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Inscription of waveguides and beam splitters in borosilicate glass using a femtosecond laser with a long focal length

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Abstract

Femtosecond-laser enable the internal fabrication of photonic components in various materials. The extremely high peak intensity due to the ultrashort pulse width leads to a nonlinear interaction in the focal point, which makes the processing of transparent materials such as glass possible. Nonlinear ionization mechanisms can lead to a local, permanent refractive index change of the material, which opens up a promising potential for the fabrication of integrated optics. If the femtosecond laser, which has a long focal length, is moved precisely relative to the glass sample, it is possible to inscribe three-dimensional geometries directly into glass. Thus, a variety of photonic components such as waveguides, beam splitter and other micro-optical components can be fabricated directly in the volume. In this work, the subsurface inscribed micro-optical structures are investigated and demonstrated as a function of the influencing laser parameters.

Keywords: femtosecond laser; integrated micro-optical components; long focal length; borosilicate glass

1. Introduction

Analog to the development of integrated electric circuits, which form the miniaturized core of electronic circuits in many electrical devices and consist out of thousands of small electronic components, the focus of research is also on the development of integrated optical circuits. In these optical circuits many micro-optical components such as waveguides and beam splitters can be integrated (Cai & Wang, 2022).
Ultra-short-pulsed lasers enable the microfabrication technique to laser direct write these micro-optical structures and devices in the glass volume (Stoian, 2020). When the intense ultrashort laser pulses are focused into the glass sample a series of complex dynamic nonlinear absorption processes such as multiphoton

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absorption or tunnel ionization occur in an ultrashort time scale. The emergence of the first free electrons in the conduction band enables a self-reinforcing process that avalanches more electrons into the conduction band. This process is called avalanche ionization and leads to a correspondingly large energy deposition of the material, leaving behind a localized permanent material modification and therefore a change of the refractive index (Mao et al., 2004).
In general, the change in the refractive index is due to various processes in the glass network structure, such as photo-induced defects, the reorganization of the glass network structure, or thermal processes and the resulting densification of the material (Thiel, 2018). Depending on the inscription parameters and the used glass type itself the refractive index change of the laser track can be either positive or negative (Lapointe & Kashyap, 2015). In fused silica glass, the modified laser track causes an increase of the refractive index compared to the surrounding unmodified material (Krol, 2008). In borosilicate glass on the other hand the fs-laser-interaction results in a decrease of the refractive index, while material in the surrounding area experiences an increment in the refractive index, due to the densification of the material (Dharmadhikari et al., 2011). Therefore, two different types of waveguides have to be distinguished. Type-I waveguides form the simplest realization and can be used for fused silica glass, were the laser track results in a positive index change. Here the light can be guided directly in the laser track. For borosilicate glass, where the laser track itself results in a negative refractive index, Type-II waveguides can be used. Type-II waveguides are realized by two laser inscribed tracks with a suitable separation. Because the surrounding material of the laser tracks experiences a positive refractive index change, the light-guiding region is found in the overlapping volume of the two parallel laser tracks (Cai & Wang, 2022).To produce these different waveguide types or other micro-optical components microscope optics with a high numeric aperture and therefore a small focus diameter are normally used. The advantage of the use of microscope optics is that the small focus diameters depress the formation of a heat-affected zone so waveguides can be inscribed with small dimensions and a high resolution.

One method that has not yet been investigated much is the fs-laser direct writing method of micro-optical components in glass with laser systems, which uses a scanner optic with a long focal length instead of a microscope optic. Scanner optics provide a high degree of flexibility, allowing three-dimensional structures to be inscribed in the glass volume with high scanning speeds and precise positioning. However, the long focal length also leads to a larger focal diameter which means that higher pulse energies are required to achieve the same intensities as when using microscope optics. The larger diameter also leads to a larger heat-affected zone which causes stress in the material that can lead to the formation of cracks (Gstalter et al., 2019). Accordingly, when using scanner optics to inscribe waveguides in glass, it is necessary to find the optimal parameters that do not lead to damage of the material and enable the guidance of light.

In this paper, the subsurface inscribed waveguide structures in borosilicate glass are investigated and demonstrated as a function of the influencing laser parameters. The influencing laser parameters include the repetition rate, the pulse energy, the scanning speed, the focus depth as well as the separation distance of the two laser tracks for Type-II waveguides.

