Lasers in Manufacturing Conference 2019

Laser deposition of fused silica coreless fibers to generate functional waveguides

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Abstract

There is an increasing demand for highly integrated optical and optoelectronical devices that provide active laser emission, adaptability and low losses. A well-established production technology for customized structures with high functionality and geometrical flexibility is additive manufacturing (AM). Commercial AM systems for metals and polymers are ubiquitous; whereas glass AM systems only exist in scientific environments. In this paper, the deposition of coreless fused silica fibers with a diameter of 400 µm and a 50 µm thick polymer coating onto a glass substrate with defocused CO_2-laser radiation (10.6 µm) is demonstrated and investigated. The guiding efficiency, surface smoothness and internal stress of the deposited fiber are characterized and compared with an untreated fiber. This results in functional, nearly stress-free waveguides for light transmission with high position stability and opens a range of applications for optical system integration.

Keywords: Laser glass deposition; fused silica fibers; waveguides

1. Introduction

In many application areas of optics and high-power lasers, almost all optical components are made of glass. Quartz glass fibers are used especially in the data and light transfer technology due to their low transmission losses, temperature resistance and cost effective availability [Jahns, J.]. Additive manufacturing

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(AM) offers an alternative to conventional manufacturing processes for a wide range of applications. Hence, new constructional degrees of freedom are introduced to overcome the limitations of subtractive material processing such as milling and drilling. This enables a high degree of flexibility, new design and application possibilities [Klahn, C. et al.]. The manufacturing of optics with an AM principle is a significant challenge. Glass materials are difficult to handle and process in AM considering the high melting temperatures, the thermomechanical properties, sensitivity to tensile stress, and the exclusion of binders in the process. Another challenge is the fact that optical components must exhibit a high quality of material homogeneity and a low surface roughness. The most suitable process for the requirement of working without binders for the production of components consisting of pure material is therefore a fiber extrusion process. [Lou, J. et al.].

In this work, we present first experimental results of AM based waveguides fabrication. For this purpose, the effects of the laser deposition welding process on the fibers and substrate are determined and the optical properties of the glass fibers are investigated.

2. Experimental Setup and Experiments

A CO_2-laser (DC 0045, Rofin) is used to manufacture the individual waveguides with different parameter sets. The laser beam source is operated at the lowest output power that guarantees a constant beam quality and stable performance. After an attenuation with two 50 % beam splitters there is a residual power $P_{L,P}$ = 100 W in the process zone (Figure 1).

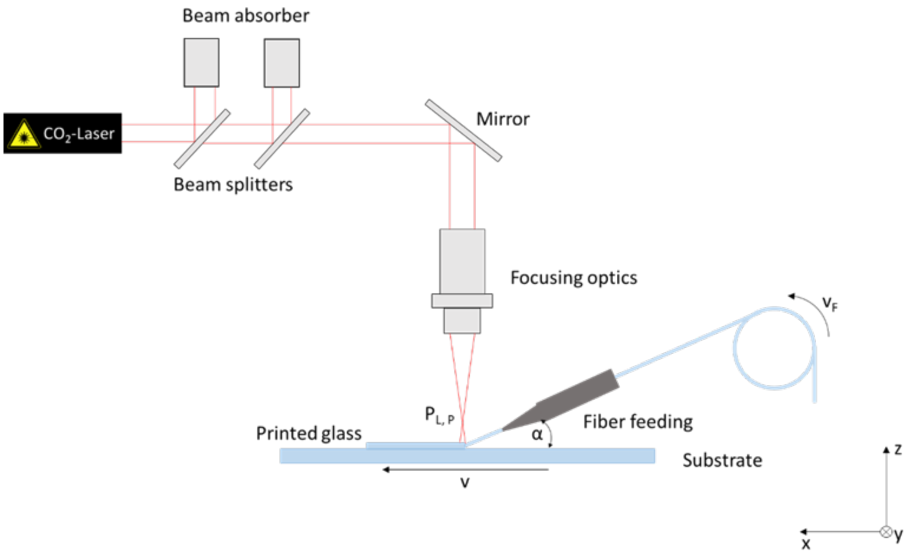

Fig. 1. Schematic illustration of the optical setup for the laser based fiber deposition [according to Von Witzendorff et al.].

