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Towards integrated optical systems with glass-based additive manufacturing by Laser Glass Deposition

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Abstract

Laser Glass Deposition as an additive manufacturing method is a promising alternative to conventional manufacturing processes for individualized optical components. This process uses a CO_2 laser as a heat source to melt fused silica filaments for additive manufacturing. By adapting the process strategy, optical components can be produced, such as waveguides or beam shaping lenses. In this paper, on-chip production of additively manufactured optical waveguides and lenses is demonstrated, paving the way for sophisticated glass-based photonic integration. For this purpose, investigations on the manufacturing of the components under variation of laser power, filament feed rate and line spacing are presented. The focus is to preserve the optical properties of waveguides and lenses and at the same time exploit design flexibility in an automated production environment. The printing of the lenses through fusion of several layers must result in a homogeneous topography. The functionality of the printed components is verified by optical and geometric characterization.

Keywords: Glass additive manufacturing; Direct energy deposition; Laser 3D printing; Integrated photonics; Laser etching

1. Introduction

Glass as a material is used in various applications due to its chemical inertness, thermal resistance and optical transparency in the NUV to NIR spectral range [1]. In particular, fused silica is characterized by these properties and is therefore used to fabricate high quality optical components [2]. Temperatures exceeding 2000°C are required to process fused silica, which complicates and limits component design and handling. The fabrication of optical components, such as lenses made of fused silica for high power laser applications, is mainly achieved by hot embossing or molding processes, in combination with subtractive post-processing steps like polishing, which allow high transparency and contour accuracy [3,4]. However, this leads to limitations in optics design, making complex optics difficult to realize. Glass-based additive manufacturing can overcome the limits of conventional optical design [5, 6, 7]. The design freedom of additive manufacturing can be used to realize free-form optics, or to functionalize existing optics. Additive glass manufacturing equally opens up the possibilities in the realization of integrated optical systems for various photonic applications. Thus, it is possible to print multiple optical components for beam steering, guiding and shaping as well as analysis and sensing components onto one chip. Integrated optical networks with tailored functionalities become relevant for the realization of next-generation optical technologies, such as the production of chip-scale photonic devices enabling secure communication via quantum cryptography [8] or for space applications [9, 10].

Here, a demonstrator is presented in order to highlight the capabilities of Laser Glass Deposition for the production of complex and individualized optical components in an integrated manufacturing process. For this purpose, glass-based additive manufacturing for the fabrication of beam guiding and shaping components (waveguides and lenses) is combined with selective laser etching for efficient assembly design. A schematic illustration of the demonstrator design under investigation is shown in Fig. 1. A cylindrical lens for beam shaping is printed to the edge of a glass substrate. Optical waveguides for beam guiding are printed in etched V-grooves so that a light signal can be guided over the surface and passed through the lens. The depth of the V-grooves is adjusted to the center of the lens allowing for passive alignment between waveguides and lenses.

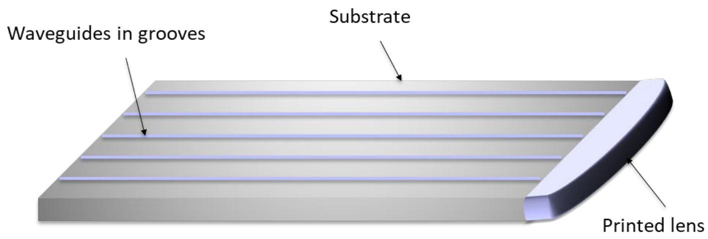

Fig. 1. Schematic illustration of the investigated demonstrator. The substrate consists of a rectangular fused silica plate with a lens printed to its edge. V-grooves are etched into the surface allowing for welding fiber-based waveguides with high positioning accuracy to the lens.

2. Methods

2.1. Laser Glass Deposition

The Laser Glass Deposition process is used to print the lens and waveguides. In this process, the radiation of a CO_2 laser (Coherent Diamond J3, emission wavelength of 10.6 µm) is used to melt the fused silica substrate (50 x 50 x 3 mm^3, Schröder Spezialglas GmbH) and the additive material, a fused silica fiber. In the following, the sequence of process steps for manufacturing the demonstrator is also investigated. Here, the cylindrical lens is printed initially and then followed by the laser etching of the grooves with finally the single mode fibers welded onto the substrate.

