Advanced Thin Glass Based Photonic PCB Integration

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Abstract

The central aim of the overall is the realization of electro-optical circuit boards (EOCB) by using thin glass as known from display technology. Such technologies give the possibility to develop products with improved performance, higher reliability, lower costs and higher energy efficiency. A crucial building block is the integration of optical signal transmission within the EOCB. A presentation of size-enlarged EOCB with holohedrally integrated glass foils is subject of the paper. These EOCB are capable to provide future bandwidth standards through integrated optical waveguides for high speed intra system optical data transmission as well as sensor technology. Therefore structuring technologies have been developed that are compatible to the industrially introduced PCB manufacturing. Already established processes as well as new approaches were analyzed for their eligibility and have been applied for the EOCB process.

Introduction

Researches for the integration of optical connection methods in EOCB have been affected already for more than one decade. The rising demand for transmission bandwidth also inside the systems because of the increasing processor's clock rate (Figure 1) is a decisive factor.

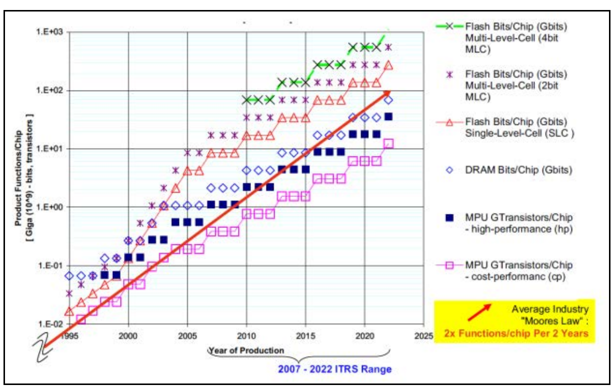

Figure 1: Increase of processor capacity, forecast until 2025 [1]

There are different standards already existing or in discussion for intersystem data transmission (e.g. Fibre Channel FC16G (17 Gbit/s, 2009), Infiniband (20 Gbit/s, 2011), FC32G (34 Gbit/s, 2012), CEI-25 (25…28 Gbit/s) and USB 4.0 (20…60 Gbit/s expected). For such transmission bandwidth optical interconnects are regarded as more efficient in power and cost (Figure 2).

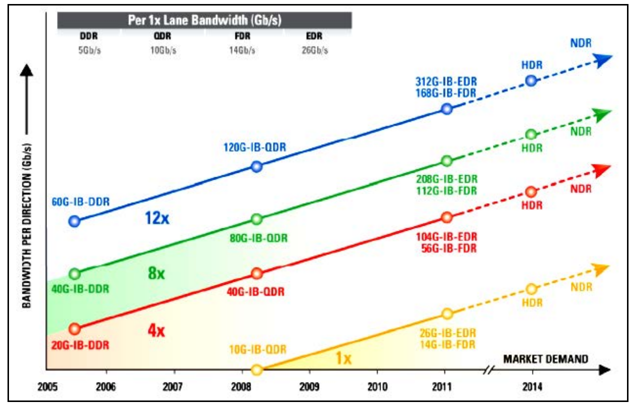

Figure 2: Infiniband-Roadmap for parallel optical links [2]

The changeover to optical data transfer in the field of short intersystem ranges (in data centers) becomes apparent through the more frequent use of Active Optical Cables (AOC). The further development for transmitter components supports this trend: vertical cavity surface emitting lasers (VCSEL) with 25 Gbit/s have been shown, 40 Gbit/s is under way [3]. The efficient provision of high transfer bandwidth within the systems with a range less than 1 m – the problem to be solved as proposed herein – also requires optical signal transmission, but fiber technology does not apply. The data rates for newly developed backplanes should support at least 10…25 Gbit/s per channel [4]. By now 10 Gbit/s·m have been shown electrically [5,6]. In this field further increases are possible and can be attended. But additional driver and detection components must be integrated and costly base material which is suitable for high frequencies has to be used to keep high signal integrity. Furthermore the necessary efforts for electromagnetic shielding lead to low channel density especially in the areas with plug contacts on the edge of the circuit board. These disadvantages can be avoided by implementing hybrid, electro-optical integrated interconnection technologies as argued later in more detail. High interference resistance, low power loss, reliability, scalability, highly efficient performance and low required space are fundamental reasons – besides the high bandwidth-length-product – for the use of optical interconnection technologies for racks in systems.

