Single-mode Glass Waveguide Platform for DWDM Chip-to-Chip Interconnects

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Abstract

Due to high bandwidth potential, optical single-mode signal transmission is superior to electrical as well as optical multi-mode signal transmission. For years, optical single-mode fiber cables have been used in telecommunication networks. However, there is a lack of photonic system integration based on optical single-mode interconnects in printed circuit boards and modules for signal transmission between electro-optical components and optical fibers. Therefore, a thin glass-based photonic integration concept for single-mode signal transmission was developed. Optical waveguides and optical free space interconnects are integrated in a single or a stack of thin glass sheets for module and printed circuit board packaging. For light routing inside a thin glass sheet, a single-mode waveguide technology on wafer level (150 mm) was developed promising for scaling up on panel size (45 x 60 cm²). The waveguides show single-mode behavior, low propagation (0.05 dB/cm) and fiber coupling (- 0.3 dB) losses at wavelength of 1550 nm. Different waveguide structures such as 180°-bends, S-bends, splitters and crosses have been integrated in thin glass and characterized in detail. Coupling mechanism and misalignment loss has also been studied. Technologies for fiber laser joining on glass as well as laser structuring of an optical mirror are introduced and first results are presented. Generic module and board-based photonic packaging solutions can be put into practice by applying all introduced technologies and will be demonstrated for a chip-to-fiber module package platform.

Introduction

The International Roadmap of Semiconductors (ITRS) forecasts a number of 3420 signal pins for high-end processors having together an off-chip data rate of 230 Tb/s in year 2022 [1] [2]. This corresponds to a data rate of 67.3 Gb/s per pin, which can only be achieved through single-mode optical off-chip interconnects. A board level single-mode waveguide technology is the straightforward development for future high-bandwidth optical interconnects between silicon nano-photonic based transceiver nodes. Such silicon based transceivers with integrated modulators, photodetectors, multiplexers and hybrid bonded lasers will be integrated in multi-core processing, memory or through-silicon-via (TSV) processor units [3]. Due to the optical high-bandwidth potential using the dense wavelength division multiplexing (DWDM) technique, the whole optical path on-chip but also chip-to-chip or board-to-board has to be single-mode. Multi-mode based electrical-optical circuit boards (EOCB) together with hybrid transceiver packages called active interposers are just an interim solution because of limitations in DWDM signal routing and coupling to silicon nano-photonics for very high-speed data communication in high-performance computers, data-centers or switching-units. Silicon nano-photonic devices assembled on a single-mode EOCB are the best choice. Of course, silicon nano-photonics are still under development but showing great potential [4] [5]. Light coupling in single-mode waveguides is challenging because of lower coupling tolerances compared to multi-mode waveguides. On the other hand, smaller waveguide dimensions result in higher integration density. A single-mode glass waveguide platform processed on wafer level or panel size will bridge the gap between silicon nano-photonic devices and telecom glass fiber interconnection for fiber-to-chip and chip-to-chip communication.

This paper presents a photonic integration concept called *glassPack* based on thin glass substrates with planar integrated optical single-mode waveguides for optical routing between electro-optical components as well as optical glass fibers shown in Figure 1. This novel integration concept merges micro-system packaging and glass integrated optics. This kind of packaging consists of a thin glass substrate with planar integrated single-mode waveguide circuits, optical mirrors and lenses providing a platform for silicon nano-photonic device assembling and optical fiber interconnection. Thin glass is commercially available in wafer and panel formats and exhibits excellent optical and electrical high-frequency properties. That makes it perfect for micro-system photonic packaging.

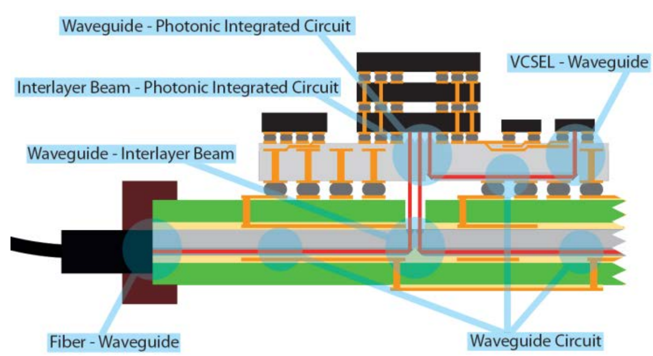

Figure 1: *glassPack* based on thin glass substrates with planar integrated optical single-mode waveguides for optical routing between electro-optical components and fibers on module and board level

Thin glass substrates will be used as substrate for 3D interposers or as embedded core layer in the electrical-optical