2.1.1. Beam shaping components - 3D printed lens

The glass filament (0.4 mm diameter, Weinert Industries AG) is fed laterally into the process zone at a speed of [252 - 324] mm/min, while the substrate is moved in the printing direction at a constant axis speed of 60 mm/min. To print the lens onto the edge of a fused silica substrate, the laser power [100 - 120] W, the feed rate and number of the layers are varied to form different surface curvatures. A schematic sketch of the setup is shown in Fig. 2. The surface curvatures are then determined by optical coherence tomography (OCT), the bubble content is investigated by optical microscopy, and the thermal stress with a polarimeter.

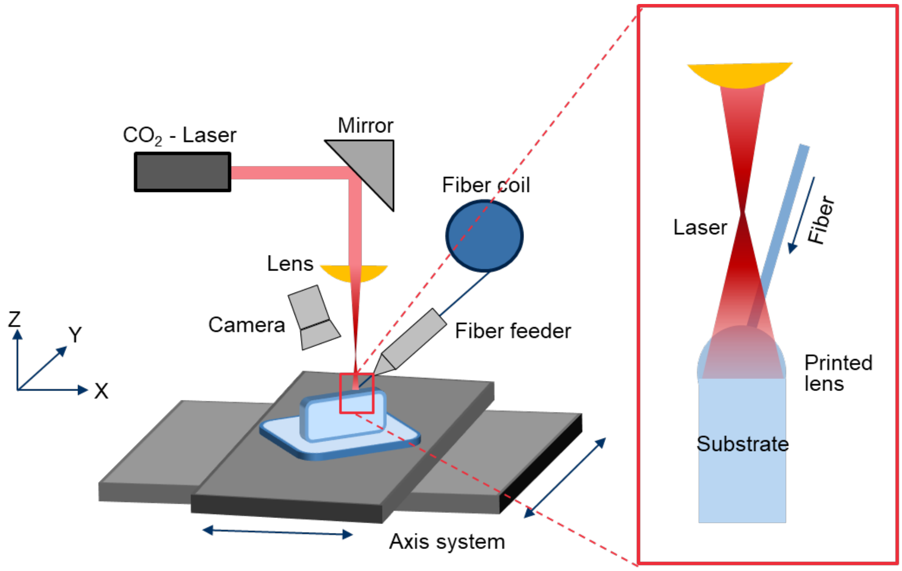

Fig. 2. Schematic sketch of the experimental setup for Laser Glass Deposition. A glass fiber is melted onto the edge of the substrate and bonded as a lens. The laser spot is defocused with a laser spot size diameter in the process zone of about the substrate thickness in order to establish a sufficient heat zone.

2.1.2. Beam guiding components - single mode waveguide

Glass filaments with fundamental mode characteristics (1060XP, 125 µm diameter, Thorlabs Inc.) are welded into the V-grooves on the surface of the fused silica substrate. For this purpose, the polymer coating is removed by mechanical stripping of the optical fibers. Then a 60 mm long fiber is created by mechanical cleaving with a diamond blade to obtain coupling end facets with optical quality. The prepared fiber is then placed in the V-groove and fused to the fused silica substrate using CO_2 laser welding (Synrad, Firestar Ti100). The process parameters like the laser power and the axis speed are chosen to maintain the optical properties of the single-mode fiber in terms of low propagation losses [7]. The optical functionality of the welded optical waveguides and the printed lens are characterized by beam profile measurement.

2.2. Selective Laser Etching

Selective laser etching (SLE) is a subtractive manufacturing process and consists of multiple steps. First, the structure needs to be designed digitally. Subsequently, the structure is transferred into the glass substrate by the fs-laser (Light conversion, Carbide CB3-10W). In contrast to additive manufacturing processes, SLE requires only a structuring of the contour if the modified area is completely attached to the surface which reduces the process time significantly. In a further step, the substrate is placed in an etchant for a certain time, depending on the structure depth. Hereby, preferably a potassium hydroxide solution heated up to 90°C is used which enables etching of modified fused silica or sapphire [11,12], among others. To etch other materials, such as borosilicate glass, HF is required as etchant which is not as comfortable as KOH for multiple reasons, especially safety issues. Finally, the structure is flushed with distilled water to remove remaining lye odds and etched particles. The whole process is depicted in Fig. 3.