The conversion pressure is especially strong in high performance computers (HPC). Concerning security, these high-end-products have to be rated critical, thus they have to be reliable. The additional components which are necessary for the changeover to optical data transfer (o/e emitter and receiver, corresponding drivers and amplifiers) lock this transformation. The changes in design and technology affect some risks and generate initial costs. Both counteract the trend to optical system integration. Nowadays optical interconnects are mostly realized on the base of fiber connections containing e/o-modules near the processors. As can be seen in Figure 3 the increase of the system performance in notebooks will follow the one in HPC, but with an 8 to 10 year delay. So also the consumer is concerned by this difficulty.

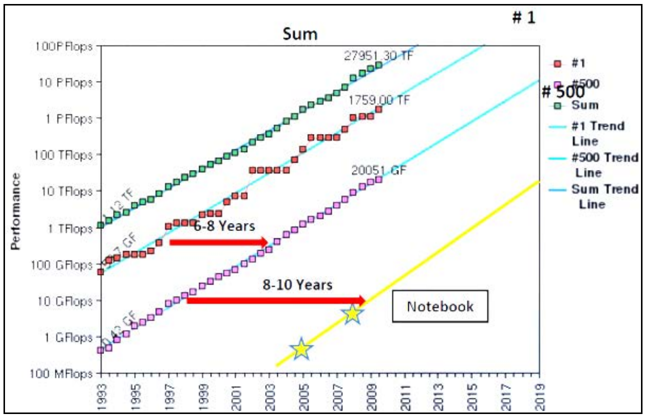

Figure 3: Increase of the system performance in HPC, forecast until 2019 and comparison with Notebooks [7]

The technological aim of these researches (apart from the aforementioned development of components) is the development of planar structuring procedures for optical integrated waveguide laminates, which are grouted in the assemblage of printed circuit boards (PCB) resulting in EOCB laminates [8]. Many polymer materials have been developed for these laminates [9]. The structured waveguides are multimodal step index waveguides with core dimensions of 30…70 µm. The polymer properties and the different structuring technologies define basically the length of the waveguides and the obtainable optical loss [10]. The use of thin glass – as treated in this paper – is subject of research for not many years; but the existing results are already very encouraging [11].The benefits of glass as carrier material for electrical and optical interconnects compared to conventional materials like silicon, ceramic or polymer based laminates caused by its excellent dielectric and transparent properties that are important for electrical high-frequency signal wiring as well as for optical wave guiding, and the high dimensional stability are discussed extensively in [12]. Especially the high integration potential and the thermal stability of the waveguides are important for the system. The high spectral transparency in the infrared wavelength range and the gradient refractive index profile are optically advantageous. The latter provides a lower dispersion and therefore a higher bandwidth than step index waveguides usually characteristics of a polymer waveguide technology [13,14].

Architectures, which connect electro-optically converted signals from one CPU on a hybrid electrical optical daughter card via an optical backplane to another daughter card, are needed to realize High-End-Server applications with symmetric multi-processor systems. For today's multi-processor capacities with a range of multiple Tbit/s optical waveguides per daughter board would be necessary. An increase in packaging density is required because of the limited space on the board due to system standards [15]. To increase the channel density the space between the waveguides can be diminished or further optical signal layers can be placed one upon the other [16,17,18].

Fabrication of optical waveguides in panel size thin glass foils

Important is the compatibility to the post processes of integration in the PCB assemblages and the component assembly of the final EOCB. It has to be paid attention to basic conditions as if the product is technologically reliable and if it fits with existing standard interfaces (e.g. the structuring of registration markers and holes for the mechanical registration to the multi-layer composite during the laminating procedure or as electrical contacting between the different layers). Thin glass was already proven as practical basic material for the integration of optical waveguides [12]. In an already tested procedure on wafer level optical waveguides in thin glass type D263T sodium ions were exchanged between the glass matrix by silver ions coming out of the molten salt. Hereby waveguides are fabricated by a diffusion process through a diffusion mask on the thin glass without geometrical modification of the thin glass. The precise photolithographical patterning for the fabrication of the waveguide diffusion mask and the salt bath process for the thermal ion exchange have to be regarded as technologically critical. The processing for panel formats to produce such optical waveguides in thin glass is not yet subject in manufacturing. Neither high precision exposure techniques nor process oven for the fabrication of such, that match with the requirements, are commercially available. Hence it was necessary to develop

- process techniques themselves and
- the parameters which are relevant for the process

The aim of process development was to reach the specifications which were achieved during the fabrication of optical waveguides on wafer level also when scaling the technology on PCB formats. An overview showing the technological requests for the large scale waveguide process is given in Table 1.