2. Experimental details and setup

The experiments in this work were performed using a TruMicro 2000 (TRUMPF GmbH, Ditzingen, Germany) ultra-short-pulsed laser system, which emits laser pulses at a wavelength of λ =1030 nm with an adjustable repetition rate from single pulses up to 2 MHz with a pulse duration of 400 fs. The maximum pulse energy is 20 μJ. The TruMicro 2000 is integrated in a 5-axis high-precision machining system, microcut UKP system (LLT GmbH, Ilmenau, Germany) to enable the laser micro machining. The focusing device contains a 100 mm F-theta lens (JENOPTIK Optical Systems GmbH, Jena, Germany) and an excelliSCAN14 (SCANlab, Puchheim, Germany) galvo scanner system. The laser beam can be preceded by a beam expander (JENOPTIK Optical Systems GmbH, Jena, Germany). The resulting focus diameter is about 17 µm and can be focused and moved into the volume of the glass sample.

The waveguides were inscribed in a polished parallelepiped borosilicate block (BK7). Borosilicate glass is a widely used material in optical devices. The size of each sample is 40 mm x 40 mm with a thickness of 15 mm. Prior to the laser micro inscription, the glass samples were cleaned with optical residue-free cleaning wipes and ethanol. The Inscription of the waveguides were achieved by translating the focused laser beam relatively to the BK7 glass sample. Therefore, the glass samples were placed in a custom-made sample holder, which allows repeatable positioning of the samples. The experimental set-up and the LLT microcut UKP system is shown in Figure 1.

Fig. 1. Experimental set-up for the waveguide inscription and LLT microcut UKP system

The experimental set-up allowed it to variate parameters like the repetition rate, the focus depth, the pulse energy, and the scanning speed. To investigate the influence of the repetition rate, the number of pulses per second was variated, while the pulse energy and the scanning speed was kept constant.

The repetition rate was variated with 200 kHz, 400 kHz, 600 kHz, 800 kHz and 1 MHz, while the pulse energy was kept constant at 6 and 10 µJ. To achieve a constant pulse overlap, the scanning speed was adjusted for every repetition rate from 17 mm/s to 85 mm/s. To investigate the influence of the focal depth, modification tracks were inscribed at different depths across the thickness of the glass sample from 0.5 mm to 11 mm using constant laser parameters. The extent of the modification and the resulting dimensions in the glass volume were investigated as a function of the pulse energy. Therefore, the pulse energy was increased successively from 1 to 17 µJ. The structures were inscribed at a scanning speed of 17 mm/s and a resulting pulse overlap of 99,5 % with a pulse energy of 10 µJ. Another investigated parameter was the scanning speed. V_{Scan} was variated from 17 to 102 mm/s and a resulting pulse overlap from 97-99,5 %, while the pulse energy was kept constant with 10 µJ. At last, the investigation of Type-II-waveguides with promising parameters from the previous studies were performed. Therefore, double-track arrangements as well as multi-track arrangements were inscribed. The multi-track arrangement consists out of four laser tracks separated by d_x = 17 µm and another overhead track arrangement with a distance of d_y = 250 µm. The track spacing was variated for a single structure as well as for a bundle structure. Another optical device, a so-called beam splitter, which fabrication requires a curved shape of a waveguide arrangement is shown. Analyzed are the produced waveguides by microscopic images with the Zeiss Axio Zoom.V16 stereo-microscope.

3. Results and discussion

In order to obtain smooth and homogeneous waveguides the repetition rate in particular is an important parameter. The repetition rate determines whether the time between two subsequent pulses is greater or less than the relaxion time of the used material. If the time between two successive pulses is shorter than the relaxion time, the temperature in the focal volume is increasing stepwise by each pulse. This process is called heat accumulation and takes place in a very short period of time. At higher repetition rates, the heat-affected zone is much larger. This leads to stresses in the material, which result in the formation of cracks. Figure 2 shows the microscope images of the inscribed waveguides with different repetition rates from 200 kHz to 1 MHz for 6 and 10 µJ.