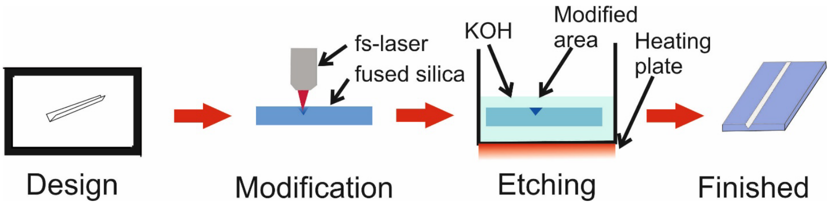

Fig. 3. Required process steps to fabricate V-grooves in a fused silica substrate using SLE. First, the structure has to be designed. Subsequently, the glass will be modified using a fs-laser according to the designed structure. Afterwards, the fused silica is placed into a KOH bath at 90°C to remove the modified area. Finally, the structured glass needs to be cleaned with distilled water.

3. Results

3.1. 3D Printed Lens

To investigate the resulting focal length and the homogeneity of the printed lens, the process parameters are varied. For the laser power, 100 W, 110 W, 120 W are chosen, for the feed rate 252 mm/min, 288 mm/min, 324 mm/min and for the number of layers 1 layer, 3 layers, 5 layers, respectively. For simplicity, the individual layers are printed here on top of each other in order to avoid multiple printing parameters such as the overlap of the lanes in the investigations. The focal length is calculated using the surface curvature of the printed glass via the lens formula. For this purpose, the printed lenses are evaluated using optical coherence tomography (OCT). An example measurement is shown in Fig. 4a). It can be seen that the lens has a homogeneous shape and covers the entire edge of the glass substrate. By using a strongly defocused laser spot, in the order of the thickness of the glass, the viscous glass can spread over the entire edge surface. A photograph of the printed lens is shown in Fig. 4b).

In Fig. 4c) the focal length is plotted in dependence on the feed rate for a constant laser power of 100 W for different numbers of layers. From the graph, a decreasing effect on the focal length with an increasing feed rate can be observed. If the feed rate is increased at constant heat input, a reduction of the focal length can be observed in all layer heights. The reason for this is the conservation of mass at constant heat input, so that at increased feed rates the glass melts less, resulting in a lager curvature radius, i.e. a smaller focal length. Similarly, it can be observed in Fig. 4c) that the focal length generally decreases for higher numbers of layers, despite a constant feed rate. In the first layer, the molten glass can cover the entire edge and thus forms a small surface curvature, whereas in the higher layers the covered area is smaller and thus stronger surface curvatures are formed, resulting in smaller focal lengths.

In Fig. 4d) it can be seen that the focal length changes only slightly with increasing laser power at all layer numbers, at a constant feed rate. Despite the increased heat input, the glass filament does not fuse stronger with the glass substrate because the propagation area is limited by the substrate thickness. Due to the defocused laser spot, the printed glass covers the entire edge surface. Since homogeneous melting is already observable for a power of 100 W, this will also be true for higher laser powers. Note that for a constant laser power, the change in focal length decreases with the number of layers, as can be seen in Fig. 4d). This indicates that the surface curvature tends towards a minimum possible value.

The measurement results show that the focal length of the printed lenses can be specifically changed by adjusting the process parameters. Within these investigations, focal lengths of 2.5 – 5 mm could be achieved.