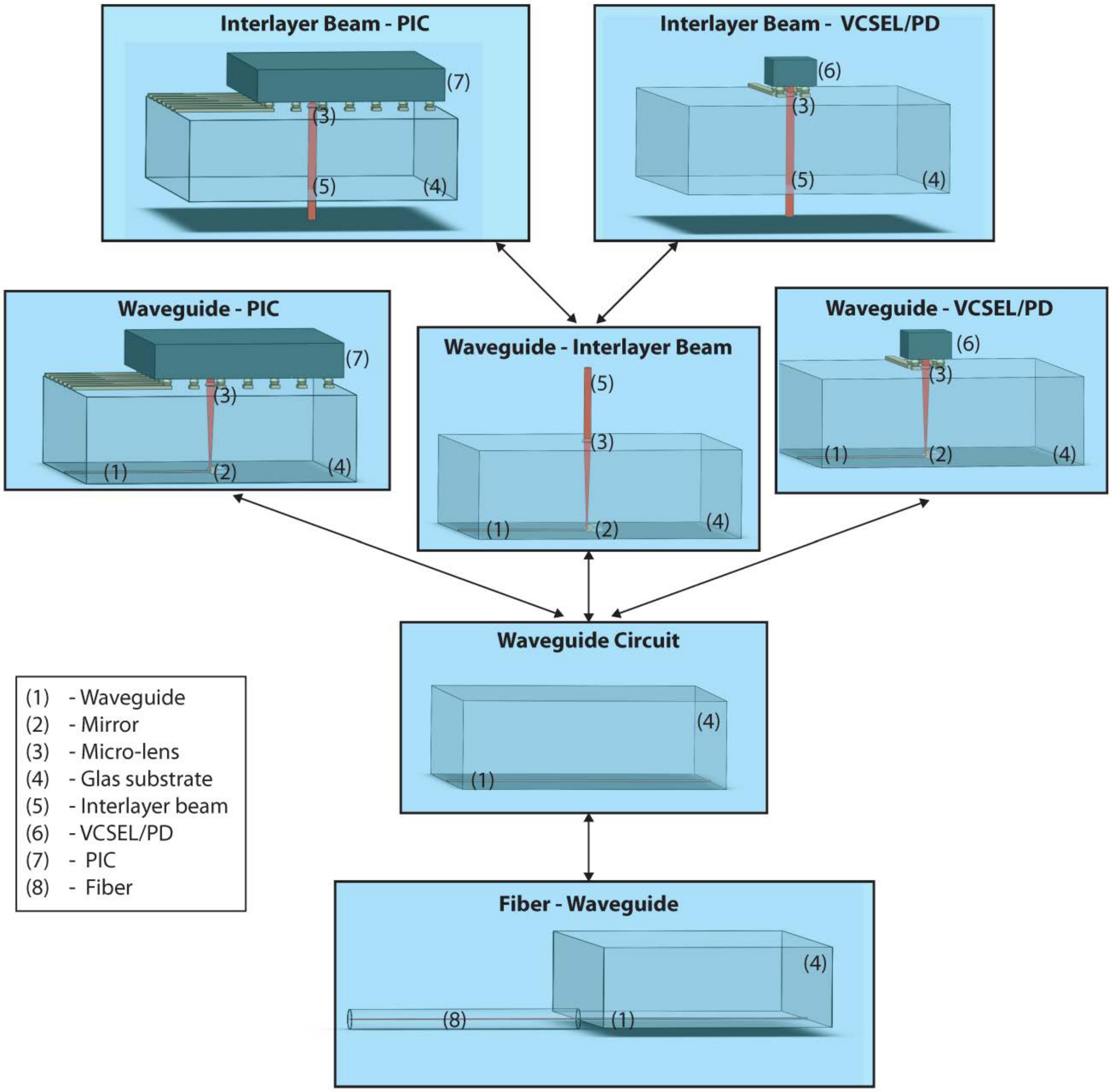

Figure 2. Building blocks sub-divide the photonic integration concept called *glassPack* in generic units. The red lines are the optical signals passing integrated lenses, mirrors and waveguides

circuit board (EOCB) as shown in Figure 1. The integration concept consists of a through-glass-via (TGV) interposer with electrical and optical interconnects that is mounted on an EOCB having a glass core with integrated optical waveguides as well. Red lines in Figure 1 are optical signals passing integrated lenses, mirrors and waveguides. Electrical and electro-optical components like lasers, photodetectors or photonic integrated circuits (PIC) are assembled on the same glass substrate. The concept was already proofed on a multi-mode based demonstration for the TGV interposer [6] as well as for the EOCB [7].

