Multi-layer Electro-Optical Circuit Board Fabrication on Large Panel

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***Abstract* - Introduction of proposed electro-optical circuit board (EOCB) technologies based on embedded glass waveguides in the system enclosure of data storage, compute or switch platforms will be instrumental in accommodating the prohibitive bandwidth densities projected in exascale data centers, access networks and high performance computing environments in future. The main focus of this paper is, therefore, on the fabrication of large panel EOCB backplanes 350 mm x 465 mm with passive dual star interconnect topologies and stacking of multiple glass layers with double sided integrated optical waveguides. The waveguides are embedded inside glass panels using a two-step thermal ion exchange process. The fabricated embedded waveguides are characterized for propagation and coupling losses across different wavelength ranges and for different coupling arrangements. The modified EOCB fabrication process for these large panels is elucidated.**

Keywords – optical waveguide, electrical-optical circuit board, thin glass, display glass, ion exchange, datacenter

I. INTRODUCTION

Optical interconnections have gained interest over the last years and several approaches have been presented for the integration of optical interconnects into the printed circuit board (PCB). Most research focuses on embedding of one or two polymer optical waveguide layers in the PCB [1,2]. But for server applications there will be the need to route multiple optical layers from one point to another and optical fan-out circuit designs will be required similar to electrical pad areas, which requires many electrical layers. One example is the icPhotonics™ optical module having bi-directional 168-channels each with 8 Gbps and operating at wavelength of 1000 nm. So far the device was demonstrated with an off-chip communication in total of 1.344 Tb/s full duplex [3]. In our work we address three upcoming problems: Firstly, we describe thin glass as an alternative to polymer waveguides which have high losses in telecom wavelength range (with exception of certain perfluorinated polymers because of a change to the bond vibration overtones [4]). Secondly, integration of multiple optical layers into the same EOCB for very high channel density, and thirdly, the technology have to be suitable for large panel fabrication. Requirements for the developed glass waveguides are low optical propagation loss in bends and straights for wavelength ranges of around 850 nm up to 1550 nm for datacom and telecom application. The technology behind this is planar integration of waveguides by thermal ion-exchange [5] on one or both sides of display glass and embedding of multiple one or dual-layer glass waveguide panels in the core of a EOCB. The generic EOCB fabrication process consists of stacking of multiple optical and electrical packages with low-built in stress utilizing a low temperature lamination process. The paper describes, firstly, the design, fabrication and characterization of an optical octa-layer/ electrical dual-layer EOCB in detail. For planar optical waveguide integration in display glass different process parameters are evaluated for reaching low loss and high NA optical waveguides in 550 µm thick alkali-aluminosilicate glass, which is used primarily as cover glass for portable electronic devices.

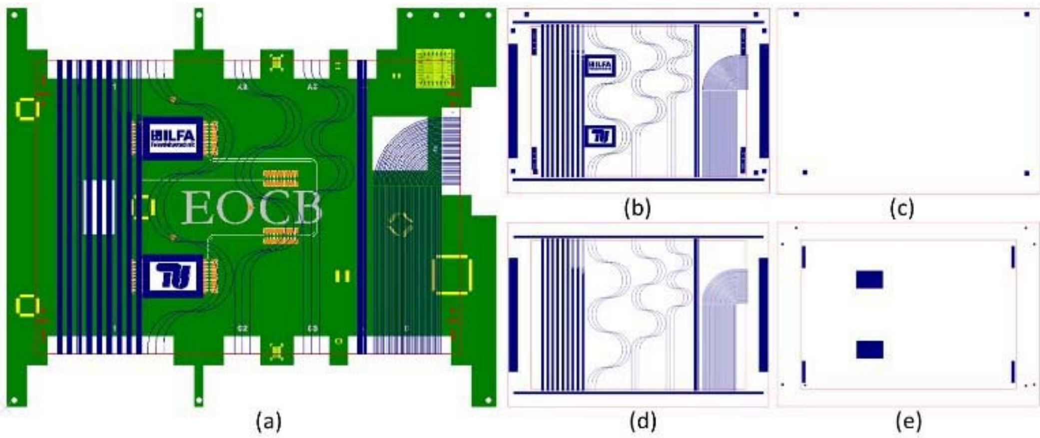

Figure 1: Octa-layer-board: Full EOCB test-bed design (a), optical trace geometry and alignment marks LDI layout for litho#1 front-side glass panel (b), window etching LDI layout for litho#1 back-side glass panel (c), optical trace geometry LDI layout for litho#2 back-side glass panel (d) and etch cover LDI layout for litho#3 front-side glass panel (e).

The same technology is also demonstrated, secondly, for fabrication of a large panel EOCB having size of 460 mm x 350 mm with one optical layer only. Two of these large panel EOCB are used to build a "large panel backplane demonstrator" as schematically shown in Figure 3. The paper will present the generic low temperature lamination EOCB technology, glass waveguide panel fabrication and characterization results for both electro-optical circuit demonstrators which could be successfully achieved with waveguide propagation loss of less than 0.05 dB/cm at all key wavelength data and telecom wavelength.

II. TEST-BED ÊOCB DESIGN FOR OCTA-LAYER AND LARGE PANEL

We have been designed 2 demonstrator layouts: the "octa-layer board" with eight optical layers in 4 stacked glass sheets and the "large panel EOCB" with 4 glass layers in one level on fourfold panel size.

Octa-layer-board: To integrate the optical waveguides on both surface sides of sheet glass by a two-step thermal ion-exchange the process has to be suitable for low-cost batch processing of large area glass panels. One of the challenges is to handle the thin glass sheets. Multiple of such processed dual-layer glass waveguide panels have to be integrated between base material like FR4, prepregs, adhesive and copper layers for HDI-EOCB fabrication.