Based on laser deposition welding, the fiber is fed externally at a tilt angle α of 40° into the processing zone and is melted or fused by the incoming laser beam. The fiber is applied to a quartz glass substrate with a thickness of two millimeters. The substrate is mounted on an axial table of a two-axis system (x, y). By means of a third axis the glass print head moves with the beam direction of the laser (z direction). The defocused laser beam has a diameter of 4 mm. A schematic setup of the system is depicted in Figure 1. With this method, coreless and core fibers can be deposited, while the diameter of the supplied glass fiber can be varied [Von Witzendorff et al.].

The coreless fused silica fiber with a diameter of 400 µm is surrounded by a polymer coating with a wall thickness of 50 µm, resulting in a processed total fiber thickness of 500 µm. This coating is necessary in order to transport the fiber into the processing zone without breaking. Due to the high laser power, the acrylate coating is pyrolised completely while the fiber is transported into the processing zone without inclusions and organic impurities [Pohl et al.].

For depositing the fibers on the substrate, the speed of the fiber feeder is adapted to the axis speed ensuring constant material flow ($v = v_F$ = 90 mm/min). In order to guarantee a subsequent finishing of the fiber ends, the depositing process is started 5 mm before and end 5 mm behind the substrate. Thus, the fiber end can be cleaved and finished in a separate process. The best results were achieved at a laser output power in the process zone of $P_{L, P}$ = 100 W. The current process and the preparation of the substrate in the process are shown in the following Figure 2.

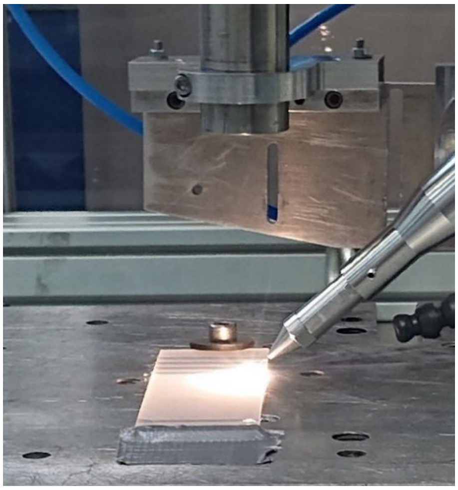

Fig. 2. Deposition process on a glass substrate.

To remove residual dirt and dust from the manufacturing process, the fibers are cleaned with compressed air and isopropanol. The fiber must be cleaved approximately 500 µm before the substrate, otherwise the separated fiber pieces cannot be removed because they are still fused to the substrate. Typically, fiber cleaving is performed by scribing a fiber under tension, e.g. with a diamond blade. The resulting ends are very short, consequently the fiber does not break at the scribed point but at the end of the substrate. Due to the fixed connection to the substrate, a predetermined breaking point appears to occur at the transition to the overhanging fiber. For this reason, a non-mechanical cleaving technique with a CO_2-laser (48-2SAM, Synrad) with a maximum output power of 25 W is used. According to the manufacturer, $M^2 < 1.2$ and the radius of the collimated output beam is 3.5 mm with a beam divergence of 4 mrad [Lévesque, L. et al.]. For the cleave process, the laser is operated at a repetition rate of 5 kHz at a pulse width modulation duty cycle of 95 %. The beam is expanded by a factor of 4 using a commercial beam expander (BEC-19-4.0-10.6, Haas Laser Technologies Inc.) and focused afterwards by a scanner head (intelliSCAN14, Scanlab GmbH) with a 75 mm focusing lens. This results in an estimated beam spot radius of about 50 µm in the focus [Boyd, K. et al.]. To cleave the fiber, the scanner head deflects the beam to a straight 2 mm long line perpendicular to the fiber position on the substrate. The beam path was inclined by 18° to the optical axis of the scanner, as preliminary experiments have shown that better cleave results were achieved. The marking speed of the scanner head is 0.25 m/s. The substrates with the fibers are clamped on a stage which can be rotated in all three spatial directions and was mounted on a 3-axis motion table to allow the positioning of the fiber perpendicular to the laser beam. The positioning is monitored with a camera, which images the fiber in the focal plane of the scanner head.