The introduced photonic integration concept is sub-divided in building blocks that are marked in Figure 1 and shown in Figure 2. Of course there are more optical interconnect scenarios of lower relevance that will not be considered at the moment for keeping focused. The generic building block approach is applied for glass compatible technology evaluation, optimization and development. Photonic modules and EOCBs will be generated by combining several building blocks. The **“Wavguide Circuit”** building block involves all 2D waveguide circuit elements like straight waveguides, bends, splitters and crosses. In plane interconnecting an optical glass fiber with the integrated waveguide is described by the **“Fiber-Waveguide”** building block. The **“Waveguide - Interlayer Beam”** building block covers the waveguide out of plane coupling for interlayer beam connection. Coupling the light out of the waveguide plane requires optical mirror integration for light deflection about 90 degrees and micro-lens integration for light collimation. Collimated light gives more coupling tolerances between different glass layers and can be applied as optical coupling interface between the EOCB and TGV interposer. On top of the TGV interposer electro-optical components are assembled like PICs **(“Interlayer Beam – PIC”** building block) or VCSEL and photodetectors (**"Interlayer beam – VCSEL/PD"** building block). The interconnection between the integrated waveguides and electro-optical components on substrate top surface side are presented by the **"Waveguide – PIC"** and **"Waveguide – VCSEL/PD"** building blocks. The optical design for specified components and packaging parameters was determined for each building block based on a ZEMAX optical simulation. Micro-lens parameters have been calculated by optimizing the coupling efficiency of each building block. As result lens radius and conic constant could be determined for evaluating micro-lens integration technologies in glass substrates [8]. In contrast this paper focuses on waveguide circuit, fiber coupling and optical mirror integration technologies.

Waveguide Circuit Technology

The ion-exchange technology in glass was developed and optimized for single-mode glass waveguide manufacturing using commercially available thin glass sheets. The waveguides are planar integrated below the glass surface. The investigations focused on a waveguide technology development for wafer and panel formats. Therefor a thermal diffusion process is best choice because of batch processing and scaling potential. So far the developed waveguide technology has been demonstrated for 150 mm wafer level.

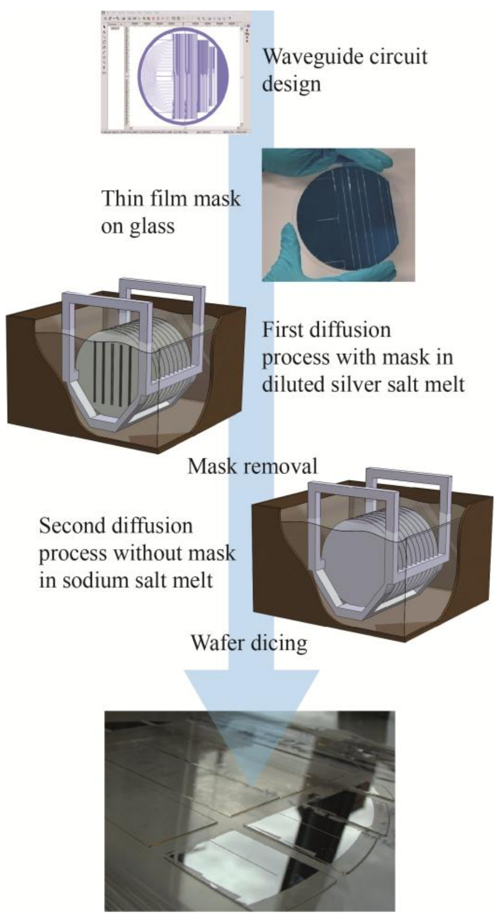

Figure 3. Process flow of ion-exchange single-mode waveguide technology on wafer level

After the waveguide circuit design the waveguide layout is transferred as aluminum mask on the glass wafer surface performing thin film processing. The process flow for the waveguide circuit technology in glass is shown in Figure 3. Waveguide manufacturing consists of two thermal diffusion steps. The first diffusion step is performed in a diluted silver salt melt at a temperature of 350°C. The structured aluminum mask deposited on the glass surface supports the local confined diffusion process between the glass and the salt melt. Silver ions of the salt melt diffuse into the glass and exchange places with sodium ions of the glass network. As a result of differences in electronic polarizability and ionic radii between the exchanged ions, the refractive index of the glass increases. After removing the aluminum mask, a second diffusion step in a silver free sodium nitrate melt decrease the refractive index below the glass surface because of back diffusion behavior of silver ions at the glass surface area into the melt. The waveguides are planar integrated below the glass surface. Because of planar waveguide integration post-processing like thin film metallization or optical lens and mirror structuring can be applied on wafer level. Finally the wafer is diced into separate waveguide samples.