Fraunhofer IZM developed a glass waveguide panel process for area of 305 mm x 228 mm (12" x 9"). Glass sheets containing sodium ions are subjected to a masked diffusion process with silver ions for planar waveguide integration and following mask less processing in pure sodium salt melt for waveguide profile forming. In the work we used Corning Gorilla Glass 1 (distributed by Schröder Spezialglas, Germany) only available in a thickness of 550 µm. The distance between top and bottom glass waveguide layer is dependent on the glass thickness. The goal is to achieve a vertical pitch of 250 µm or a multiple of 250 µm for channel matching to standard MT-ferrules having up to 72 channels in a 12 by 6 array with 250 µm horizontal and vertical channel pitch. In case the maximum of the planar integrated ion-exchanged waveguides is 25 µm below the glass surface the channel to channel pitch in 550 µm thin glass is two times 250 µm. For a 300 µm glass thickness the vertical channel pitch can be 250 µm.

High alignment accuracy is required for the double-sided lithography applying visual alignment and laser direct imaging (LDI). For that alignment marks (flash with diameter of 1 mm) are patterned during top side lithography (Figure 1) on which the bottom side layout Figure 1d) is aligned. Also, marks with line thicknesses of 2 mm for layer registration during PCB lamination are patterned directly on glass during the top side lithography (Figure 1b). By embedding four of those dual-layer glass waveguide panels, all glass layers have to be accurately aligned to each other and the distance in-between have to be 200 µm or 450 µm reaching a vertical waveguide pitch of 250 µm or 500 µm accordantly. It's the first time that multiple glass waveguide layers are embedded in the same EOCB and full process demonstration has the primary priority at this stage.

The optical trace geometry for a glass waveguide panel with an area of 305 mm x 228 mm comprises 17 waveguide groups including arrays of 12 straight waveguides with a pitch of 125 and 250 µm, straights with crossing stubs at an angle of 20°, 45°, 60°, 75° and 90°, splitters, cascading bends with radius of curvature of 10, 15 and 20 mm and 90° arc bends with radius of curvature in range of 1 mm up to 40 mm (see Figure 1b). The optical trace geometry of the top side of the glass is mirrored and integrated from the bottom side, too (see Figure 1d). The waveguide layout and EOCB test-bed design was optimized for optical insertion loss characterization in the lab. Based on our experiments we found out that it's straight forward to fully process the glass before embedding which involves waveguide integration, patterning of alignment marks and glass cutting including end-face preparation. After finished waveguide process the waveguide panels have a size of 170 mm x 245 mm. The waveguide layout overlaps that area by about 5 mm and is positioned in the center of the 305 mm x 228 mm glass panel. After separation the cut is through the waveguides ensuring in-plane coupling interfaces at the edge of the glass waveguide panel in optical quality. For laser separation alignment marks (square 0.5 mm x 0.5 mm) are patterned on the panel. Beside different alignment marks two partner logos are located inside a frame. The outer dimensions of the EOCB is 233 mm x 285 mm and therefore larger as the waveguide panel itself which is center located with cut-outs on three sides for access to the glass waveguides coupling interfaces. The design of the EOCB test bed's outer shape is defined by the trace geometry and size of bulky insertion loss measurement arrangement for optical waveguide characterization in the lab. Figure 1a shows the full octa-layer EOCB design with all optical, electrical and FR4 layers with optical trace geometry in blue, glass panel and marks in red, FR4 in green, electrical traces in orange and yellow.

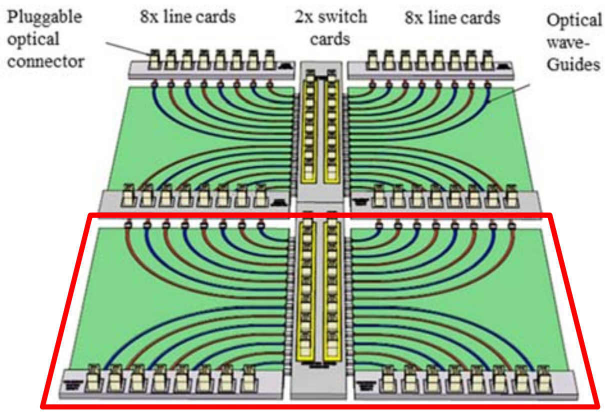

Figure 2. Large-panel-backplane: Optical dual-star interconnection design for (700 mm x 465 mm) for server rack application. The demonstrator consists of 2 large panel EOCB (one of them is indicated by the red line) each having four optical waveguide glass sheets in

Large panel backplane: A design concept was devised for an EOCB backplane appropriate for a data center system enclosure, which incorporated a “dual star” interconnect topology in order to ensure failover redundancy in the system. The dual star interconnect design basically implements a central switching architecture whereby two independent central switch cards are each connected to 16 peripheral line cards allowing data traffic routing and switching within the enclosure. This is a common failover architecture in data center and access network systems, providing a strong level of redundancy, in that, should one of the switch cards fail, the other switch card will continue the required data routing functions on all peripheral line cards, allowing the failed card to be replaced without disruption. The embedded optical interconnections are depicted in blue (going to switch card 1) and red (going to switch card 2) in the large panel backplane layout in

Figure 2.