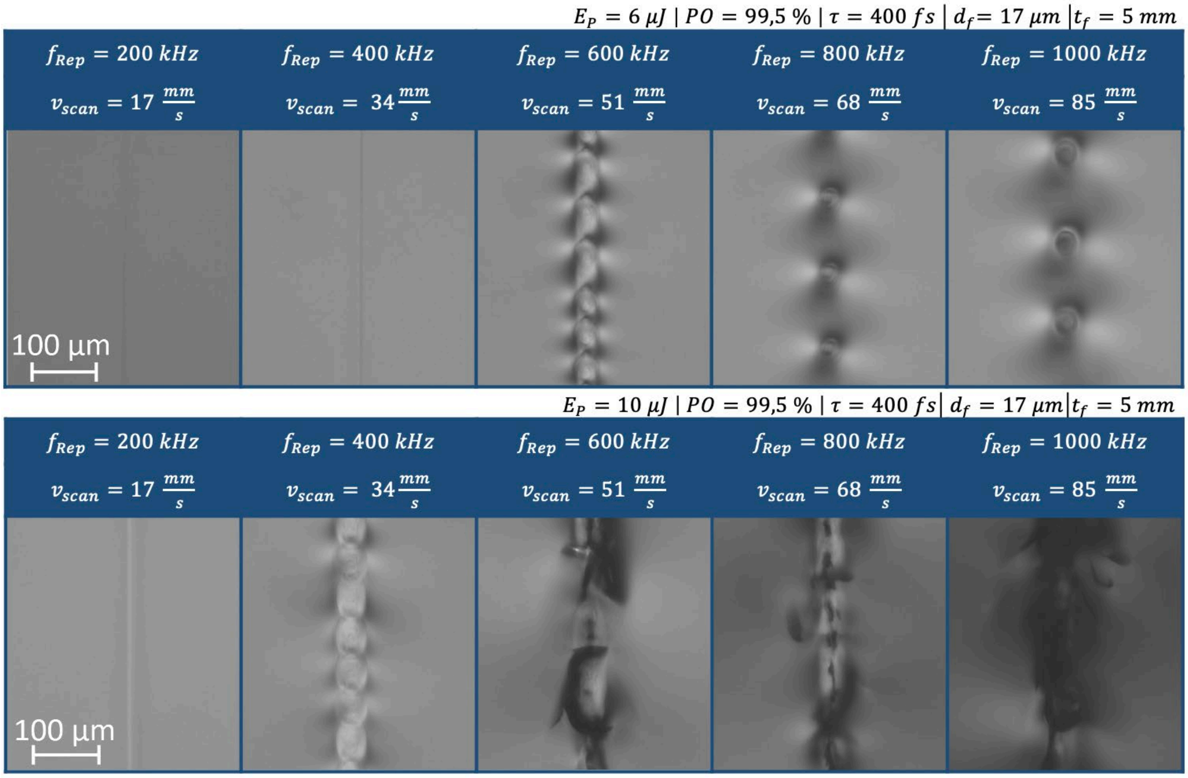

Fig. 2. Light microscope images of waveguides inscribed with different repetition rates for 6 and 10 µJ

For 6 µJ instead of a continuous line a periodic pearl-chain like structure starting for a repetition rate of 600 kHz up to 1 MHz can be observed. The distance between those pearl patterns is higher with higher repetition rate. Below 600 kHz a homogenous modification tracks can be observed. For a higher pulse energy of 10 µJ the pearl-chain structure can be observed starting at 400 kHz. The reason for the formation of the pearl-chain like structure is not yet fully understood. A possible explanation for the pearl-chain like structures at higher repetition rates concerns the hydrodynamic instability of a liquid. It is assumed that a molten volume of liquid glass spontaneously decays into drops, analogous to the breakup of a water jet in air (Eggers, 1997). The liquid material, which has an energetically unfavorable shape, contracts into a ball due to surface tension. For the waveguide writing process, the material is melted by sequence of laser pulses resulting in the heating of the molten liquid which is unstable and decays into drops. Another possible explanation for the pearl-chain like structure concerns a threshold-like absorption. A certain size of the emerging material modification scatters so much light and distorts the beam in a way that the absorption of the material drops. By continuously translating the focus through the material, the absorption increases again as soon as the light hits unmodified material and the process repeats itself periodically resulting in the this pearl-chain like structure (Graf et al., 2007). Below 400 kHz a smooth modification track can be observed. For higher repetition rates like 600 kHz the track results in a formation of cracks. Due to heat accumulation, stresses have built up in the material which are relieved by cracks. At 200 kHz a continuous homogeneous modification track can be obtained at both 6 and 10 µJ, which is why the repetition rate is kept constant at 200 kHz for the following experiments.