Table 1: Scaling of multimode waveguides from wafer format to PCB format

Process	Technological requests	Wafer Level	PCB Level
Photo resist coating	high resolution resists, effective consumption of resist, high sensitivity for fast exposure	Spin coating	constant resist lamination, dip coating
Structuring of the diffusion mask UV exposure	Line-space-resolution minimum 20 µm for multimode waveguides, sharp and smooth mask edges (also in waveguide bendings, no pixel interpolation) Profitability (costs for masks vs. LDI), scalable in size	Mask contact exposure	laser direct imaging (LDI), contact exposure with large format masks

Structuring of the waveguides	process homogeneity and – stability mechanical stabilization of the glass	Standard oven	Batch process, automatic course of processes, vertical processing
Thermal ion exchange	Working temperature ≤ 400 °C safe handling of molten salt		
optical front surface preparation, separation , structuring	avoid micro cracks mechanically reliable Polish ≤ λ/10	sawing, breaking polishing laser structuring	CNC milling, laser cutting
operating test	quality check, spectral absorbability (α ≤ 0,1dB/cm)	automatic loss measuring station	automatic loss measuring station

The process, which was recently developed to fabricate multimode waveguides scaled to a PCB format of (297 x 210) mm², will be described in the following: Aluminum is suited for diffusion mask material for the fabrication of the diffusion masks. It is deposited by sputter technology with a layer thickness of 400 nm on both sides. The structuring of masks openings for the process of waveguide diffusion is provided by using wet chemical etching.

Therefore a resist mask was fabricated by dip coating, following exposure in a laser direct exposure system (Orbotech "Paragon 9000") and development. The dip coating of the metalized samples has many advantages, as it provides a very homogeneous resist layer of 2…6 µm on both sides. Furthermore the procedure can be scaled on much larger formats. After a regular usage nearly no loss of resist can be observed and the thin glass samples are mechanically not affected, so no corrosion appears.

The structure to be developed is exposed by a UV-laser that transfers the mask layout directly in a writing procedure sequentially via a pixel matrix. Also a both-sided exposure with a measured layout pitch of about 5 µm is possible. The pixel's rim length is at 2.5 µm. During the exposure of diagonal waveguides the rim is shown as pixel steps, which leads to an increase of absorption in the finally realized waveguides. Hence waveguides with different diffusion mask widths and bendings were used for testing reasons.

Alternatively contact exposure large format masks can be used for waveguide curves and diagonal structures, but there the exact both-sided exposure will be hindered. Apart from this a change in design always requests a new precision pattern mask. For an optimum usage of the laser direct writing operation for the exposure of optical waveguides it is necessary to use systems with continuous vector based writing operations.

After diffusion mask structuring by wet chemical etching the sample is disposed for the first diffusion step. The waveguides will be realized by two diffusion steps in different molten salts. Between the diffusion steps the diffusion mask will be removed.

The first diffusion step is a depth diffusion of silver ions up to a depth of about 50 µm. The concentration gradient of the silver ions from the surface to the depth is processing analogically to the refractivity gradient. The concentration of the silver ions in the surface area is downsized in a second diffusion step until the surface refraction index reaches the value of the original thin glass. The result is an elliptic gradient waveguide, whose width is larger than the depth by reason of the isotropic diffusion performance (Figure 7). The processes of ion substitution took place in salt bath furnaces.

Mechanical structuring

Besides a process technology avoiding damage when fabricating the thin glass optical wave guides, it is necessary to develop technologies for mechanical structuring of vias and component openings. It has to be paid attention to format cuts as well as to the drilling of edge holes for the multilayer registration before and during the lamination process in the lamination press. When proceeding in a standard format the format cut can be done externally at the thin glass supplier responsibility. The described wave guide process below has been adapted to a format of 297 mm x 210 mm (DIN A4).