Figure 3 shows the design of the EOCB backplane having an area of (350 x 465) mm², which represents one half of the full layout design concept depicted in

Figure 2. In order to implement the full concept, two of such EOCB backplane’s would have to be combined for a rack backplane with total area of 700 mm x 465 mm. The design incorporates four separate glass panels inside one EOCB backplane, each having an area of 143 mm x 190 mm. This development work will show for the first time the lamination of up to four separate glass panels in the same layer and allow the possibilities and effectiveness of such an approach to be evaluated. The reason for using four separate panels instead of one or two larger glass waveguide panels is to reduce the risk and primary costs for pass-test of glass waveguide panels reaching the full performance on all channels. As studied in previous work, the processed glass waveguide panels are separated by CO_2 laser scribing and mechanical breaking, resulting in coupling interfaces with a high surface quality and well-defined shapes (Figure 8). Direct in-plane coupling with optical fiber arrays can be achieved through openings in the FR4-layers, granting access to the inner glass coupling interface and allowing the assembly of optical waveguide termination. The width of the FR4 openings is defined to 12.3 mm for assembling of MT receptacle mounts or fiber assemblies directly on the glass in this area. The EOCB backplane design comprises also two windows for partner logos and to show sections of the glass waveguide panels embedded within. There are also multiple 3 mm holes for mounting purposes included on the left and the right margins as well as along the central axis in the design.

Given that, the higher the average radius of curvature of a given waveguide group, the longer its average length, changes in waveguide bend loss are compensated by changes in propagation loss from group to group. The waveguide of WG1 has a length of 25 cm. In contrast the length of WG8 is 4.4 cm.

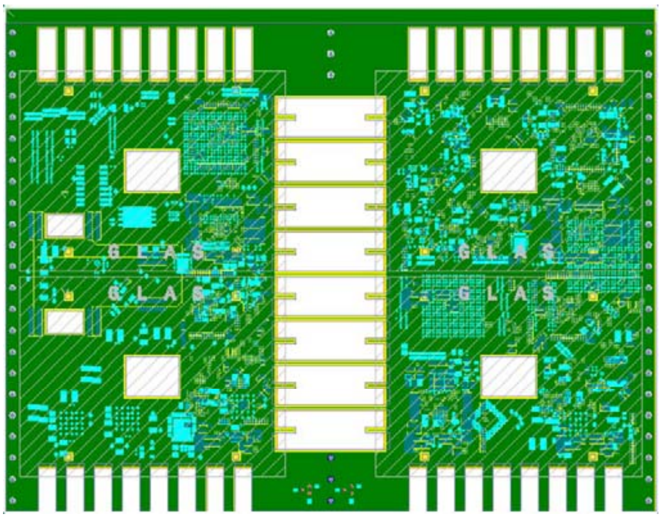

Figure 3. Large panel EOCB layout design with FR4 layer (green) with area of 350 mm x 465 mm, electrical layer (blue) and four embedded glass waveguide panels each 143 mm x 190 mm (grey lined).

For alignment assistance in different steps of the fabrication process there are some alignment marks present at the corners of the glass panels. These marks are made of aluminium and have different structures for different purposes. The rectangle alignment markers with 0.5 mm x 0.5 mm dimensions are for laser cutting and the point and line markers are used for layer alignment during lamination. The glass panels also contain partner logos inscribed in the aluminium surface. Four of such glass waveguide panels are patterned on one large glass panel having size of 420 mm x 570 mm for panel processing and subsequent separation by laser cutting before waveguide processing. The full glass panel layout for waveguide processing is shown in Figure 5.

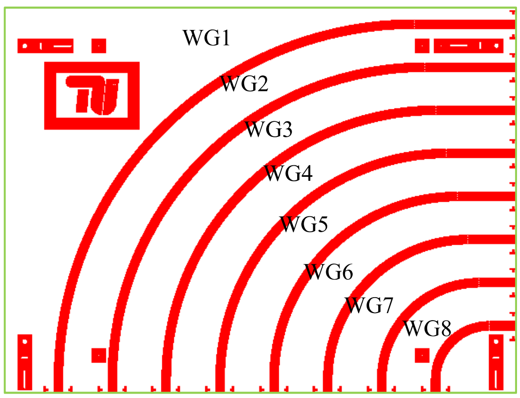

Figure 4. Layout of waveguide panel 143 mm x 190 mm with eight waveguide groups each with 12 channels. Radius of curvature is 137, 121, 105, 89, 73, 57, 41, and 25 mm.

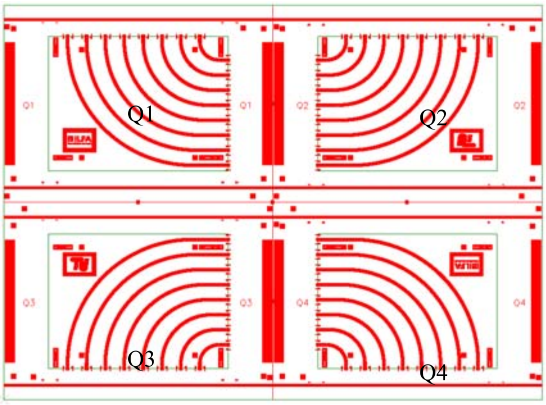

Figure 5. Layout of four waveguide panels (Q1, Q2, Q3, Q4) with area of 143 mm x 190 mm are patterned on one glass panel for combined fabrication

III. WAVEGUIDE FABRICATION PROCESS

The waveguide fabrication process consists of a two-step thermal ion-exchange between hot salt-melt and glass suitable for large panel and batch processing. The process is formerly described in [6,7,8]. The equipment of the glass waveguide panel process line at Fraunhofer IZM is shown in Figure 6. Process steps like sputtering (PVD), lithography (Dip-Coater, LDI, etc.) and glass panel separation (Laser-Cutter) are suitable for formats up to 610 mm x 457 mm. The panel size for ion-exchange process is currently limited to panels having area of 305 mm x 457 mm because of hot salt-melt bath size restrictions. So far we have processed waveguide panels with a maximum size of 305 mm x 228 mm. The focus in this work is twofold: to demonstrate higher yields by processing the diffusion mask of four separate sub-panels (Q1…Q4) on one large panel, separate the large panel after lithography and process in parallel four panels in the hot salt-melt bath by batch processing. The second goal is to show double sided waveguide processing to have two optical layers in on glass sheet.