Another big requirement for the laser direct writing of complex waveguide structures beside the control of the structure parameters is an accurate positioning in the glass volume. Therefore, the influence of the focal depth was investigated. For the investigation of the focus depth adjustability of the waveguides in the glass volume, the focus was placed starting from the glass surface across the glass width to different focal depth to the back side of the glass. The laser processing parameters were kept constant with a pulse energy of 10 µJ and a scanning speed of 17 mm/s. After the laser processing the cross-section of the sample with the inscribed modification tracks were measured with light microscopy images to determine the start of the modification track. The results of the measurement show a linear downward shift of the focus, leading to a larger effective focusing depth $t_f{}'$. The reason for the shift in the focal position is, according to Snellius´ law of refraction, the various rays of a focused beam are refracted to different degrees at the interface between air and material with a refractive index n. The outer rays, which strike the surface at a shallower angle, are refracted more strongly than the inner rays. Therefore, the focus is shifted in propagation direction by $t_f{}' = t_f \cdot n$. The different focal positions along the optical axis with the glass must therefore be multiplied by the refractive index of the material (Sun et al., 2005).

In the following, the extent of the modification and the resulting dimensions as a function of the pulse energy will be presented. Figure 3 shows light microscopy images of six cross-sections inscribed with different pulse energies.

$$v_{scan} = 17\ \frac{\mathrm{mm}}{\mathrm{s}}\,|PO = 99{,}5\ \%\ |f_{Rep} = 200\ \mathrm{kHz}\ |\tau = 400\ \mathrm{fs}|\ d_f = 17\ \mu\mathrm{m}|t_f = 4\ \mathrm{mm}$$

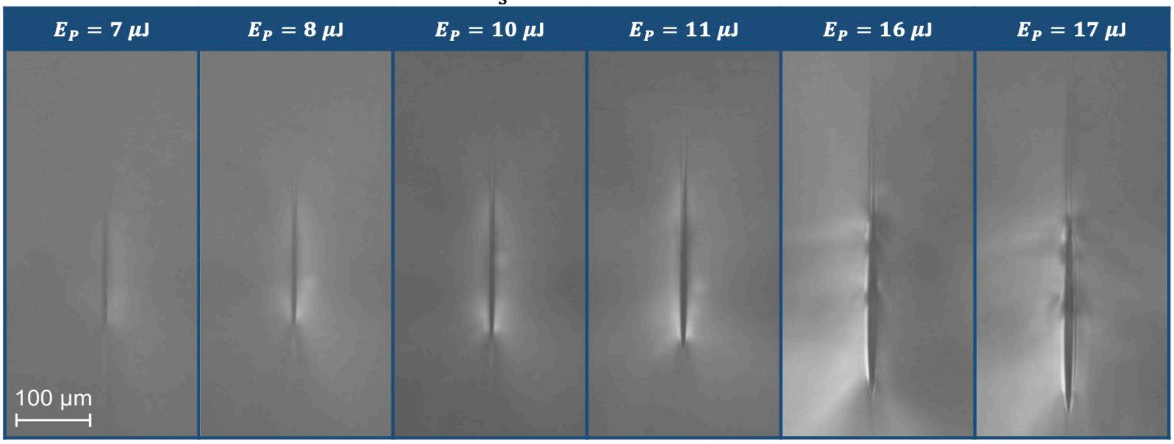

Fig. 3. Light microscope images of the cross-section of waveguides inscribed with different pulse energies

While the pulse energy was variated the scanning speed was kept constant with 17 mm/s. The optimum pulse energy for writing the waveguide structures was found to be in the range of 6–8 µJ. Below a laser energy of 5,8 µJ no modification could be observed. For 6 µJ a small modification track with a width of about 2,3 µm and a height of about 150 µm can be seen. In principle, the cross-sectional height is larger than the cross-sectional width. The reason for this is the prolonged focus in the propagation direction of the laser radiation due to the larger diameter of the laser beam compared to the diameter of the focal point. For pulse energies over 9 µJ, the appearance of an additional outer structure can be observed. The cross-sectional height and width of the inner structure (h_i und b_i) as well as the outer structure (h_a und b_a) increase with increasing pulse energy. This correlation is shown in Figure 4. The diameter of the outer structure is about the factor ~1,75 bigger than the diameter of the inner waveguide structure itself. A possible reason for the appearance of the outer structure is analogous to higher repetition rate heat accumulation effects (Eaton et al., 2005).