In order to determine the ability for optical guidance of the deposited fiber, the optical power transmitted through the waveguides is measured. For this, a fiber-coupled laser diode (BF-A64-0180-S5F, Sheaumann Laser, Inc.) with an emission wavelength of 1064 nm is used. The single-mode laser beam of the diode is collimated with a f = 6.24 mm-lens and focused into the waveguide with f = 20 mm-lens. Both lenses have an anti-reflection coating for the used wavelength to prevent additional losses. The substrate with the waveguide is mounted on a 3-axis motion table to allow precise positioning of the fiber. A power head (3A-FS, Ophir Optronics Solutions Ltd.) is used to measure the optical power. Due to the measuring setup, measurements are not recorded directly in front of the fiber but between the two lenses. The losses at the second lens are negligible due to the antireflection coating.

3. Results and Discussion

The experimental results of the laser based deposition process show a varying connection behavior, when the laser power is adjusted in the process zone from 90 W to 135 W. The adhesion of the fiber to the substrate is influenced by air inclusions in the joining zone between substrate and fiber if the set laser power is less than 100 W. The fiber can be removed with little mechanical effort in this case. Individual melting points are formed from fiber segments, which solidify into spheres with a defined distance when the energy input is too high (Figure 3). For a functional waveguide, the light guiding properties such as a uniform shape and surface have to change as few as possible.

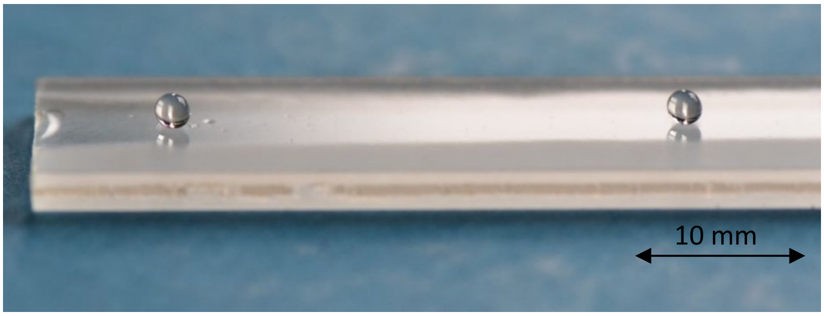

Fig. 3. Glass spheres with a diameter of 2 mm melted together from fragments of the supplied fiber as a result of an too high energy input of 135 W.

With the increasing processing time, the fused silica substrate is subjected to further heating. The heat conduction coefficient of quartz glass is low at 1.15 W/mK (at room temperature) compared to metals, which means that the generated thermal energy cannot be transferred sufficiently [Weißbach et al.]. With an additional aluminum plate as heat sink underneath the glass substrate, tensile stress is induced in the substrate and fiber during the process and after cooling. Figure 4 shows the picture of the substrate after the deposition of the fibers recorded with a polarimeter (StrainMatic M4/140, ilis GmbH) in order to compare the internal tension of the substrate in its original state. The polarimeter measurement of the untreated substrate depicted a homogenous distribution of the internal stress of 0.1 MPa.