Figure 6. Fraunhofer IZM glass panel waveguide process line.

First, the diffusion barrier was deposited on both glass surface sides. We were using an aluminium layer of 400 nm thickness, which is DC-sputtered by Creavac Creamet 600 physical vapor deposition (PVD) equipment (Figure 6, left side). Then one lithography (litho#1) and wet-chemical processing step are required to pattern the aluminium mask on the front-side of the panel and on both sides for the octa-layer board. For lithography we used dip coating for double-sided photoresist deposition (Figure 6). The exposure of the optical trace geometry and alignment marks was carried out on an Orbotec Paragon Ultra 200 laser direct imaging (LDI) system (Figure 6) transferring the diffusion mask layout to the photoresist layer. Then the aluminium layer was opened with acid treatment and the photoresist was removed completely as shown in Figure 7 for the large panel EOCB.

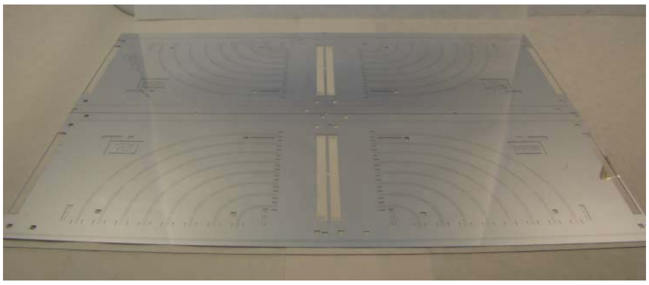

Figure 7. Aluminium diffusion mask layer on glass according layout of Figure 5

After completing the diffusion mask processing, the large glass panel was separated into the four similarly sized sub-panels Q1…4 for the large panel EOCB. Therefore the aluminium layer has two separation traces, one central vertical and the other one central horizontal located for laser-cutting. For glass separation we used a MDI LD600-H system for the CO_2-laser scribing of glass. Afterwards the glass waveguide panels were manually broken along the scribe seams, resulting in high optical quality waveguide end facets. In principle, the panel separation could be automated, in a process similar to that widely used for the separation of Liquid Crystal Display (LCD) panels. Such a sub-panel with area of 220 mm x 285 mm is shown in Figure 8.

To get double side waveguide sheets an additional lithography (litho#2) and wet-chemical processing steps are required to pattern the aluminium mask on back-side of the panel. Therefore after front-side patterning the glass panel is flipped and the back-side is exposed with a very simple design of four rectangles firstly (see Figure 1c). These are for etching windows in the back-side aluminium layer underneath the LDI point fiducials for later alignment of back-side optical trace geometry through the transparent glass. The exposed glass panel is developed and the aluminium layer on both sides is structured with acid treatment. After resist removal the lithography step (litho#2) follows for completing mask etching on back-side starting with dip coating. In the LDI the optical trace geometry of back-side (see Figure 1 d) is exposed by aligning the layout using the front-side alignment marks visible through the etched windows. Then the panels are placed for a second time in the developer, aluminium acid and remover before the mask layer is completed on back-side as well. The double-sided patterned aluminium mask serves as a diffusion barrier and the glass panel is completed in readiness for planar waveguide fabrication.

Figure 8. Glass panel 220 mm x 285 mm with diffusion mask after laser separation.

During the thermal ion exchange process all panels were vertically immersed into the hot bath containing salt melt. For the salt melt we used a diluted $AgNO_3$ mixture in the first diffusion step. In the last stage of the panel fabrication, the glass was cut into the appropriate size panels in accordance to the design requirements. This was done using a CO_2 laser cutting system (see right side at Figure 6) with the ability to produce substantially higher optical end facet qualities than could be achieved by diamond reel cutting. With four-fold increase in the edge strength and trace stability along with an RMS surface roughness of 40 nm, the glass edges processed by this cutting method guarantees low loss optical coupling to the waveguides without post-processing steps, such as polishing. For waveguide termination, aluminium fiducials were patterned on the glass surface and a pair of fitting bores was drilled by green laser for each waveguide group normal to the surface.

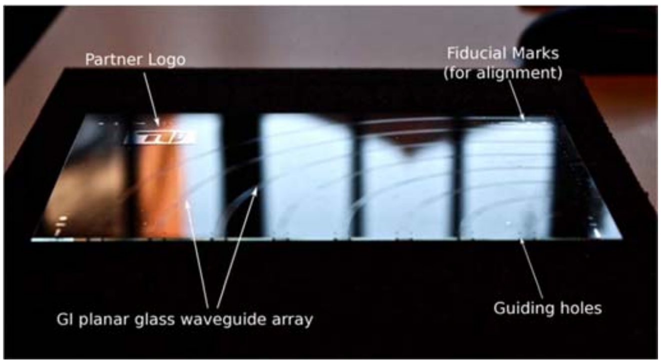

Figure 9. Appearance of graded index (GI) glass panel after planar waveguide integration and laser separation to panel size of 143 mm x 190 mm according to layout of Figure 4 for large panel EOCB

For drilling the glass panels we selected an EDGEWAVE solid state laser (Nd:YVO_4) with optical output power of 20 W in combination with an optical galvo scanning system for cylindrical through glass via drilling. The laser beam is focused on the glass panel backside and starts drilling from there by moving the laser beam focus position continuously up to the glass surface. The completely prepared glass waveguide panel after waveguide integration and laser separation is shown in Figure 9. In addition to the waveguide layout shown in the schematics it also contains other features such as alignment marks, guiding hole structures and partner company logos.