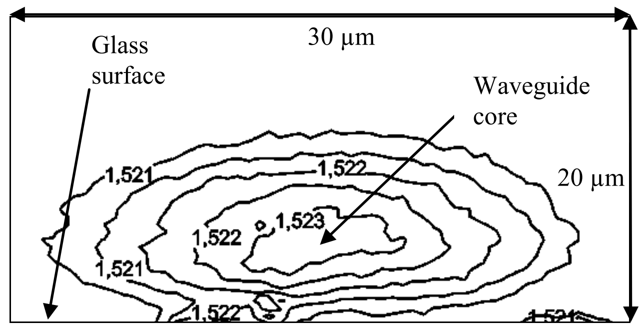

Figure 4. Single-mode waveguide profile measured with refractive near field method at wavelength of 678 nm

Single-mode waveguides have been integrated in Schott D263Teco thin glass by the introduced purely thermal ion-exchange technology. A waveguide processed in this manner is characterized by an elliptical waveguide profile. The resulting refractive index profile (Figure 4) was measured by a two dimensional refractive near field scan at a wavelength of 678 nm. The refractive index profile of the waveguide shows an index modulation of 0.003. The waveguide core is located 5 µm below the glass surface.

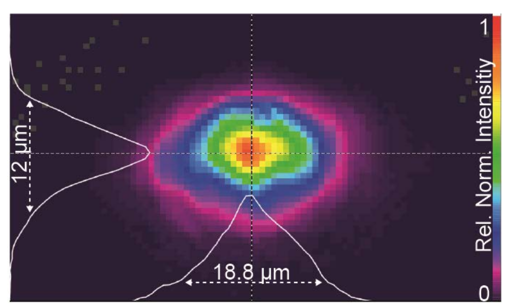

Figure 5. Propagating waveguide mode at wavelength of 1550 nm

As result of the elliptical index distribution the propagating mode at 1550 nm is also elliptical with 18.8 microns in horizontal and 12 microns in vertical diameter as shown in Figure 5. To examine the waveguide propagation losses, the cut-back method was utilized. Therefore the polished thin glass substrate was butt-coupled with a single-mode fiber for insertion and multi-mode fiber for detection. To minimize coupling losses, the launching single-mode fiber was controlled in six different axes. It was possible to demonstrate a coupling loss smaller -0.3 dB and propagation loss smaller than -0.05 dB/cm at 1550 nm wavelength.

If a single-mode waveguide has to be processed both diffusion processes have to be adjusted to control the refractive index profile and the waveguide dimensions. The gradient index profile characterizes a low mode confinement. Such waveguides characterize larger waveguide dimensions and higher bend radius compared to high mode confined waveguides. In addition to straight waveguides, which are only suitable for point-to-point interconnects, passive optical waveguide circuits require the implementation of bends, crosses and couplers. For studying the propagation characteristics in bends, crosses and couplers, different waveguide layouts with varying geometries were designed and processed on the basis of the developed 150 mm wafer process.

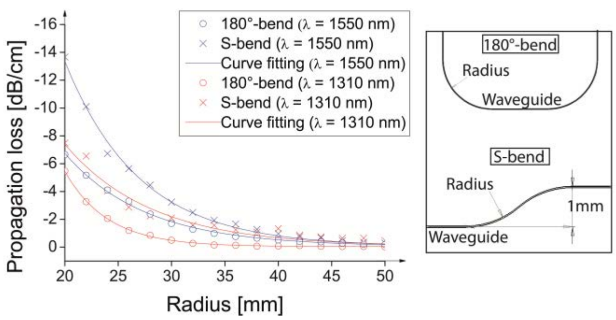

Figure 6. Propagation loss of 180°-bend and s-bend waveguide elements as function of bend radius (R)

S-bends and semi-circles (180°-bends) having radii smaller than 30 mm characterize high propagation loss (Figure 6) because of low mode confinement. Furthermore, signals propagating at shorter wavelengths (here a comparison between 1310 and 1550 nm) show lower losses. S-bends have additional losses at the turning point of opposite curves compared to 180°-bends. The results indicate that low loss waveguide bends need appropriate footprint because of radii larger 30 mm.

When placing all waveguides in a plane, waveguide crossing can occur. Characterization of waveguide crosses make clear that waveguides with crossing angles greater than 10 degree are free of crosstalk. For small angles the measured excess loss because of over coupling increasing dramatically as shown in Figure 7.