The centers of the edge holes for the multilayer registration have to be structured at ≤ 5µm tolerance to the diffusion mask to maintain the maximum range of tolerance of 50 µm after the laminating process. The diameter for the pins used during the mechanical registration is at 3 mm. The edge holes in the optical thin glass sheet therefore should have a diameter of 3,05 mm, to allow adjusting them in the registry by hand without being damaged and, on the other hand, to be adequate with the geometric tolerances of the electro-optical multilayer. The structuring method has to fulfill the following requests:

- no initial cracks and mechanical tension which cause corrosion of the optical foil
- appropriate handling time and safety
- commercial availability and transferability of the developed process, respectively

Drilling, milling and laser processing as current procedures in circuit board industry have been tested. It has been proved that only laser processing fulfills the requiremnents. Edge holes with a diameter of 3 mm have been successfully realized in thin glass with a size of 300 µm and equipped with a position identification system (as in Figure 4). Here a CO_2-Laser was used.

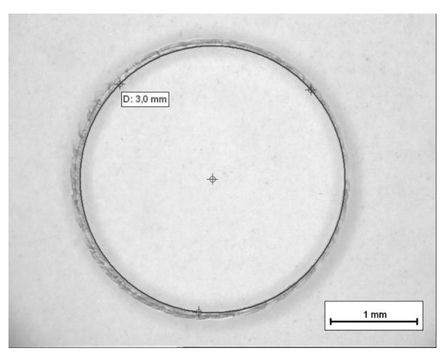

Figure 4: Structuring of edge holes for the mechanical pin registration of the optical layer for lamination in the electro-optical multi layer EOCB

A faster handling time is a basic advantage of CO_2 lasers compared to picosecond lasers which are used for glass structuring processes. Thus the handling time to fabricate a 3-mm-edge hole was at 47 seconds. Disadvantages are higher thermo-mechanical stress and lower micro-structurability, whereby the thermo-mechanical tensions can be minimized when using the correct process parameters. When using a CO_2 laser it is also possible to fabricate holes (see Figure 5) for the electrical through plating, which can be used as “stacked holes” in the electro-optical circuit board. Handling time per hole is at 0.2 seconds only. Minimum time when using picosecond lasers is 2 seconds.

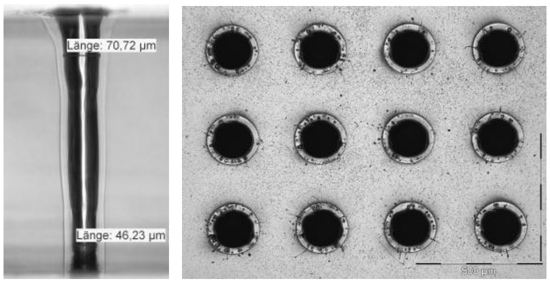

Figure 5: Structuring of through holes in 500 µm thin glass sheets for electrical through vias (cross section, left, and array with 300 µm pitch)

Optical characterization

An important issue for the developed large panel process is a waveguide profile that is formed homogeneously over the whole surface with design compliance. A simple check of optical function after the waveguide process and cutting can be made by transmission microscopy at the edge showing illuminated waveguide profiles. Process failures are well visible by waveguiding dimensions (Figure 6).

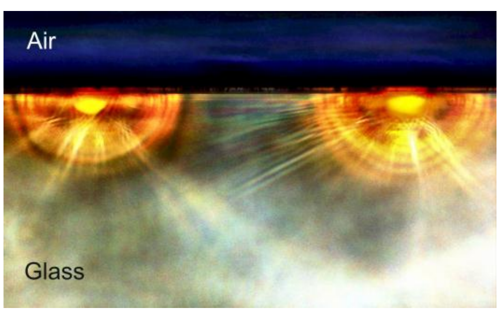

Figure 6: Optical micrograph of waveguide cross section showing two waveguides back illuminated, 250 µm pitch

The refractive index profile is characterized by refractive near field measurement. It provides the only direct measure of the waveguide refractive index profile as processed and is used for process adjustment. A typical refractive index profile for multi-mode wave guides can be seen in Figure 7. According to the used process parameters here the position of the refractive index maximum arises 15 µm below the glass foil surface (bottom line of the 2D scan in area in Figure 7. The maximum refractive index difference can be controlled in a range of $\Delta n = 0.01 \ldots 0.15$.