IV. Experimental results

Glass waveguide panels were fabricated with seven different process parameter sets (set 1 to 7) and characterized for comparing the waveguide performance. The resulting panels differ in waveguide dimension, NA and distance of the maximum refractive index point from the glass surface, which will have an impact on coupling efficiencies for waveguide-to-fiber and fiber-to-waveguide assembly and propagation losses of waveguides. These variations were investigated by characterizing the waveguide panels in terms of refractive index profiles, propagation losses, coupling losses and misalignment tolerances. Seven different waveguide profiles could be measured vertically and horizontally through the waveguide cross-section by refractive near field (RNF) method at wavelengths of 678 nm. The refractive near field (RNF) results are shown for 2 sets. Figure 10 shows the refractive index profile of set 1 and Figure 11 the profile for set 7. For the case of waveguides fabricated according to parameter set 1, the maximum refractive index point resides at a depth of around 15 µm under the glass surface, whereas, for those waveguides fabricated according to parameter set 7, it reside at a depth of 30 µm. The refractive index difference between core center and cladding is 0.025 for set 1 and 0.029 for set 7 with corresponding NA´s of 0.27 and 0.3 respectively. High NA reduces the bend loss of higher order modes thus NA must be high for tight waveguide bends here down to 25 mm. Comparing Figure 10 and Figure 11 it becomes quite clear that the waveguides fabricated by set 7 have larger dimensions compared to waveguides fabricated by set 1 because of increased diffusion process time and change in silver salt melt concentration.

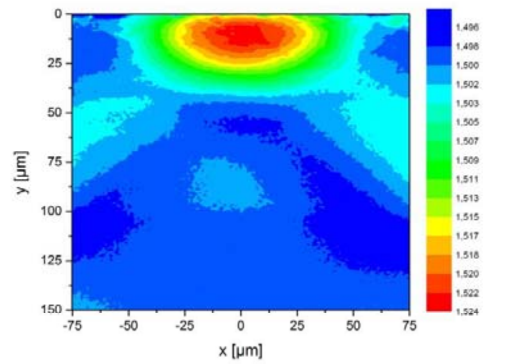

Figure 10. Refractive index profile of waveguides with parameter set 1.

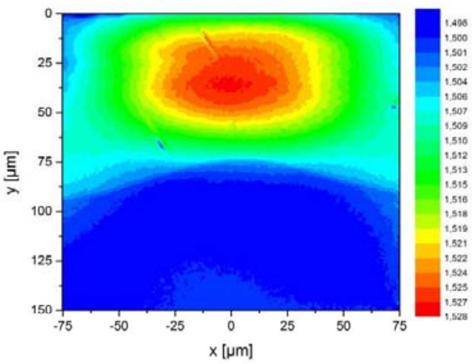

Figure 11. Refractive index profile of waveguides with parameter set 7.

The propagation loss and the coupling efficiency in dependence to misalignment for the different waveguide sets have been investigated to select proper coupling interfaces to parabolic gradient-index multimode glass fibers. The insertion loss was investigated on straight waveguides with 250 µm channel pitch and lengths of 250 mm and 235 mm for set 1 and set 7, respectively, and coupling losses evaluated by the cut-back method. The characterization was done with 4 different measurement arrangements with signals of 850 nm, 980 nm and 1310 nm wavelength. Lasers were fiber coupled by 50/125 GI-MMF with NA of 0.2 to a modal conversion system (Arden Photonics ModCon) and then coupled to the glass waveguides with defined 5 µm air interface. On the opposite glass waveguide end the light was captured with a 50 µm diameter core gradient-index or 200 µm step-index diameter core multimode fiber connected to a photodetector. For the cut-back method, insertion loss measurements were carried out on straight waveguide panels at 4 different lengths by cutting away 30 mm after every measurement. All fibers were actively aligned to find the best position for insertion loss minimum. The cut-back characterization results are summarized in TABLE I. Our investigations show a dependency of propagation loss on different waveguide properties between waveguides of set 1 and set 7 because of differences in waveguide properties as described above. The data marked with an asterisk is considered anomalous and is expected to be lower.

TABLE I

PROPAGATION LOSS FOR TWO DIFFERENT GLASS WAVEGUIDES

Measurement arrangement	Set 1	Set7
	Propagation loss [dB/cm]	Propagation loss [dB/cm]
850nm 50-50 MMF	0.10±0.01	0.05±0.01
980nm 50-50 MMF	0.08±0.02	0.04±0.01
1310nm 50-50 MMF	0.04±0.01	0.04±0.01
1310nm 50-200 MMF	0.06±0.01*	0.03±0.00

The coupling loss for the different measurement arrangements could be observed by the cut-back method and results are given in TABLE II. For wavelength of 1310 nm the coupling loss is lower for 50-200 MMF measurement arrangement because of larger core diameter of detection fiber. For that test the lowest value with only 0.25±0.06 dB could be achieved because of excellent mode coupling between 50 µm core diameter GI-MMF in larger waveguide dimensions of set 7 and also low loss waveguide to 200 µm core diameter SI-MMF coupling. The large diameter detection detects all light on the waveguide end-facet without additional coupling loss. The results show that larger portion of the coupling loss for coupling a 50-50 MMF setup occurs at the waveguide-to-fiber interface with a coupling loss of around 1.6 dB for set 7.