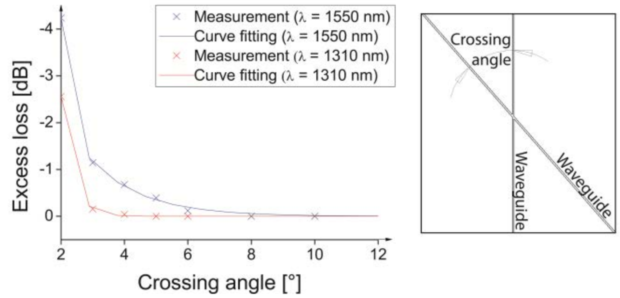

Figure 7. Excess loss as function of waveguide crossing angle

Waveguide couplers are necessary to combine from or split optical signals to multiple pathways. Couplers based on a Y-branch design have been characterized. The dependence of the geometric parameters as shown in Figure 8 was investigated in detail.

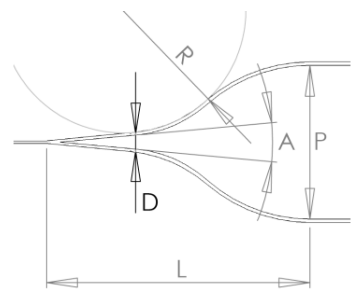

Figure 8. Schematic of 1x2 coupler based on two diverging straight waveguides followed by s-bends. The separation angle (A) and distance (D) between the straights as well as the bend radius (R) are related to the coupler's characteristics. The output pitch defines length (L) of the coupler

Table 1. Parameter and result overview of different 1x2 Y-branch couplers based on two diverging straight waveguides followed by s-bends

A	**R**	**D**	**P**	**L**	**Coupling ratio**	**Excess loss**
[deg]	**[mm]**	**[µm]**	**[µm]**	**[mm]**	**[%]**	**[dB]**
1	40	30	250	5.6	48.0 : 52.0	-1.3±0.1
2	40	30	250	4.5	49.3 : 50.7	-2.5±0.2
3	40	30	250	4.0	51.0 : 49.0	-2.9±0.1
1	30	30	250	5.1	49.3 : 50.7	-2.8±0.3
1	20	30	250	4.5	49.3 : 50.7	-7.0±0.4
1	40	50	250	6.5	51.0 : 49.0	-1.1±0.3
1	40	10	250	4.6	51.2 : 48.8	-2.0±0.3

Together with geometric parameters the characterized values such as coupling ratio and excess loss are summarized in Table 1. All coupling structures have a balanced coupling ratio. Losses are particularly affected by the s-bend radius and separation angle.

Combining the demonstrated passive waveguide structures results in passive waveguide circuits planar integrated in thin glass. The technology is so far developed for 150 mm wafer level. Because of the thermal processing, up-scaling on larger panel formats is feasible and under progress.

Fiber Waveguide in Plane Coupling

A low butt-coupling loss of -0.3 dB has been determined by cut-back method characterization. Since all measurements were realized with glycerin as index matching material between fiber and waveguide sample, a working distance of 5-10 microns between fiber and glass was inevitable during alignment. There was no remarkable influence on the overall attenuation for the operating distance.

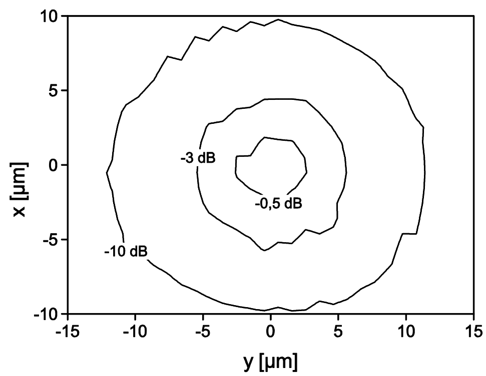

Figure 9. Contour plot of lateral position dependent attenuation

The x- (vertical to glass surface) and y-position (parallel to glass surface) dependent attenuation for fiber misalignment in front of the integrated waveguide end face where determined as shown in Figure 9. Results for additional coupling loss of α_c= -0.5 dB and α_c= -3 dB caused by angular and lateral misalignment are plotted in Table 2.

Table 2. Additional coupling loss of -0.5 and -3 dB because of angular and lateral misalignment

Axis	**Misalignment**	
	α_c = -0.5dB	**α_c = -3dB**
Δx	±2.2 µm	±5.3 µm
Δy	±2.5 µm	±6.1 µm
Δθ	± 1.1°	± 2.7°
Δφ	± 1.2°	± 3.1°

For permanent butt-coupling the optical fiber has to be fixed on the glass substrate in front of the waveguide end face. In contrast to UV-curing epoxy a laser fusion technology for direct glass-to-glass (fiber-to-waveguide) fusion has been developed.