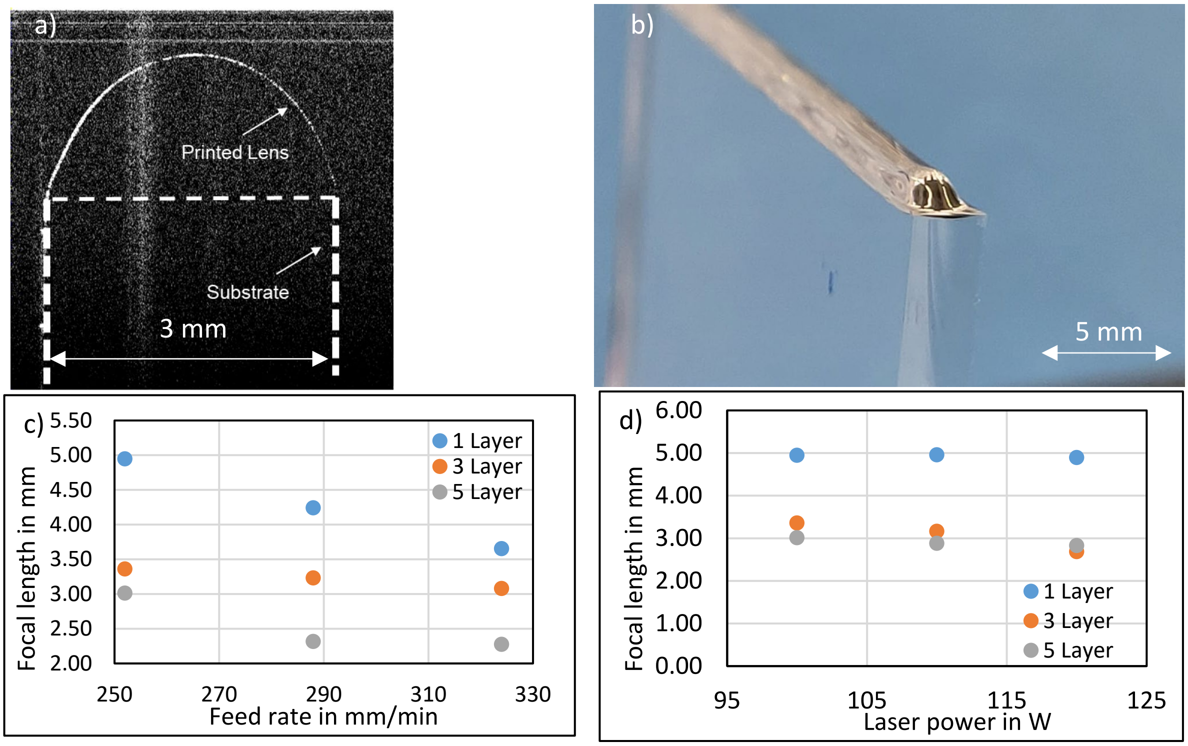

Fig. 4. (a) Optical coherence tomography image of a printed lens. The lens extends across the entire width of the substrate and no interface layer to the substrate is visible; (b) Photographic image of the printed lens; (c) Focal length as a function of the feed rate for different layer heights at a constant laser power of 100 W. The focal length decreases at each layer height with increasing feed rate since a stronger curvature occurs with increased mass flow; (d) Focal length as a function of laser power for different layer heights at a constant feed rate of 252 mm/min. Only a slight change can be observed at a constant layer height since the propagation area is limited by the substrate thickness and thus the contact angle remains the same.

3.2. Demonstrator Characterization

In the following investigations, the parameter pair [110 W, 288 mm/min, 5 layers] was used to prepare substrates with lenses, which are subsequently processed via SLE and a fiber-based waveguide is welded [laser power = 10 W, axis speed = 180 mm/min, laser spot diameter = 700 µm] into the V-groove. A photographic image of a prepared sample is shown in Fig. 5a). A computer tomographic image of the frontal cross section is shown in Fig. 5b) and in the lateral cross section in Fig. 5c). The groove made via SLE shows a clear and homogeneous course in the frontal cross section, also the positioning of the fiber in the groove can be seen. In addition, the distance of the fiber to the lens can be seen in the lateral cross-section.