TABLE II

COMBINED COUPLING LOSS FOR TWO DIFFERENT GLASS WAVEGUIDES

Measurement arrangement	Set 1	Set7
	Coupling loss [dB]	Coupling loss [dB]
850nm 50-50 MMF	1.70±0.11	2.29±0.14
980nm 50-50 MMF	1.82±0.35	2.25±0.20
1310nm 50-50 MMF	2.14±0.20	1.87±0.10
1310nm 50-200 MMF	0.51±0.11	0.25±0.06

TABLE III

MISALIGNMENT TOLERANCE FOR SET 1 AND 7; ADDITIONAL LOSS IN dB FOR VERTICAL MISALIGNMENT IN DIRECTION OF THE BULK GLASS V (+), IN DIRECTION OF GLASS SURFACE V (-), IN HORIZONTAL DIRECTION H

Disp. [µm]	Set 1			Set7		
	Additional coupling loss [dB]			Additional coupling loss [dB]		
	V (+)	V (-)	H	V (+)	V (-)	H
10	1.1	1.7	1.0	0.9	0.9	0.3
20	4.2	4.8	3.2	2.9	3.4	1.6
30	9.4	8.5	7.0	7.4	5.5	3.5
40	22.2	19.7	12.6	16.2	10.0	6.2
50	46.8	30.0	19.5	36.0	13.7	11.5

Misalignment in the butt-coupled fiber to the waveguide arrangement results in decreased coupling efficiency. The variations in tolerances in terms of displacement direction and waveguide difference between set 1 and set 7 are depicted in TABLE III.

The elliptical refractive index profile properties of the ion-exchanged waveguides show different excess loss dependent on direction of misalignment. The investigations were carried out on the output side of the waveguides for waveguide-to-fiber coupling. Similar results have been observed for fiber-to-waveguide misalignment. The characterization was performed with a 50/125 GI-MMF with NA=0.2 at 1310 nm.

For set 1 waveguides, 10 µm of displacement results in 1 dB excess loss in the horizontal axis, while the same misalignment in the vertical axis adds around 1.7 dB of coupling attenuation. For set 7 the numbers are 0.3 dB and 0.9 dB for the horizontal and the vertical misalignment of 10 µm respectively. Because of larger dimensions of set 7 waveguides the excess loss is lower compared to set 1 waveguides. For higher displacements, the variations are even more prominent for set 7 than set 1 and also for different axes. For example, a 20µm misalignment in vertical direction results in 4.8 dB of additional loss for set 1, which is around 3.4 dB for set 7. Same amount of misalignment in horizontal direction results in 3.2 dB for set 1 and not more than 1.5 dB for set 7.

V. Development of generic EOCB fabrication process

The multilayer fabrication consists of separately fabricated optical and electrical sub-packages. Then the different sub-packages can be stacked regarding customer demands in symmetrical or mixed stack-up configurations. This unique process benefits from a low temperature lamination technique with low built-in stress although combining materials with different coefficients of thermal expansion (CTE) like FR4, copper and glass. So the octa-layer EOCB consists of four glass waveguide sub-panels in the center covered with FR4 and copper layers. The glass panels with thicknesses of 550 µm and an area of 245 mm x 170 mm were inlayed in a FR4 frame having a large cut-out. In parallel, intermediate layers made of two adhesive foils and one FR4 layer were prepared by cold lamination, building the optical sub-packages. In parallel, the electrical sub-packages were processed by via drilling, plating and electrical trace etching followed by lamination of FR4 layers. This process can be repeated multiple times for electrical multi-layer stack-up fabrication. Optical and electrical packages were visually aligned to each other by aluminium fiducials on glass during the stack-up process. In that work we simplified the electrical packages and fabricated an electrical package with one copper layer. The electrical packages are then laminated by adhesive foils to the optical packages resulting in a final PCB thickness of 4 mm. Finally vias were drilled outside the glass area, plated and the outer electrical traces are etched for defining pad arrays in the EOCB. The last process step was the solder mask application, stencil printing, pad surface finishing and milling of windows (cut-outs) to achieve optical access to the glass waveguide coupling interfaces.

For the large-panel-EOCB the processing is the same but the formats are different. The 4 glass panels with individual thicknesses of 550 µm and areas of 143 mm x 190 mm were inlayed in an FR4 frame having a large cut-out. In parallel, intermediate layers made of two adhesive foils and one FR4 layer were prepared. The optical sub-packages are fabricated by laminating the FR4 layers with adhesion foils to the glass core and surrounding FR4 frame with the mentioned low temperature lamination technology. The glass is visually aligned to the FR4 layers by utilizing the fiducials on the glass surface and on the FR4 frame and the FR4 layers are passively aligned by pins to each other called “pinlam method”.

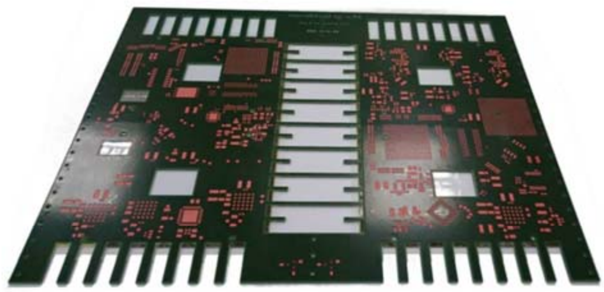

Figure 12. Fabricated large-panel-EOCB with area of 350 mm x 465 mm.