Laser joining of fiber optic interconnects

For the coupling of an optical fiber to a glass substrate, a method that realizes a direct glass-to-glass-connection was developed - the laser joining. It is a thermal process, by which the heat input for fusing the components is placed precisely via a CO_2-laser. Numerous types of glass in various configurations can be connected according to this principle. In Figure 10 the process flow of an in plane interconnection between an optical fiber and a glass substrate is shown.

At first, the fiber is actively (passively possible) aligned to the integrated waveguide, with a resolution in the sub-micron range. Then both joining partners are brought in contact under a defined mechanical tension. Afterwards a controlled heat input is placed by the CO_2-laser, by which within the fusion zone a homogeneous interconnection develops. The laser joining step itself takes about 1 second. The preservation of the optical functionality and the formation of a diffusion layer in the joint could be proven. With unidirectional laser irradiation, this is ensured for fibers up to an outer diameter of about 200 microns. Since the fiber in this case has to be accessible for the laser only from one side, a high-density fiber-array (with a minimum fiber pitch corresponding to the fiber diameter) is possible. Similar to a splice or an unprotected glass fiber, the joint has low shear strength. Therefore, it is necessary to mechanically stabilize the fusion zone in an appropriate way, e.g. by recoating.

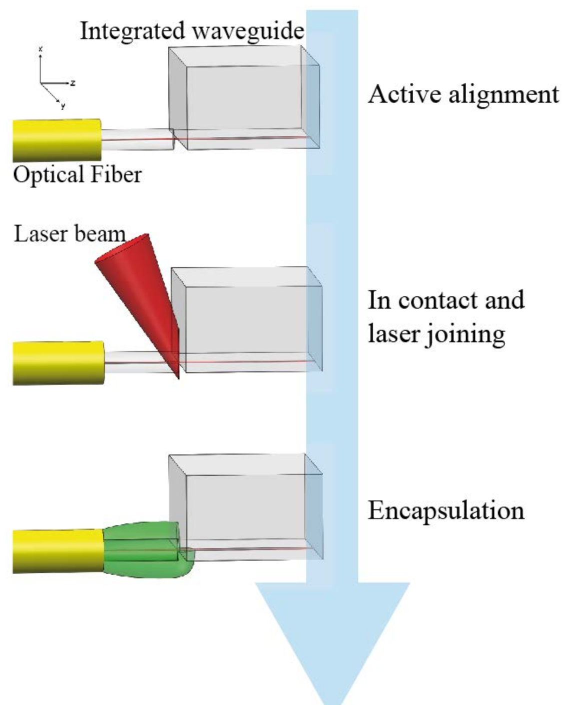

Figure 10. Process flow of CO_2-laser joining technology

The change in the coupling loss caused by the laser joining process has been determined exemplary for the connection of 6 single-mode fibers to integrated waveguides in a glass substrate and is shown in Figure 11. Therefore, after the active alignment and contacting, the optical power transmitted through the fusion zone was measured before and after the laser joining process. Comparing both variants the laser joining resulted in an average improvement of the coupling loss of α_c= +0.46±1.38 dB.

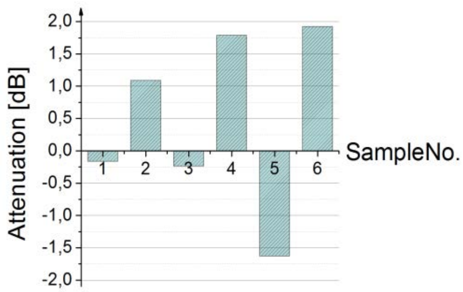

Figure 11. Coupling loss change caused by laser joining

The rather wide variation of values can be explained by the superposition of several effects. On the one hand, an improvement of the transmission properties is reached primarily by removing the optical interfaces (air gap), as well as by reducing the existing surface roughness and by refractive index matching. On the other hand, a reduction of the transmission properties can occur, when the insufficient angularity and parallelism of the end faces lead to misalignment. Here a suitable preparation and handling of the samples are important and are subject of future work.

An interconnection between a single-mode optical fiber and a thin glass substrate produced by laser joining is shown in Figure 12.