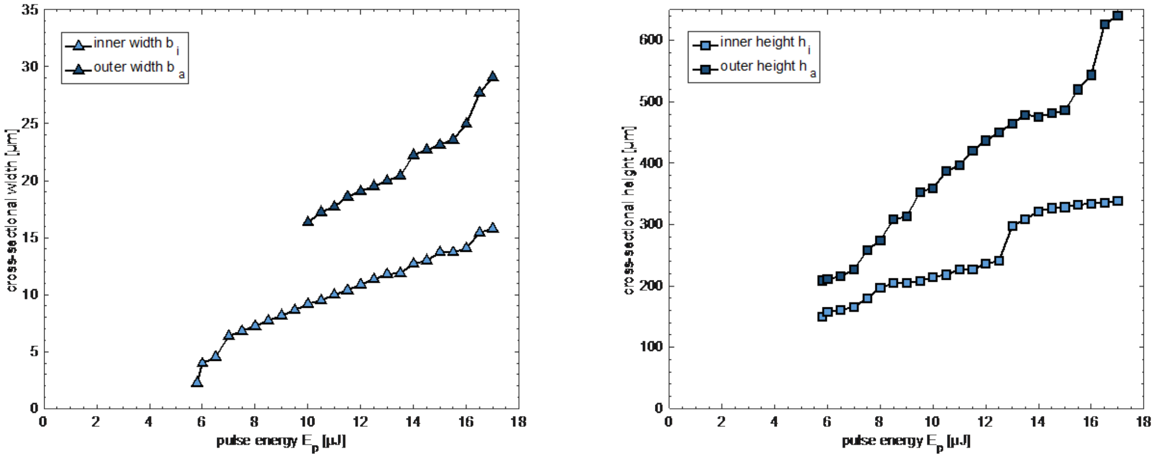

Fig. 4. Cross-sectional width and height of the inner and outer structure as a function of the pulse energy

For a constant pulse energy of 10 µJ the morphology of the modification tracks for different scanning speeds and therefore for different pulse overlaps is not constant. Figure 5 shows microscope images of several modification tracks inscribed with different scanning speeds. In general, the higher the scanning speed, the smaller the resulting pulse overlap and the weaker the modified track. For lower pulse overlaps an inhomogeneous structure with a frayed looking edge structures can be observed. With smaller scanning speed the laser track becomes more even and homogenous, so that a even waveguide structure can be ensured. For a scanning speed of 17 mm/s and a pulse overlap of 99,5 % we obtained an even looking laser track.

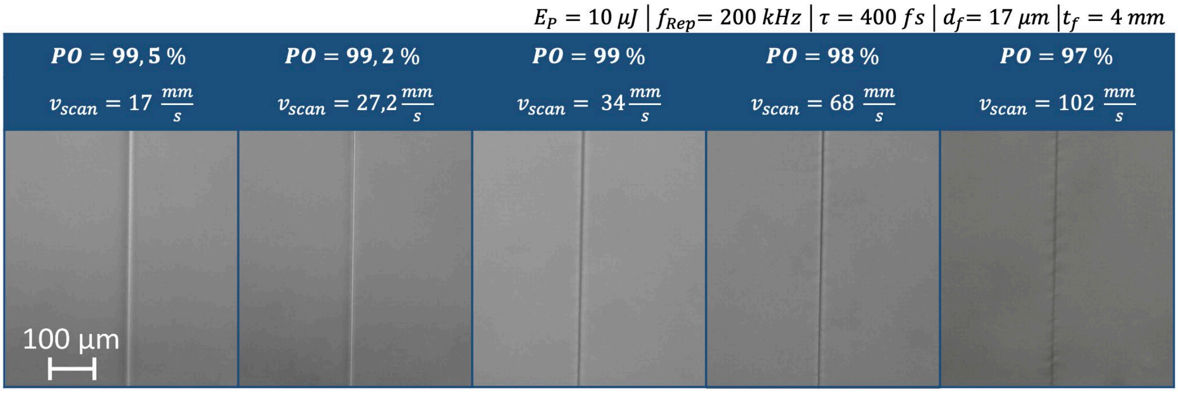

Fig. 5. Light microscope images of waveguides inscribed with different scanning speeds