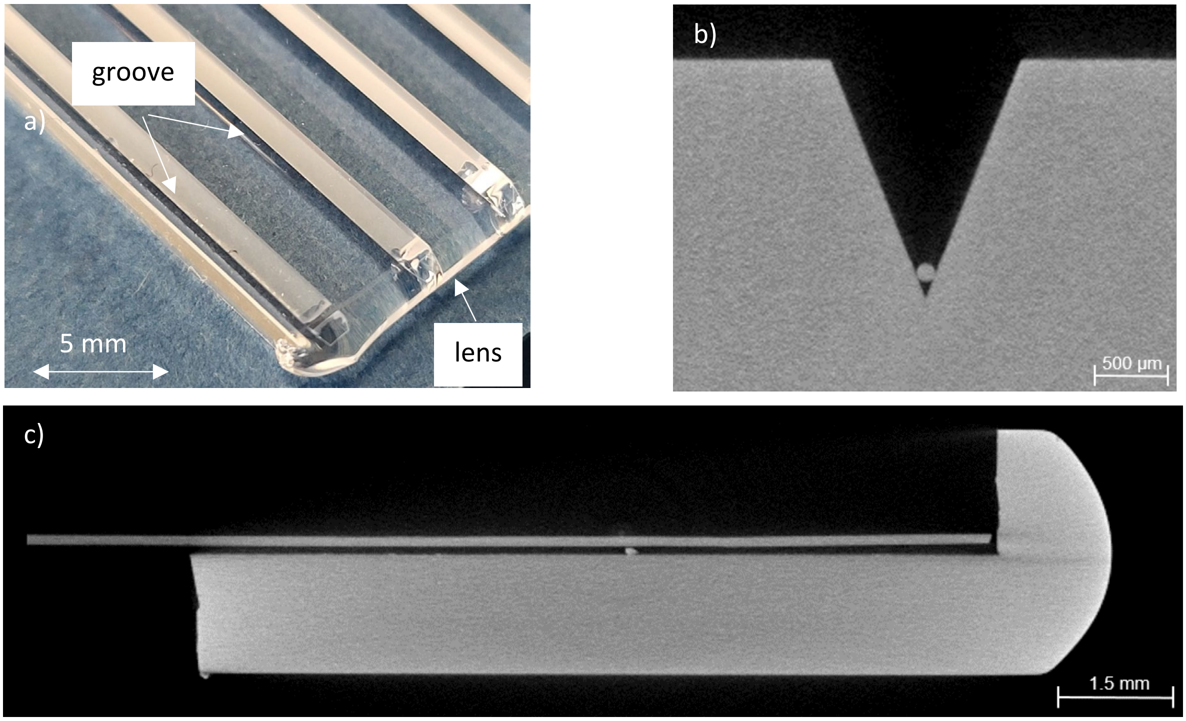

Fig. 5. (a) Photographic image of the printed lens with attached waveguides in grooves; (b) Computer tomographic images of the frontal cross-section; (c) Computer tomographic image of the lateral cross-section.

In order to investigate the optical functionality of the assembled demonstrator the optical intensity beam profile was measured in relation to the propagation distance. A fiber-coupled laser source with emission wavelength of 1550 nm and a beam quality of $M^2 < 1{,}1$ was used. The results can be seen in Fig. 6. At a distance of 11.5 mm from the waveguide's output end facet, a nearly Gaussian intensity beam profile was measured. Over the distance of 26 mm slight deformations are observed, which can be attributed to the inhomogeneous transition area from the waveguide to the lens or to imperfections in the lens shape. An optical simulation for the validation of the optical functionality was conducted. The measured and simulated horizontal and vertical components of the propagated beam are plotted in Fig. 7. The horizontal component of the beam shows no optical effect since it is the non-curved part of the cylindrical lens. In the vertical component of the beam a weak lens effect is observable. Since the thickness of the lens in this experiment was in the same range as the focal lengths (see Fig. 5c), only a weak optical effect was measured. With a higher etch-distance to the printed lens, a stronger optical effect is expected.

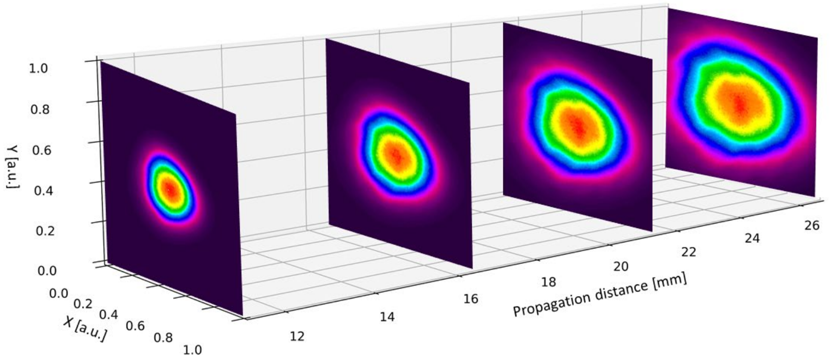

Fig. 6. Measured optical intensity beam profiles in a distance of 11.5 mm to 26.5 mm from the optical waveguide's end facet.

