveguides are to be achieved. Initial trials have shown that directly printing core liquid onto the cladding surface leads to broad tracks with low height, unsuitable for waveguide applications (Fig. 7 a). Control of the contact angle between core and cladding by variation of the cladding surface energy is one approach that may enable narrower features to be printed. In order to investigate the efficacy of this approach, the core-solvent mixture was jetted onto a glass substrate that had been modified to make it hydrophobic (low surface energy). The results indicated that much less spreading of the core-solvent mixture took place on the surface. Low volumes of fluid created clearly separated drops on the surface (Fig. 7 b) which with increased volume and / or reduced separation merged into tracks that were considerably narrower than those observed on the cladding (Fig. 7 c). However, the height of these features compared to the width still only gave an approximately 1:5 aspect ratio indicating that this may still not be the optimum approach. In addition, this technique also led to the generation of some unstable features (Fig. 7 d). Further work is underway to establish if a combination of techniques utilising barrier structures and areas of different wettability on the surface will enable the constraint of the core material such that the required shape and form can be achieved.

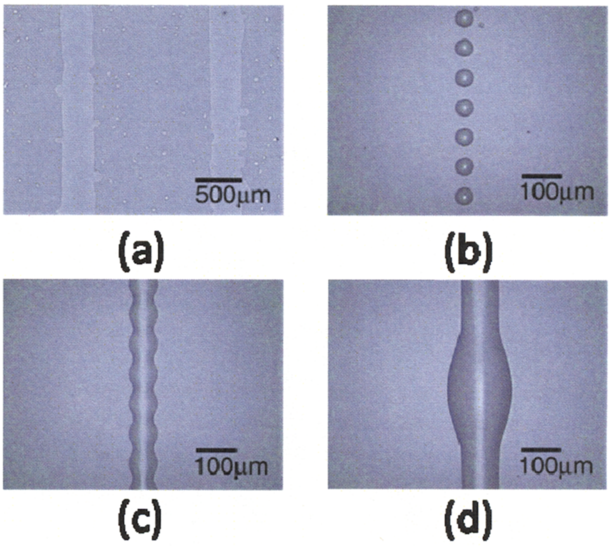

Fig. 7 Inkjet printing of polymer optical waveguide material diluted with solvent. (a) tracks formed on a cladding substrate, and (b, c, d) deposits on a hydrophobic, modified glass surface. Figs a, b, c deposited with the same droplet frequency and separation. (a) and (b) 8 pl per drop, (c) 32 pl per drop. (d) 32 pl per drop deposited at 4 times higher frequency than (c).

Heriot-Watt University Research

Heriot-Watt University has previously developed a direct UV-laser-writing technique and custom photo-polymer so as to form multimode polymer waveguides and embedded 45° out-of-plane mirrors. In the OPCB project, the key aim is to explore how these techniques can be extended to suit optical backplane applications – both in the context of scale and manufacturability. The figure shows an optical microscope image showing an end-on view of a back-illuminated clad laser-written polymer multimode waveguide core on an FR4 substrate. The core was written at 100 mm/s i.e. an effective writing speed of 50 mm/s.

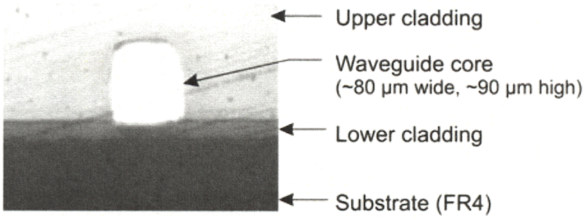

Fig. 8 Cross section of an optical waveguide using laser direct writing

Conclusions

The paper reviews the I*e*MRC Flagship Project known as OPCB, its aims and consortium structure and details some of the research progress.

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