Figure 6 shows the approach of creating waveguide Type-II arrangements, where two femtosecond laser inscribed laser tracks are placed beside each other with a suitable separation, as schematically shown below. This type creates a horizontally distributed refractive index increase to its left and right flank. Therefore, different spacing distances d_{sp} were investigated. Following illustration shows the microscope images for a spacing distance of 30 and 60 µm. By placing several laser tracks beside each other a so-called multi-track structure or bundle structure is created. The modification tracks were moved as close together as possible except for a single variable spacing distance in the middle. By placing the laser tracks close to each other, they establish a quasi-continuous low-index potential barrier that provides the optical trapping of the guided light. The distance d_x between the tracks is set with 17 µm, so that they do not overlap in their volume. To enhance this effect even more, another row is placed above the initial structure with a distance d_x=250 µm.

$$E_P = 10\ \mu J \Big| v_{scan} = 17\ \frac{\text{mm}}{\text{s}} |PO = 99{,}5\ \% \ |f_{Rep} = 200\ \text{kHz}\ |\tau = 400\ \text{fs}|\ d_f = 17\ \mu\text{m}\Big| t_f = 4\ \text{mm}$$

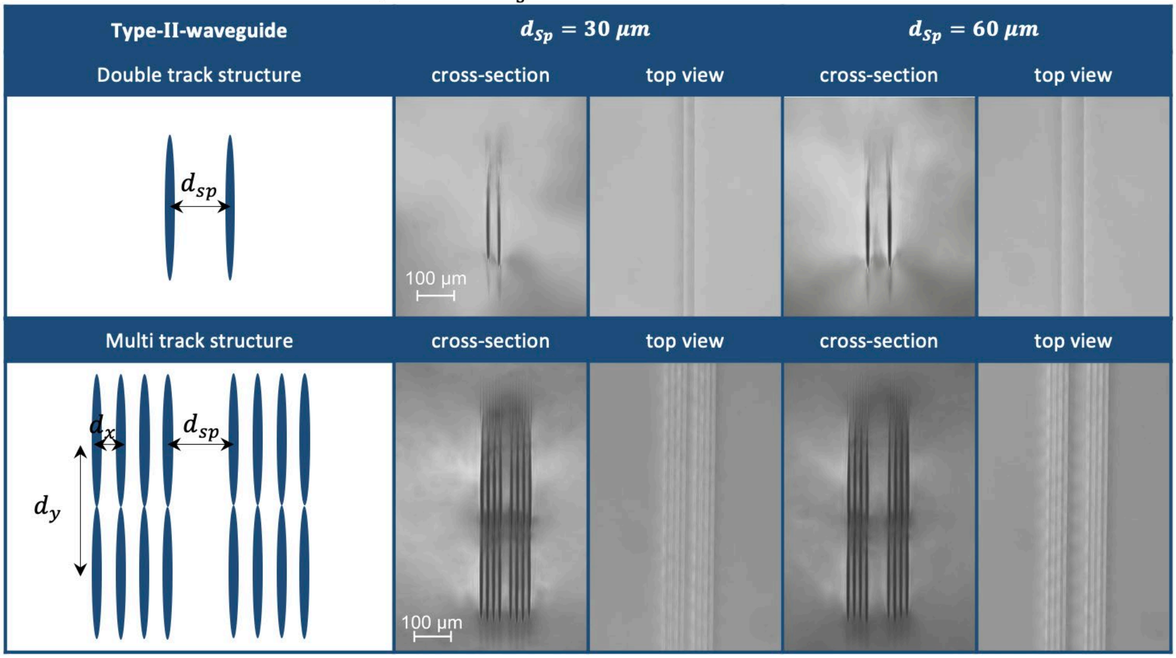

Fig. 6. Light microscope images of the cross-section of double-track- and a multi-track-waveguide structures

After a detailed look on the fabrication procedure and possible geometries of femtosecond laser inscribed waveguides, the final section of this paper will provide another possible application for an integrated optical circuit. The guidance of light to different target locations can be achieved by a so-called beam splitter (Mittholiya et al., 2017). Beam splitters can be inscribed in a two- and three-dimensional arrangement. The fabrication requires waveguide structures that have a curved shape and split into two Y-shaped coupler arms. They have an interaction region, where two waveguide structures are placed close enough so that their evanescent fields overlap so light can be coupled from on to the other due to an interaction of the evanescent fields with each other. An important characteristic is the coupling length, which influences the amount of light, that is coupled between the two waveguides (Skryabin et al., 2019). After the light coupling the splitting of the guided light is achieved by the two coupling arms. The shape of each arm consists out of two circular arcs placed one behind the other with reversed angular sign. Normally Type- I waveguides suit best for implementation of the complex structures for beam splitters. The fabrication of such elements with Type-II waveguides which is necessary for borosilicate glass, faces substantial challenges like the design of the interaction region and the cladding alignment in a circular or rhombic shape. That is why the subsequent description shows the simplified design structure with Type-I waveguides instead of a cladding structure. Figure 7 shows the microscope images of an 1x2-Y-beam splitter with different spacing distances. It was inscribed with a pulse energy of 6 µJ and a scanning speed of 17 mm/s in a depth of 4 mm under the surface of the BK7 glass sample.