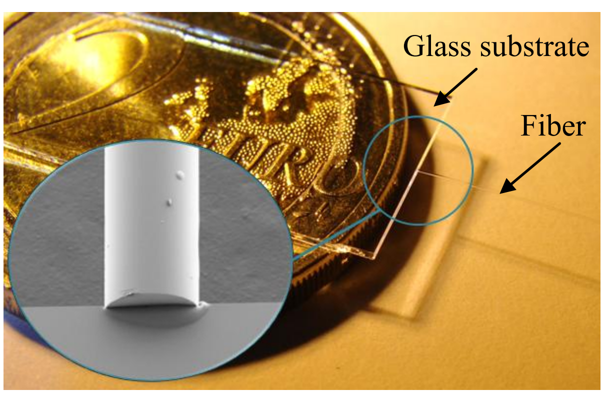

Figure 12. Laser joining of an optical fiber to a glass substrate with SEM picture magnification

Altogether, laser joining is a promising method for direct glass-to-glass-connection, with which single-mode and multi-mode fibers can be joined to optically active or passive components made of glass with high mechanical and optical quality.

The advantages of direct laser joining are:

- No intermediate layer (e.g. polymers, air), enables high power transmission, superior optical transparency
- No shrinkage, no depositioning, high optical coupling efficiency
- No degradation
- Suitable for harsh environment
- High-density arrays (1D or 2D) possible
- Excellent automation ability.

Waveguide out of plane coupling

For waveguide out of plane coupling a tilted mirror is integrated into the thin glass substrate crossing the waveguide profile. A total reflection at right angle or with another defined angle deflects the light out of the waveguide plane. Flip-chip assembled components like VCSEL, PD or PIC on the glass surface can be optical interconnected to integrated waveguides. Because glass is a very brittle material all mechanical structuring technologies such as milling or grinding aren't precise enough to make a mirror with optical surface quality. Wet chemical etching leads to an isotropic structure. Dry etching in combination with gray-scale lithography is limited to fused silica glass wafers. Laser technologies are promising, but suitable only for very short wavelengths for precise ablation. A thin glass with an integrated waveguide array has been structured by a F_2-laser at wavelength of 157 nm in cooperation with Laser Laboraturium Göttingen e.V.[9]. The 3.5 mm long trench has a slope of 45 degree. A SEM picture in Figure 13 shows little debris at the surface edge. The trench depth is 15 microns and covers the whole waveguide profile. Surface roughness influences the coupling efficiency.

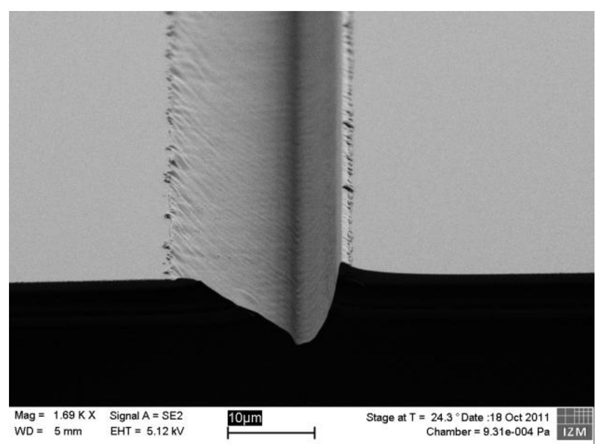

Figure 13. SEM picture of laser ablated mirror in glass

The insertion loss of the glass waveguide sample with the integrated mirror was measured by using Corning SMF-28e+ for stimulation and 100 microns core diameter multi-mode fiber for detection vertical to the glass surface as shown in Figure 14. Then out of plane coupling loss could be calculated by measuring the insertion loss of the glass waveguide sample by knowing the coupling loss (-0.3 dB) and the propagation loss (- 0.05 dB/cm). The lowest determined value for out of plane coupling loss was -2.7 dB. The high losses caused by surface roughness, warping and debris. Further optimization of the process will result in improved quality and higher coupling efficiency.

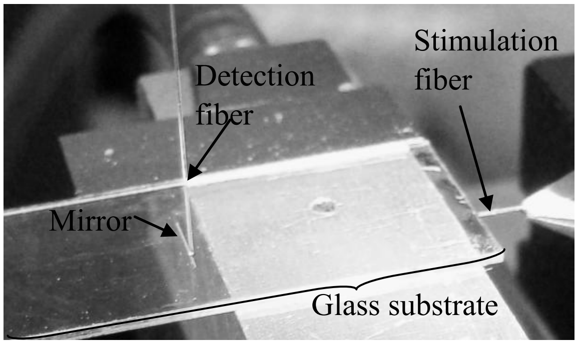

Figure 14. Test setup for glass waveguide out of plane characterization

AOC Demonstrator

For the demonstration of the generic integration concept, an active optical cable (AOC) package with CXP form factor standard was chosen because of

- High-potential application for PIC devices in short distance interconnection
- Existing state of the art data rate standard.