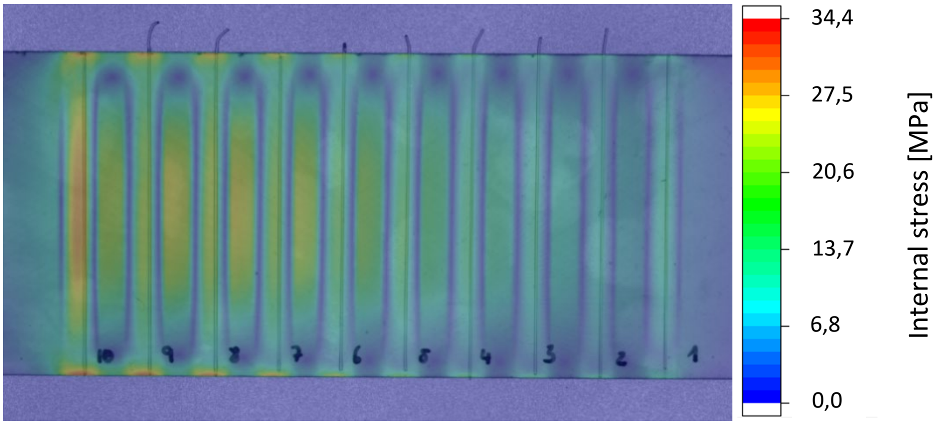

Fig. 4. Internal stress of a quartz glass substrate with deposited fibers at the same process parameters. The fiber with the number 1 was the first to be deposited.

These measurement data also show that the internal stress is significantly larger with an ongoing process from 13.8 MPa up to 31.0 MPa. This also leads to a bending of the substrate with a size of 50 mm x 150 mm. The measurement shows that this deformation and the internal stress of the substrate during the process have an influence on the residual stress of the laser deposited fibers. It is possible that this effect can be reduced or almost avoided with a heated substrate which requires further investigations [Luo, J. et al.]. A more detailed polarimetric analysis of the fiber itself is not possible due to the resolution of the measuring system. Measuring tensile stress through the fiber with a diameter of 400 µm is not possible with the polarimeter, because the area of the fiber end surface consists out of 10 pixels, which makes it impossible to clearly state the measurement results.

After the deposition process, residual fiber parts hang over the substrate (Figure 5 top). The shape of these endings varies depending on whether they are on the processing start side or the end side (Figure 5 bottom left and right). The process ends with a separation of the fiber below the extruder nozzle such in a way that the shape is retained. At the beginning of the process, the fiber appears ticker than the deposited fiber (Figure 5). Before the fiber is in contact with the substrate, the heat is transported in fiber direction and not into the substrate. With a constant laser output, a higher temperature is reached. This explains the form of the fiber at the beginning.