$$E_P = 6\ \mu J \Big|\ v_{scan} = 17\ \frac{\mathrm{mm}}{\mathrm{s}} \,|PO = 99{,}5\ \%\ |f_{Rep} = 200\ \mathrm{kHz}\ |\tau = 400\ \mathrm{fs}|\ d_f = 17\ \mathrm{\mu m}\Big|t_f = 4\ \mathrm{mm}$$

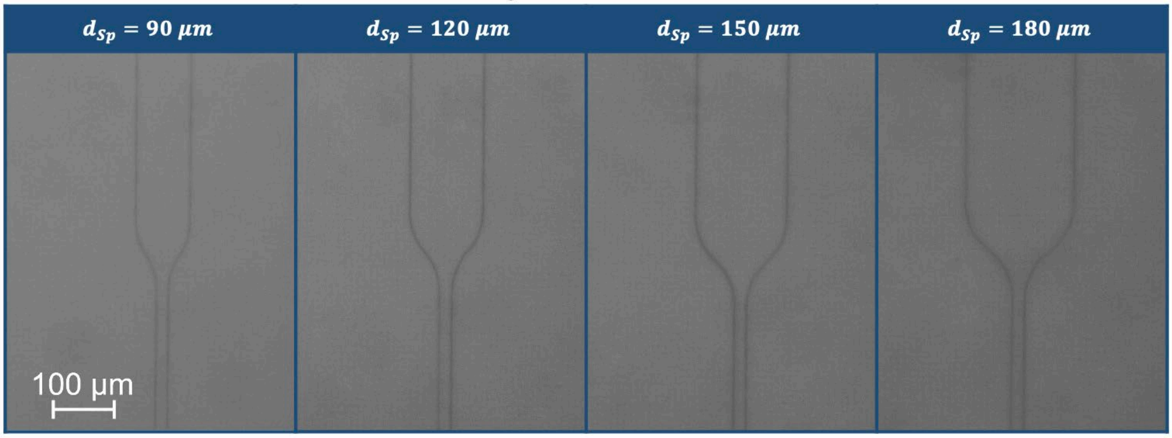

Fig. 7. Light microscope images of laser inscribed beam splitters with different spacing distances

4. Conclusion and Outlook

In the presented study, we investigated the femtosecond inscription of waveguides in BK7-borosilicate glass. Therefore, the influencing laser parameters like the repetition rate, the focus depth, the pulse energy, and the scanning speed was variated, and the resulting waveguides structures were analyzed by light microscope images. It was found out that for a homogenous waveguide writing a repetition rate of 200 kHz is necessary. With repetition rates over 200 kHz and a higher pulse energy the waveguides result in a pearl-chain like structure or with even higher repetition rates in a formation of cracks. For a precise positioning of the waveguides in the material it is necessary to consider the different refraction of the laser beam occurring at the interface of air and glass and the resulting shift of the focus. With increasing pulse energy, an increasing cross-sectional width and height can be observed. At pulse energies above 10 µJ an additional symmetrical outer structure can be observed mostly like due to heat accumulation effects. Smaller scanning speeds lead to homogenous even modification tracks while higher scanning speeds result in weaker modification tracks with frayed looking edge structures. For the fabrication of Type-II waveguides two parallel laser tracs with variating spacing distances were inscribed. Also, a multitrack arrangement, that establish a quasi-continuous low-index potential barrier and beam splitters, which allow the guidance of light to different target locations were inscribed.