The CXP cable interface is based on SFF-8632 and Infiniband industry standards. The data rate is 100Gbit/s. Of course, a functional demonstrator performing 100Gbit/s isn't demonstrated but the goal is to study the feasibility. In this application scenario three building blocks are combined as schematically shown in Figure 15.

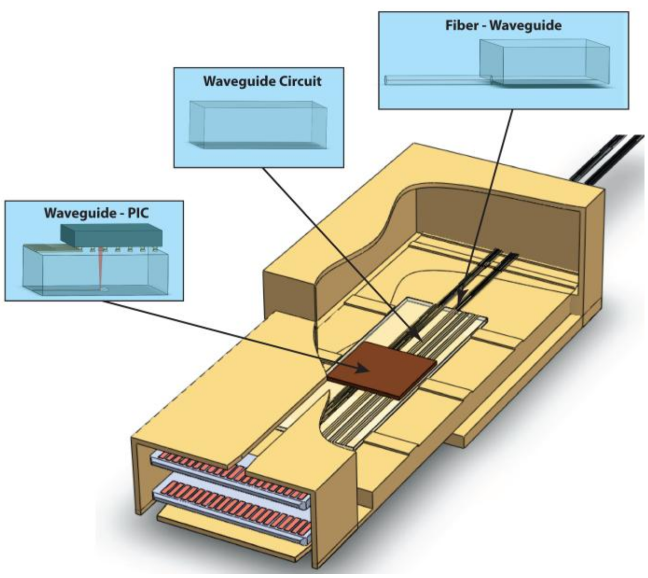

Figure 15. Draft of AOC CXP form factor consist of three building blocks (blue boxes) are combined for the optical interconnection between fiber and PIC

For fiber waveguide coupling, a waveguide circuit made of a straight waveguide array having pitch of 250 microns and a waveguide PIC coupling interface is combined for fiber chip interconnection in glass. The same configuration on the opposite fiber cable end gives the chip-to-chip interconnect throughout in glass. So far our investigations are focused on optical interconnection in glass. Because of lack of PIC components with standard grating coupling interface the micro optic design and coupling demonstration haven't been studied so far. For the demonstration on wafer level the single-mode waveguide process was performed. The layout consists of a straight waveguide array having pitch of 250 microns. The wafer was diced and end-faces were optically polished. Optical mirrors where integrated for out of plane coupling. Then the laser fusion approach was applied for fusion of multiple fibers in an array. So far arrays having a pitch of 500 µm can be realized. The glass substrate with integrated waveguides and a mirror as well as fused fibers is mounted on an aluminum base having the dimensions of CXP form factor as shown in Figure 16. Next steps of the ongoing work are:

- Reducing the fiber pitch down to 250µm
- Lens integration
- PIC assembling
- Total insertion loss improvement.

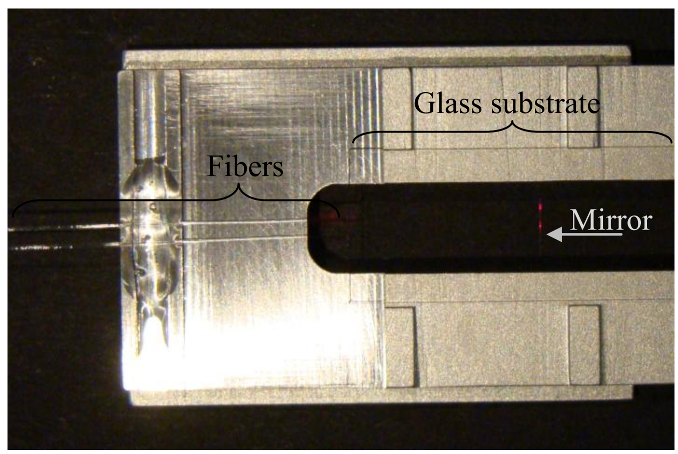

Figure 16. Top view of a thin glass substrate with integrated waveguides and two laser joined fibers on carrier; deflection of the guided red light (for demonstration) on the ablated mirror

Conclusions

The introduced photonic integration concept based on thin glass substrates is very suitable for convergence of electronic and photonic packaging. Merging technologies and processes is successfully under development. Ion-exchange waveguide technology was demonstrated on 150 mm wafer level. Excellent values for waveguide propagation loss and fiber coupling loss could be achieved using the developed ion-exchange technology in Schott D263Teco thin glass. In plane and out of plane waveguide coupling was presented for permanent interconnection. Light coupling using integrated mirror in glass was successfully demonstrated but further investigations for attenuation improvement are necessary. Fiber fusion on the glass end face is promising because of low fiber waveguide loss and was also successfully integrated. The feasibility study focusing AOC applications demonstrates the integration of those technologies.

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