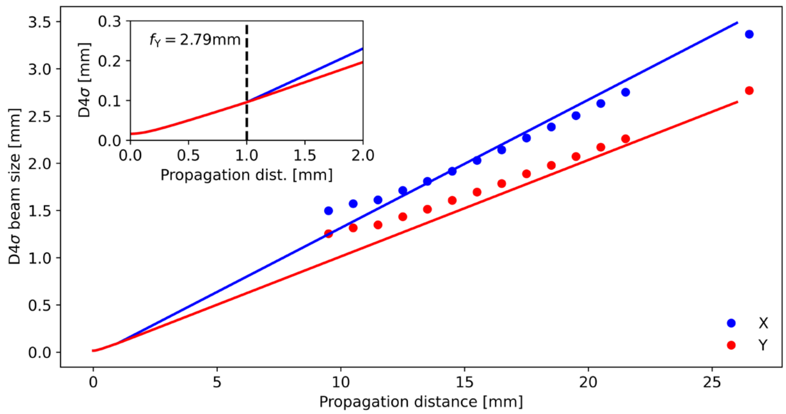

Fig. 7. Measured (dots) and simulated (solid line) horizontal (X) and vertical (Y) beam size of a laser probe beam with a wavelength of 1550 nm, coupled out of the welded waveguide's end facet (mode field diameter of 8 µm at the waveguide's end facet) and propagating through the printed cylindrical lens at a distance of 1 mm. In the simulation a focal length of f_Y = 2,79 mm has been considered based on the experimental validation of the printed lens. Inset: Zoom into the propagation distance between 0 and 2 mm with the dotted line at 1 mm indicating the position of the lens in the simulation.

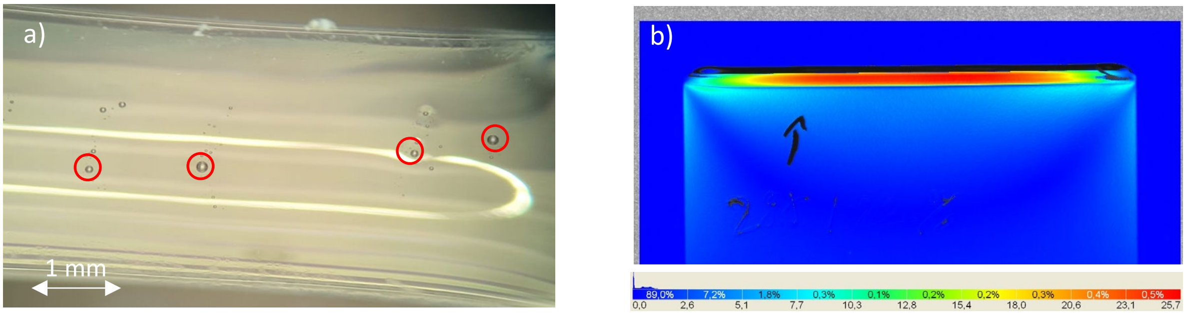

Fig. 8. (a) Light microscope image of a printed lens in top view. Bubbles are sporadically distributed over the volume with sizes of 10 - 30 µm. Some bubbles are marked with circles; (b) Polarimeter image of a printed substrate. Thermal stress of up to 26.7 MPa is visible within the printed structure.

The printed lens was examined in the optical microscope to investigate the bubble content. An image is shown in Fig. 8a). Periodically arranged bubble clusters could be identified, with single bubble sizes of 10 - 30 µm. The bubbles indicate an inhomogeneous deposition of the glass filament in the printing process and would require optimization of the process parameters in future studies. Furthermore, the sample was investigated in polarimetric measurements with respect to thermal stress. In polarimetric measurements, linearly polarized light is used to qualitatively and quantitatively evaluate the thermal stress based on the birefringence in thermally loaded glasses. The polarimeter measurements are shown in Fig. 8b). It can be observed that thermal stress is present especially in the printed structure and decreases towards the edges. The maximum thermal stress is 26 MPa, which is below the fracture strength of fused silica (50 MPa), but post processing like SLE, might cause an increase of the residual stresses when the etching is performed within the stress field. Due to the indirect proportionality of stress to propagation area, material removal would increase stress. The thermal stresses can be reduced by a subsequent furnace tempering process [13].

4. Conclusion & Outlook

In this study, the Laser Glass Deposition method was used to fabricate lenses and to weld waveguides in an integrated demonstrator device. This paves the way for the production of more sophisticated glass-based photonic chips. The influence of relevant process parameters such as laser power, feed rate and number of layers on the focal length of the printed cylindrical lens, as well as the homogeneity of the topography was investigated. Cylindrical lenses with focal lengths of 2.5 - 5 mm were realized. The bubble content in the lenses indicates further optimization potential in the process window. To demonstrate the combination of additively manufactured optical components, V-grooves were applied into the glass substrates using selective laser etching to enable laser-based welding of optical waveguides in the grooves. Via beam profile measurements, a focusing effect of the lenses and no significant deformations in the beam profile were observed. This demonstrates the optical functionality of the additively manufactured components.

In future investigations, the automation of the entire manufacturing process will be considered. In this context, the automated printing of the waveguides with subsequent laser cleaving for an optimal interface will also be implemented. Furthermore, targeted focal lengths and novel lens designs will be realized. The transfer from cylindrical lens designs to spherical and aspherical lenses will be carried out.

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