The large panel EOCB is fully functional and demonstrates the integration of four glasses within one stack-up as shown in Figure 12. The glasses are completely intact and have no built-in tensions. The logos of the partners patterned on the top glass panel are visible through cut-outs in the electrical packages. Separating the large panel EOCB into electrical and optical packages allows the electrical packages to be fabricated using standard PCB process technologies, allowing highly complex electrical functionality for customer specific demands to be accommodated including blind- and buried VIAs, HDI-layouts and embedded components etc.

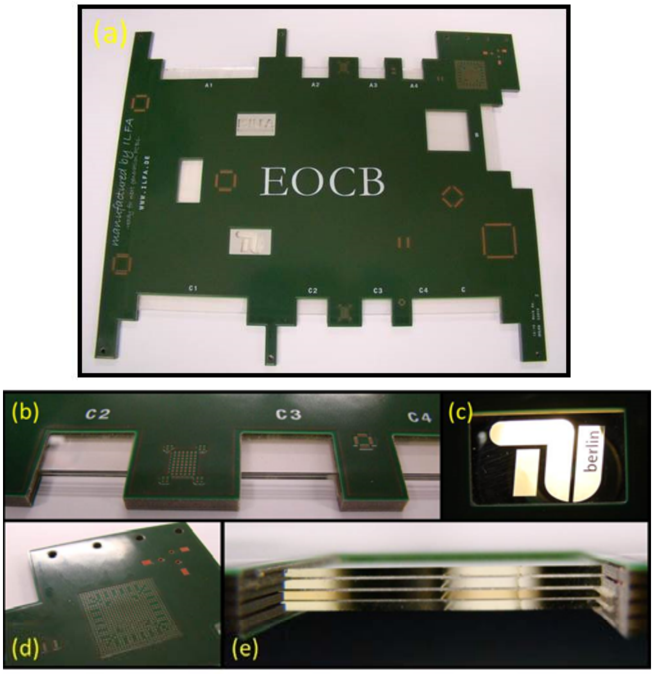

Figure 13. Fabricated octa-layer-EOCB (a) with access on the edges to glass waveguides (b), illuminated partner logos patterned on glass (c), electrical BGA pad array (d) and embedded four double-sided glass panels (e).

The octa-layer-board is also fully functional and demonstrates the integration of four glasses within one stack-up as shown in Figure 13 but still shows horizontal an vertical alignment errors within the glass layer stack-up

Two arrays of 12 waveguides were measured for all eight optical layers (L1-L8). All 96 optical channels were characterized and results are plotted in Figure 14 for 125 and 250 µm channel waveguide pitch. The mean value for 250 µm pitch for insertion loss at wavelength of 1310 nm is 3.3±0.33 dB and cross-talk was measured with 34.8 dB. Similar results could achieved for the smaller pitch of 125 µm. The mean value for insertion loss of 96 measured channels is 3.3±0.32 dB and cross-talk is 32.0 dB.

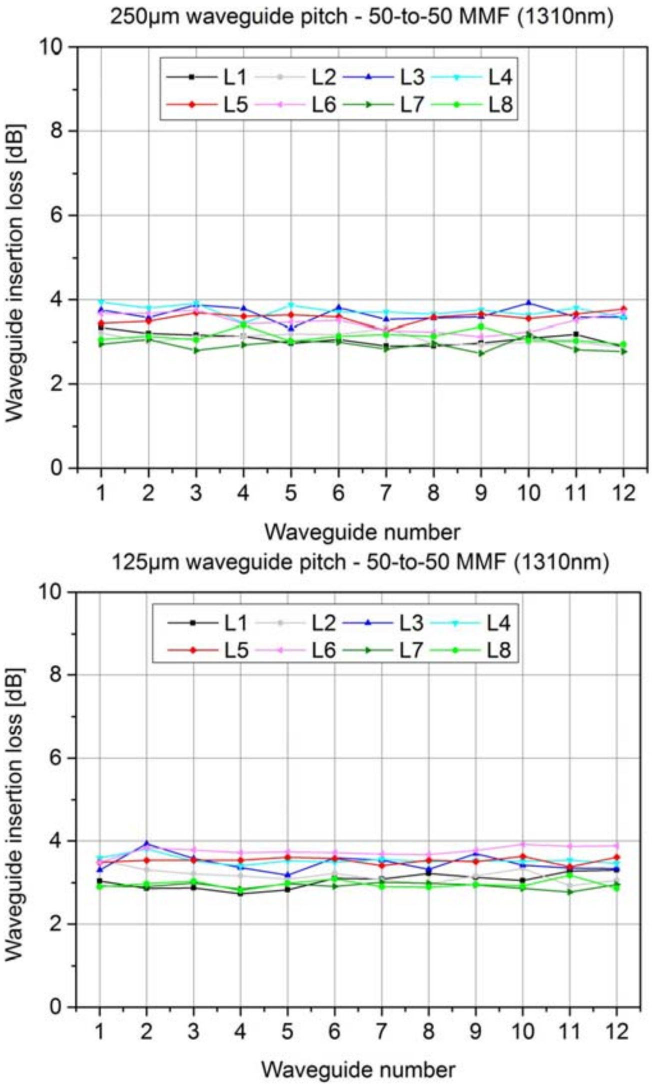

Figure 14. 2D waveguide array characterization with 12 channels and eight layers for 250 µm channel waveguide pitch (left) and 125 µm channel waveguide pitch (right).