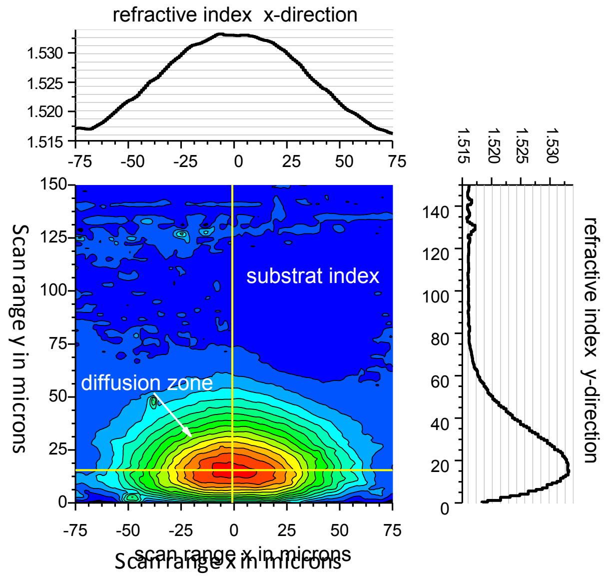

Figure 7: Refractive index cross section profile, taken by refractometric near field measuring (RNF) at wavelength of 678 nm

An outstanding advantage of glass integrated waveguides is the high spectral transparency within the important telecommunication wavelengths 1310 nm, 1550 nm, and 850 nm. Due to fractional silver reduction higher losses can be observed in the visible range below 750 nm. The waveguide loss for an optimized wave guide process (values taken from wafer level investigation) can be seen in Table 2. Standard conditions for multimode loss measurement are waveguide excitation using graded index fiber GI-50/125, NA = 0.2 and waveguide detection by means of step index fiber SI-200/230, NA = 0.37

Table 2: Typical spectral waveguide loss in dB/cm

Wavelength in nm	675	850	1310	1550
Loss in dB/cm	0.85	0.092	0.025	0.064

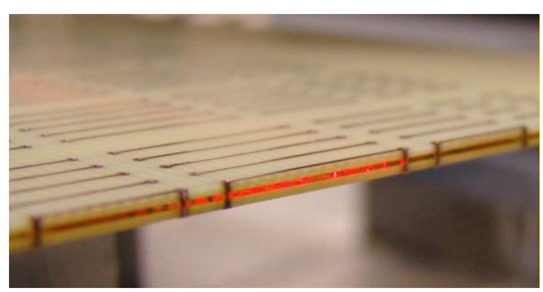

Figure 8: Red illuminated thin glass waveguide after EOCB lamination and Cu etching for daisy chain electrical test structures

In Figure 8 one of the first EOCB with holohedrally integrated glass foils is shown. Red edge illumination at the hidden opposite side causes not only the red light output line as to be seen but also out-of-plane coupling in case of cracks which can be detected by AOI systems as a fast check. A closer look at the realized build-up is shown in Figure 9.

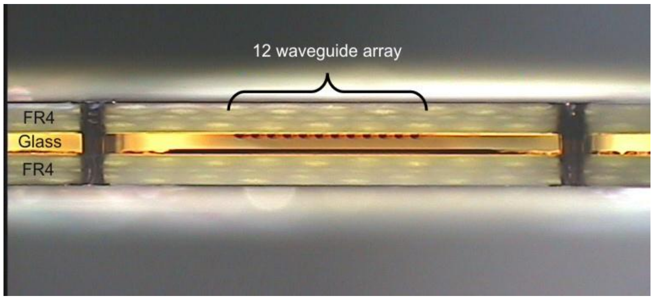

Figure 9: Optical micrograph of EOCB cross section showing 12 integrated waveguides back illuminated, 250 µm pitch

It has been found that the characterized waveguides change their loss before and after the lamination process in the large EOCB (see Table 3). The underlying physical mechanism is still unclear but regarded as a scaling problem. Improved process homogeneity over the whole panel is subject of current development to reach the wafer level performance at better yield.