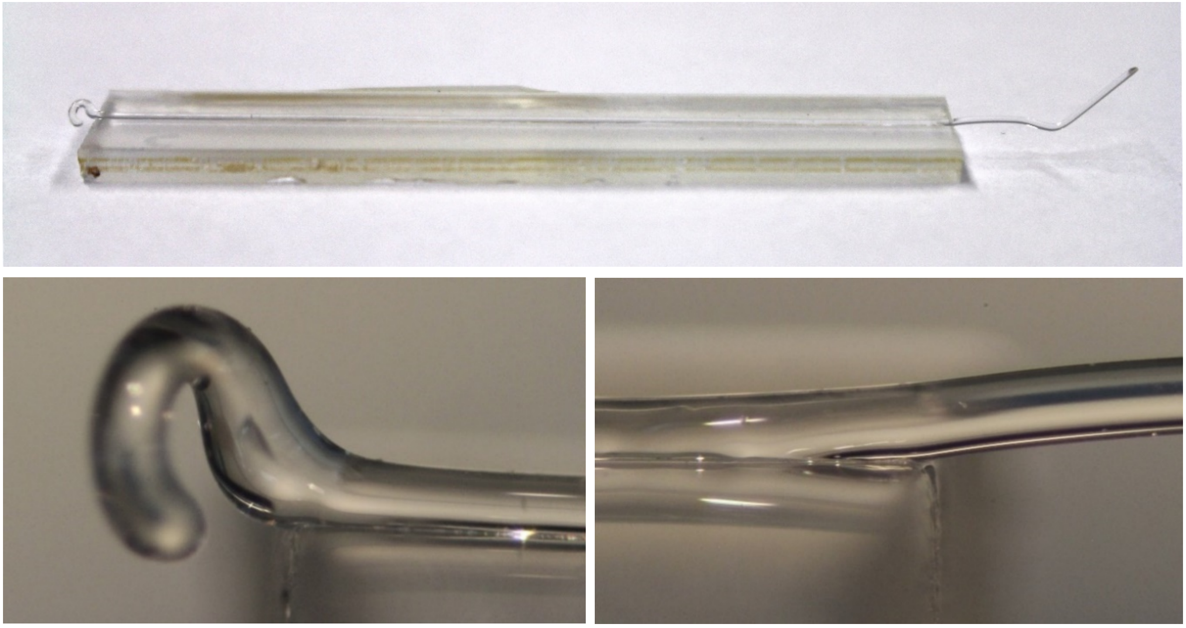

Fig. 5. Top: A substrate with a deposited fiber. The deposition process started at the left end and was finished at the right side; bottom left: Residual fiber on the starting side; bottom right: Residual fiber on the finishing side.

First, the overhanging fibers are cut off with a varying number of repeated scanned lines with the 48-2SAM system. The number of required passes depends on the different thicknesses of the fibers due to the depositing process (Figure 5 bottom). The remaining fiber ends are slightly shifted to the focal point and laser polished by several passes over it. The respective number of required passes varies also between the fiber ends due to the different thicknesses. The result is a clean and smooth fiber end face. Images recorded with a stereomicroscope at 50 x magnification and a scanning electron microscope (Figure 6) show neither precipitations nor waviness.

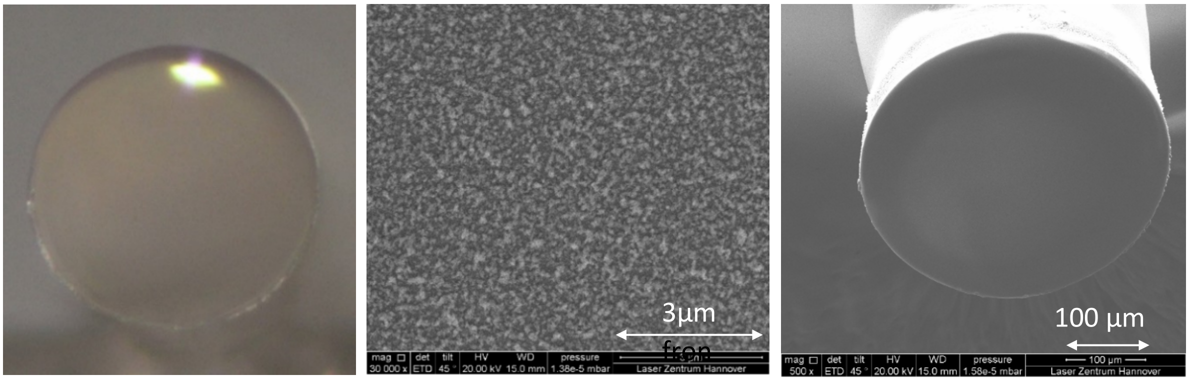

Fig. 6. Left: Front view on the cleaved fiber end surface (stereomicroscope, 50 x magnification); middle: SEM of the cleaved fiber end surface at 30000 x magnification; right: SEM of the cleaved fiber end surface at 500 x magnification.

Only at very high magnification of 30000 a structure is visible on the end surface (Figure 6 right). Furthermore, the SEM image at a magnification of 500 x (Figure 6 right) can be estimated that the used deposition parameters lead only to negligible changes in the cross-section.

Though proper cleaning of the fiber before the cleaving, the cleaving process leads to a white discoloration at the cutting edge of the fiber (Figure 7 right). In addition, dark particles are visible and the upper end of the fiber melted, which results in a rounded edge (Figure 7 middle). The left picture in Figure 7 shows that due to the oblique guidance of the beam profile, the cut surface is perpendicular to the fiber.