The multi-mode glass waveguides are located close to the glass surface. The measurements indicated no significant loss increase as result of the lamination process. Light propagation in the EOCB is presented with very low loss. Graded-index glass waveguides have been operated with data rates of up to 32 Gb/s [9] which gives a possible data traffic of 3.072 Tb/s for such 96 channel parallel optical link.

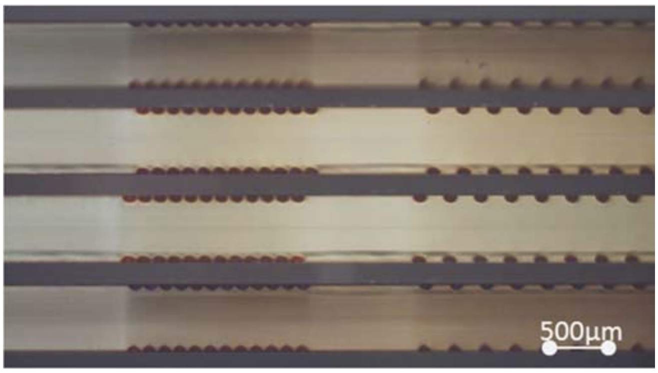

Figure 15: Octa-layer EOCB cross-section showing waveguide positions

Eight optical layers with 96 channels are embedded in the EOCB causing a high interconnection density with a total cross-section area of 2.8 mm x 3 mm for 250 µm channel waveguide pitch and 2.8 mm x 1.5 mm for 125 µm channel waveguide pitch. Distances between layers are measured to be: 188.15, 162.49 and 166.77 µm. As it can be seen, registration errors between different layers are, despite the registration effort with alignment markers, still existing. Between the first and second layer, an error of 57 µm was measured. Between the second and third and third and fourth layer, the error is 107 µm, and 11 µm, respectively. An improvement in alignment accuracies is expected by better alignment markers adapted to glass fiducial recognition. With this option and the already optimized alignment tolerances for 20 µm displacement in mind, it seems feasible to reduce registration errors down to less than 20 µm. It is target of current ongoing work.

VI. Summary

The process development and waveguide characterization of one and double-sided glass waveguide panels and embedding of multiple glass panels by standard PCB fabrication routines was in the focus of our work. Low loss waveguides with high NA for tight bends with radius of 10 mm could be demonstrated successfully. The glass waveguides have very low loss at all key wavelengths for datacom and telecom application. An optical octa-layer EOCB demonstrator with two electrical layers was successfully fabricated and optical waveguide loss and channel position accuracy studied in detail. To best of our knowledge it's the highest number of waveguide layers that has ever been demonstrated for an EOCB. The second demonstrator comprised 4 glass sheets in one layer realizing one half of a large panel optical backplane for a dual star interconnection backplane..

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REFERENCES

[1] F. R. Libsch, R. Budd, P. Chiniwalla, P. C. D. Hobbs, M. Mastro, J. L. Sanford, and J. Xu "MCM LGA package with optical I/O passively aligned to dual layer polymer waveguides in PCB," in Proceedings of IEEE Electronic Components and Technology Conference, (IEEE 2006), pp.1093-1099.

[2] M. Shishikura, Y. Matsuoka, T. Ban, T. Shibata, and A. Takahashi, "A High-Coupling-Efficiency Multilayer Optical Printed Wiring Board with a Cube-Core Structure for High-Density Optical Interconnections," in Proceedings of IEEE Electronic Components and Technology Conference, (IEEE 2007), pp. 1275-1280.

[3] K. Hasharoni, S. Benjamin, A. Geron, G. Katz, S. Stepanov, N. Margalit, and M. Mesh, "A high end routing platform for core and edge applications based on chip to chip optical interconnect," in Optical Fiber Communication Conference, (Optical Society of America, 2013).

[4] N. Tanio, and Y. Koike, "What Is the Most Transparent Polymer?," Polymer Journal, 32(1), 43-50 (2000).

[5] S. R. Najafi, "Introduction to Glass Integrated Optics", Artech House, Boston, 1992.

[6] L. Brusberg, H. Schröder, R. Pitwon, S. Whalley, Ch. Herbst, A. Miller, M. Neitz, J. Röder, K.-D. Lang; „Optical backplane for board-to-board interconnection based on a glass panel gradient-index multimode wave-guide technology"; Proc. 63st ECTC 2013, May, 28-31, 2013, Las Vegas, USA, pp. 260-267

[7] L. Brusberg, H. Schröder, R. Pitwon, S. Whalley, A. Miller, Ch. Herbst, M. Neitz, J. Röder, D. Weber, K.-D. Lang; „Electro-optical Backplane Demonstrator with Gradient -index Multimod e Glass Waveguides for Board-to-board Interconnection"; Proc. 64st ECTC 2014, May, 27-30, 2014, Orlando, USA, pp. 1033-1041

[8] H. Schröder, "Thin glass based electro-optical circuit board (EOCB) waveguide process, PCB technology, and coupling interfaces", Proc. CPMT Symposium Japan (ICSJ), 2015 IEEE, 9-11 Nov. 2015, Kyoto, Japan, pp. 109 – 117, 10.1109/ICSJ.2015.7357373

[9] R. C. A. Pitwon, L. Brusberg, H. Schröder, S. Whalley, K. Wang, A. Miller, A. Worrall, A. Messina, and A. Cole, "Pluggable Electro-Optical Circuit Board Interconnect Based on Embedded Graded-Index Planar Glass Waveguides," J. of Lightwave Technology, **33**(4), pp.741-754, (2015).