Table 3: Waveguide loss before and after lamination process of the optical glass layer

Wavelength in nm	675	850	1310	1550
Loss before lamination in dB/cm	3.04	0.33	0.09	0.23
Loss after after lamination in dB/cm	3.55	0.38	0.11	0.27

Lamination properties and PCB compatibility

Glass is different from conventional circuit board material (FR4) in basic characteristics that are relevant for fabrication. In particular the coefficient of thermal expansion (CTE) for glass is four times lower than for FR4, thus suitable actions to avoid stressing of the laminate have to be realized, A main focus has to be put on the general handling of the glass substrates, as they are explicitly more fragile than FR4 concerning mechanical damages.

The thickness of the used foils is defined by the specifications of the component's producer and the wave guide geometry. Glass foils of 300 µm size were used in the format 297 mm x 210 mm, which is lower than PCB panel formats in standard use. Hence the registration processes had to be adapted, special size adapters were used.

In opposite to former approaches a holohedral glass foil was laminated into the composite within this project. The glass (the optical foil) is located in the center, on the top and bottom side standard FR4 material is laminated. These can contain several electrical layers, if it is requested by the electrical electro-optical design. Alternative materials to standard-FR4 are possible too (Figure 10).

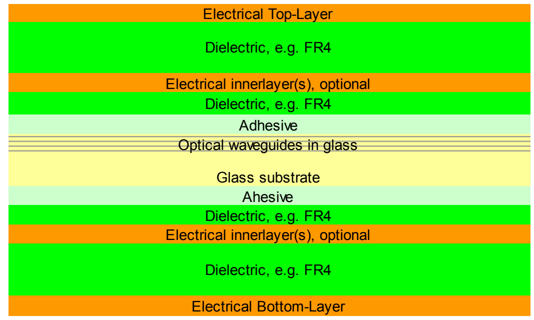

Figure 10: Schematic drawing of EOCB build-up

Lamination itself is made by conventional hydraulic PCB-pressing technique, as composite adhesive different alternatives have been tested. „Classical", fiber glass reinforced epoxy prepregs show strong shrinking behavior in x and y direction, where nominal tensile stress on the glass foil can result.

The usage of a homogeneous soft adhesive layer on both sides, which is also used in rigid-flexible PCB-technology, was leading to satisfying results. Furthermore the temperature ramp as well as the pressure ramp of the press cycle has been optimized, to avoid cross-cracks in the glass during pressing procedure (Figure 11).

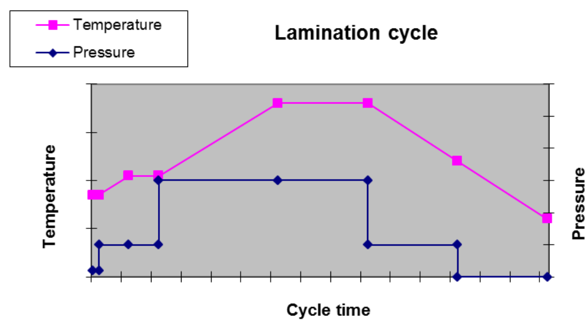

Figure 11: Temperature and pressure ramp to minimize tensions in the glass substrate

Drilling and via filling

For the inserting of drillings two approaches can generally be followed:

- Drilling of the entire pressed, hybrid assembly (FR4-Glass-FR4, Figure 12) , or
- Deepening of the holes to be metalized in the glass foil before lamination and opening of both sides after lamination (Stacked Holes, Figure 14)

The first method is preferred, but it has more technological risks. In a mechanical process, to reach an adequate drill hole quality, particularily in the glass foil, modified tools and parameters have to be used. Drill diameters < 0.5 mm have been successfully fabricated (Figure 12).

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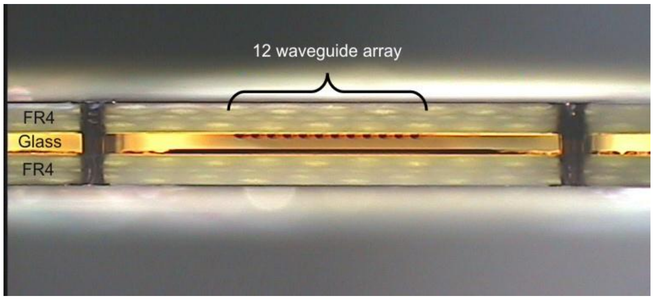