Based on the results obtained, a variety of further experiments are necessary. The Type-II waveguides inscribed in borosilicate glass have to be tested for optical functionality, therefore a more detailed characterization of the produced waveguides is necessary. First, phase contrast microscopy can be used to determine the two-dimensional refractive index distribution of the cross-section of the Type-II inscribed waveguides. This allows the most appropriate spacing distance of the parallel laser-induced tracks to be made. Also, it becomes visible whether a higher refractive index change occurs due to the bundle structure compared to the double-track structure. If the positive refractive index is detected by phase contrast microscopy, the intensity distribution on the exit facet of the waveguides can subsequently be determined by imaging the guided modes. For this purpose, a coherent laser beam must be coupled into the laser-induced optical waveguide. The intensity distribution can then be imaged, for example, onto a chip of a CCD-camera.

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References

Cai, C. & Wang, J. (2022) „Femtosecond Laser-Fabricated Photonic Chips for Optical Communications: A Review“, *Micromachines*, Vol. 13, No. 4.

Dharmadhikari, J. A., Dharmadhikari, A. K., Bhatnagar, A., Mallik, A., Singh, P. C., Dhaman, R. K., Chalapathi, K. & Mathur, D. (2011) „Writing low-loss waveguides in borosilicate (BK7) glass with a low-repetition-rate femtosecond laser“, *Optics Communications*, Vol. 284, No. 2, S. 630–634.

Eaton, S., Zhang, H., Herman, P., Yoshino, F., Shah, L., Bovatsek, J. & Arai, A. (2005) „Heat accumulation effects in femtosecond laser-written waveguides with variable repetition rate“, *Optics express*, Vol. 13, No. 12, S. 4708–4716.

Eggers, J. (1997) „Nonlinear dynamics and breakup of free-surface flows“, *Reviews of Modern Physics*, Vol. 69, No. 3, S. 865–930.

Graf, R., Fernandez, A., Dubov, M., Brueckner, H. J., Chichkov, B. N. & Apolonski, A. (2007) „Pearl-chain waveguides written at megahertz repetition rate“, *Applied Physics B*, Vol. 87, No. 1, S. 21–27.

Gstalter, M., Chabrol, G., Bahouka, A., Dorkenoo, K.-D., Rehspringer, J.-L. & Lecler, S. (2019) „Long focal length high repetition rate femtosecond laser glass welding“, *Applied optics*, Vol. 58, No. 32, S. 8858–8864.

Krol, D. M. (2008) „Femtosecond laser modification of glass“, *Journal of Non-Crystalline Solids*, Vol. 354, 2-9, S. 416–424.

Lapointe, J. & Kashyap, R. (2015) „Laser Processed Photonic Devices“, *Springer Series in Optical Sciences* [Online]. Verfügbar unter DOI: 10.1007/978-1-4939-1179-0_6.

Mao, S. S., Quéré, F., Guizard, S., Mao, X., Russo, R. E., Petite, G. & Martin, P. (2004) „Dynamics of femtosecond laser interactions with dielectrics“, *Applied Physics A*, Vol. 79, No. 7, S. 1695–1709.

Mittholiya, K., Anshad, P. K., Mallik, A. K., Bhardwaj, S., Hegde, A., Bhatnagar, A., Bernard, R., Dharmadhikari, J. A., Mathur, D. & Dharmadhikari, A. K. (2017) „Inscription of waveguides and power splitters in borosilicate glass using ultrashort laser pulses“, *Journal of Optics*, Vol. 46, No. 3, S. 304–310.

Skryabin, N., Kalinkin, A., Dyakonov, I. & Kulik, S. (2019) „Femtosecond Laser Written Depressed-Cladding Waveguide 2 × 2, 1 × 2 and 3 × 3 Directional Couplers in Tm3+:YAG Crystal“, *Micromachines*, Vol. 11, No. 1.

Stoian, R. (2020) „Volume photoinscription of glasses: three-dimensional micro- and nanostructuring with ultrashort laser pulses“, *Applied Physics A*, Vol. 126, No. 6.

Sun, Q., Jiang, H., Liu, Y., Zhou, Y., Yang, H. & Gong, Q. (2005) „Effect of spherical aberration on the propagation of a tightly focused femtosecond laser pulse inside fused silica“, *Journal of Optics A: Pure and Applied Optics*, Vol. 7, No. 11, S. 655–659.

Thiel, M. A. F. (2018) „Direkte Erzeugung von optischen Wellenleitern und Bragg-Gitter-Sensoren in Silikatglas-Substraten mit ultrakurzen Laserpulsen und deren Anwendungen“ [Online]. DOI: 10.21268/20180604-094423.