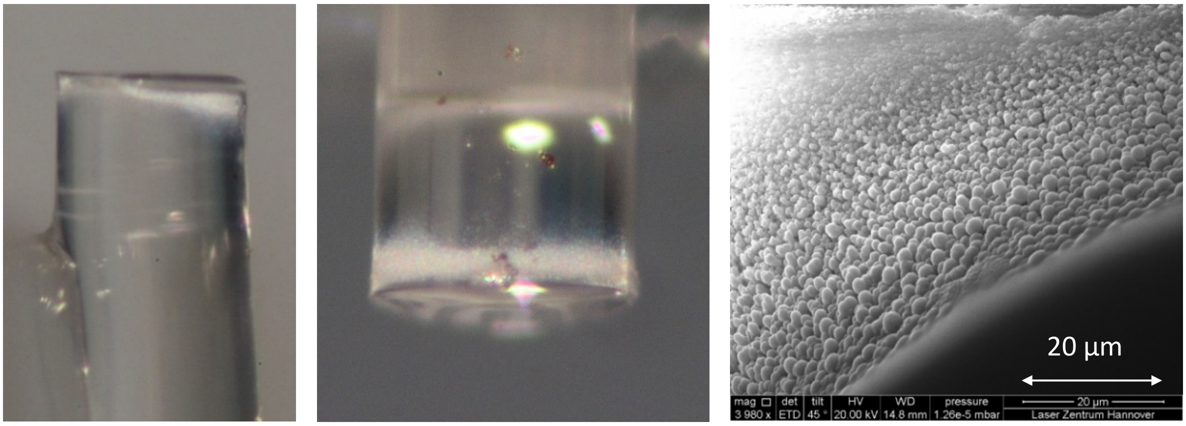

Fig. 7. Left: Lateral view on cleaved fiber (stereomicroscope); middle: View onto the cleaved fiber (stereomicroscope); right: Precipitation along the cleaved edge (SEM).

Both, the cleaving process and the transmission measurement are performed on three different waveguide samples, which are deposited with the same optimized parameters. The transmission in both directions is measured. Table 1 shows the values of the transmitted power through the samples. The error propagation based on the measurement accuracy of the power head results in a value of <0.05 % for the calculated percentages and is therefore neglected. For all measurements the transmission is between 81 and 86 %. All samples show differences in transmission for both directions. This can be a result of the directional depositing process or the cleaved ends behave differently. However, the differences are less than 2.7 %, especially for samples 2 and 3.

Table 1. Transmitted optical power through the waveguides in respect to laser power in front of the waveguide. The transmission in both directions is measured. The error for all values is negligible small.

Sample	Sample 1	Sample 2	Sample 3
Process end side	86.0 %	82.1 %	84.3 %
Process start side	83.3 %	83.3 %	85.0 %

For comparison, a piece of the untreated fiber is cleaved and measured using the same methods as mentioned above. A transmission of 91.0 % is achieved. It can be assumed that the absorption losses of quartz glass can be neglected for a transmission length of a few centimeters. Furthermore, Fresnel reflection occurs at the transition of two media with different refractive indices. Assuming a refractive index of 1.00 for air and 1.46 for the fiber, ca. 3.5 % of the light is reflected at each surface. Since the fiber has two interfaces, ca. 7.0 % of the power is lost by Fresnel reflection. In any case, the transmitted fraction of light is still high and nearly comparable to standard cleaving procedures which supports the effectiveness and reproducibility of the CO_2 induced cleaving process [Boyd, K. et al.].