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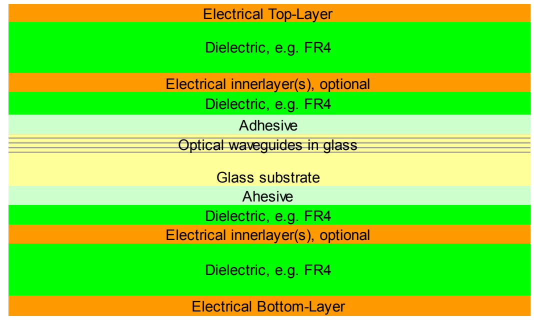

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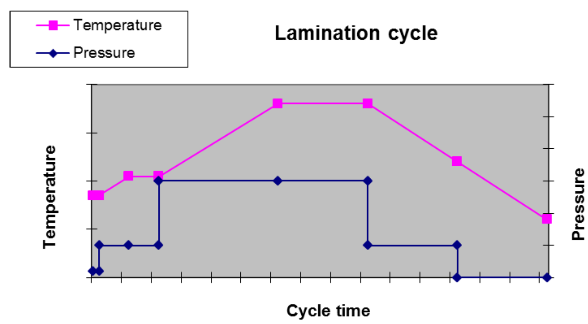

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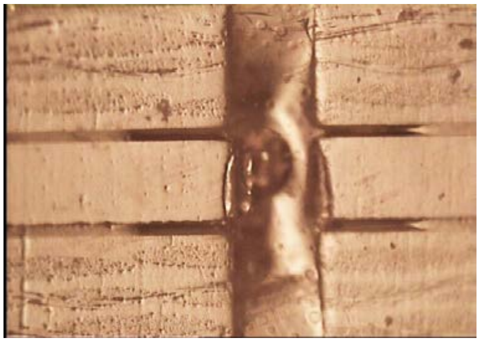

Figure 12: Cross section of mechanically drilled 0.3 mm diameter via through the hybrid-assembly without any damage

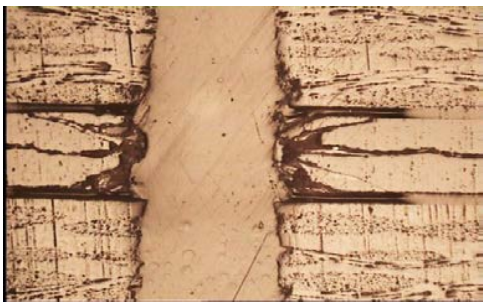

Figure 13: Cross section of mechanically drilled 0.8 mm diameter via through the hybrid-assembly showing cracks

A massive damage of the glass foil can result from larger drill diameters at a pure mechanical handling (Figure 13). Furthermore tests have been made to deepen the drills via laser respectively via combined processes (mechanically and laser). The technological potential is high, so it will be continued to test and optimize these processes.

The realization of the second alternative (Stacked holes) has been proved. In general the advantage of this process is that the holes in the glass can be generated by CO_2-laser structuring with high quality and layout precision to the optical layer, but it requires the registration technology of the PCB-manufacturer on a high level. Also in an economical issue this approach does not come up to the first process.

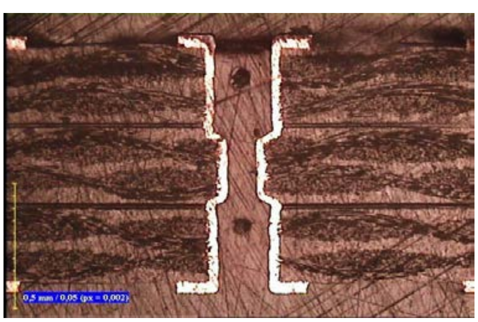

Figure 14: Stacked Holes, metalized

The metallization of the holes is provided by the following three steps (as in conventional PCB's):

- Conditioning/pre-treatment of the perimeter of bore hole
- Separation of an initial conductive layer for the following separation of copper
- Electrolytic separation of copper in the perimeter of bore hole down to a minimum of 20 µm

Especially the first and the second step make new and great demands on the processes, as the front surfaces of the glass substrate and the glue medium have to be covered, as it has to be done for the FR4.

Experiments with plasma handling and a following direct metallization process show promising results. On the glass itself damage free and adhesive copper coats could have been separated. First thermal stress tests do not show disadvantageous characteristics compared with conventional PCB-assemblies.

Optical interface

The optical interface for e/o modules is design specific in size but needs surfaces of optical quality to enable low loss optical coupling in and out of the waveguides. Such optical interfaces are needed at the card edge and at any design depending position at the card area. At the card edge polishing can be applied. But the challenge is to open windows after lamination with optical quality and at the right position (Figure 15).

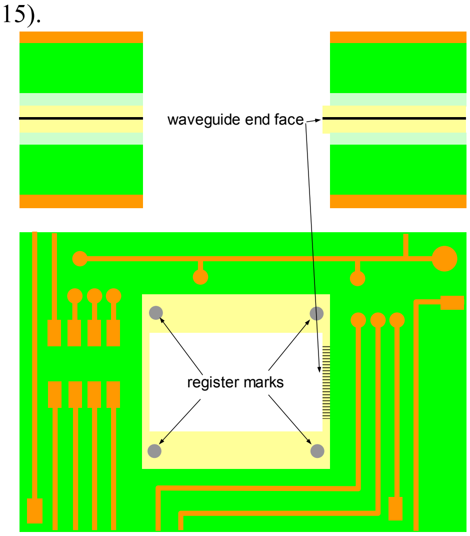

Figure 15:Schematic drawing of optical waveguide interface in top and side view

The opening position of the optical interface can be detected with optimized processes equipment using imaging registration of the markers. Crack-free optical interfaces in glass can be generated (Figure 16) by choosing appropriate cutting tools in combination with adapted milling parameters. The glass shows conchoidal fracture unsuitable for optical coupling but sufficient for opening three sides of the rectangular window. The fourth side of the window (indicated at the right side of the window in Figure 15) where optical end face quality is required has to be achieved by an even more promising technology. We tested a scribing and breaking approach for separation the fourth side where the waveguide end face is positioned and achieved optical quality in the first trails as shown in Figure 17.

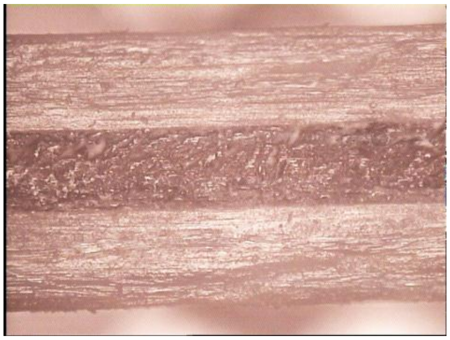

Figure 16: Conchoidal fractures occur at the glass end face by applying glass milling for glass structuring.

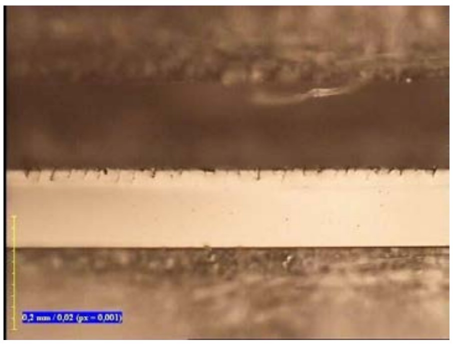

Figure 17: Optical end faces in the bright area of the glass cross view achieved by a scribing and breaking approach.

Conclusion

We carried out process development to show the feasibility of thin glass foils for large panel. We have been focused on optical integration and PCB manufacturing. The optical attenuation is still higher than on wafer level but optimization is in promising progress. most important impact can be gained by improving diffusion mask patterning. Here laser direct imaging is the most promising approach in ongoing investigations.

The PCB manufacturing results show the feasibility for large panel integration. Lamination, drilling, cutting and milling have been investigated for glass core built-ups and the results are very promising.

Future work has to be focused on waveguide process homogeneity and yield. Particularity reliable via drilling low optical loss waveguides yield have to be further improved in order to make the process ready for high volume manufacturing. To reach this goal handling issues are crucial too and are still under investigation.

Our packaging solution will be perfectly suitable for 3D heterogeneous integration and realization of complex and reliable microsystems assembled on EOCB. The benefit of glass for both module and board level results in excellent optical, electric, chemical, and thermal properties. In particular the optical pathways can be realized using one material and technology platform. Other functions like mechanical and low frequency can be satisfied by conventional packaging.

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