The remaining discrepancy can be explained possibly by different mechanisms. First, additional roughness on the input or output interface (Figure 6 right) can lead to additional scattering and thus to losses. This could explain why the untreated fiber does not achieve the full 93.0 % of maximum possible transmission. Besides, the light guidance inside the waveguide is achieved by total internal reflection at the cladding surface glass to air. Disturbances on the glass surface can lead to conditions in which the requirements for total internal reflection are no longer met and light is decoupled. The outer surfaces of the deposited and the untreated fiber are compared under the scanning electron microscope (Figure 8), which indicates similar surface quality for both fibers. Therefore, losses due to decoupled light at the air-fiber interface only account for a very small proportion of the total losses. However, the main source of the losses is likely to be light that is coupled out at the interface between the fiber and the substrate. Since the refractive indices are very similar, the light is decoupled and not reflected. This can explain the lower transmission of the deposited fibers compared to the untreated fiber.

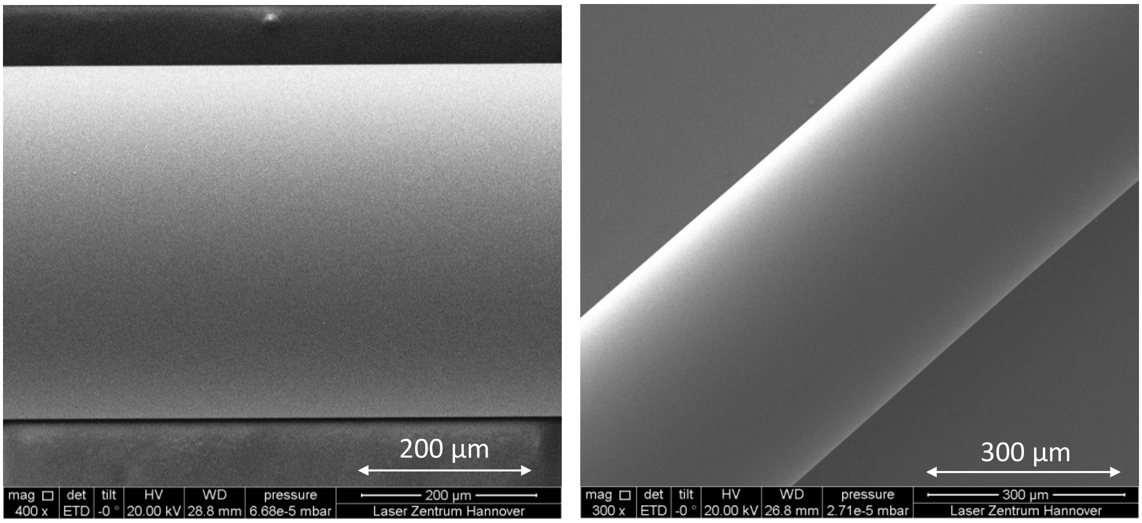

Fig. 8. Left: The untreated fiber under a SEM; right: The deposited fiber under a SEM.

4. Conclusion

In this study, the feasibility to print functional waveguides made of fused silica on a glass substrate together with a proper laser-based cleaving process is presented. The laser deposition of 400 µm fibers has been successfully implemented. The internal material stress of the substrate increases by the process from 0.1 MPa to a maximum of 31.0 MPa. The surfaces of the fibers are free of influencial roughness after the process. Furthermore, the laser-based cleaving process of the ends of the deposited fibers shows good results in terms of surface smoothness. Thereby, efficient light coupling can be realized. In comparison to the untreated fiber the transmission is only 7.0 % lower in average.

In the following series of experiments it is necessary to identify the reasons for the reduced transmission and to avoid them as far as possible. The effect of the process on the properties of the fibers needs further investigation, for example a wavelength-dependent transmission. The connection to the substrate and reduction of losses by an additional coating or variation of the material selection of the substrate are further necessary steps. Also of interest are potential waveguide shapes and different curvature radii. The technology of the cleaving can be further optimized in the future to reduce contamination. In addition, studies should be made with a fiber that was mechanically cleaved to compare the applied technique with the CO_2-laser with the conventional method.

Acknowledgements

The experiments were conducted within the framework of the project "GROTESK – Generative Fertigung optischer, thermaler und struktureller Komponenten" funded by EFRE – NBank (ZW6-85018307, ZW6-85017815).

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