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Advanced techniques in optical system fabrication with two-photon lithography

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Abstract
The two-photon lithography is an additive manufacturing process that enables the printing of complex 3D structures with sub micrometre resolutions in one fabrication step. This technology is suitable to produce optical components such as lenses or even photonic crystals. The integration of photonic crystals in optical systems printed with the two-photon lithography is still a challenge. The dimensions of photonic crystals such as woodpile structures are below the millimetre scale and are fragile. To enable the use of optical systems with woodpile structures a suitable light guide and coupling has to be designed and tested. This work gives a brief insight in the fabrication of an optical system and the problems that have to be addressed.
The main problem of optical systems written with a two-photon lithography system is the handling of the structures and the substrate. The first problem to address is the integration of such microsystems into external macro scale systems to couple the light sources and to receive the output. To encounter this problem a coupling structure is designed to enable the vertical introduction of the light source into the system. The main task of the coupling structure is to focus and redirect the light in a 90° angle, therefore a total reflection surface with a 45° degree is needed. The material has a significant impact in the fabrication, as it influences the optical and geometrical properties, e.g. surface quality. The evaluation of the optical system is another challenge. A quantifying test can be made with the light coupled into the system and a structure that has to be illuminated.

Two-photon lithography, 2PP, optical components, hybrid polymers, laser direct writing

1. Introduction

Since the development of the femtosecond laser the fabrication process of direct laser writing e.g., two-photon lithography has advanced rapidly. The two-photon lithography stands out from other manufacturing processes for its ability to produce real 3D-structures. The system uses a femtosecond laser that emits only half of the energy per photon that is necessary to polymerise the photon sensitive resin [1]. Therefore, the absorption of two photons almost simultaneously supplies sufficient energy for the polymerisation process. The energy in the focal region creates an elliptical shaped polymerised voxel, which can be used to produce features below the resolution limit of the optical setup [2]. The fabrication of 3 dimensional structures can be realised by moving the focal spot through the resin. The complexity and dimension of the structures and the process parameters define the manufacturing time that is needed [3].
The ability to manufacture real 3D structures with a high resolution enables the protentional for a new field of optical designs [4]. The manufacturing of optical components is subject to strict requirements in terms of geometry and surface quality. The functionality of the components depends on these values. While the two-photon lithography can fabricate complex optical objects, the functionality can often only be confirmed by measurements of the optical characteristics. These measurements require either an easy handling of the printed structure to insert them in the setup or a solution for measuring the printed structures on the substrate. This work focusses on the latter case to demonstrate the functionality of an optical system that contains a coupling structure, a waveguide and an illumination structure.

2. Performance evaluation

The two-photon lithography is a suitable instrument for the rapid prototyping of optical components and system. Therefore, this work focusses on the fabrication of complex systems using a FemtoLAB workstation from WOP-Workshop of Photonics (Lithuania). This workstation offers additive as well as subtractive manufacturing processes. The built-in femtosecond laser can emit the wavelengths of 1028 nm, 514 nm and 343 nm with a pulse duration of 244 fs and a frequency of <601.8 kHz. The structures were fabricated with a wavelength of 514 nm and the resin OrmoComp© and OrmoCore©. Both resins are available at micro resist technology (Germany). OrmoComp© was used in the first tests for the manufacturing of the coupling structure. OrmoCore© was specifically designed as material for fabricating optical components and waveguides together with OrmoClad©, therefore the whole optical system was manufactured using this resin. A 170 µm ± 5 µm thick glass slides were used as substrate. For the development of the structures, the substrates were immerged in a solution of 2/3 isobutyl methyl ketone and 1/3 isopropanol for 20 minutes.

2.1. System configuration

The FemtoLAB workstation can be used in different setting. In this work a Mitutoyo objective with a magnification of 50x and a NA of 0.42 was used. The maximum usable laser power was set to 712,5 mW (25% of 2,85 W). The setup of the sample can be seen in Figure 1. The liquid resin is placed between two glass slides on the sample holder.

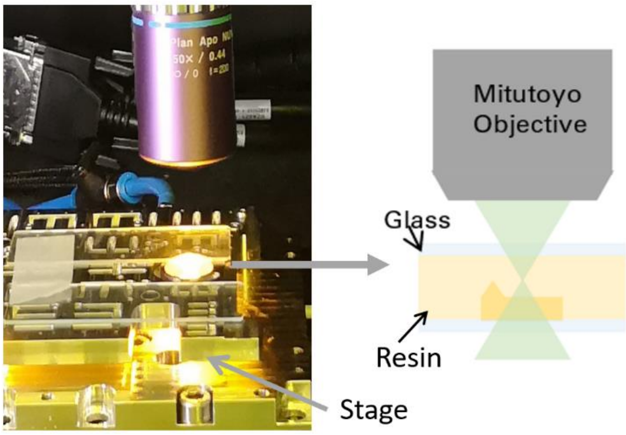

Figure 1. setup of the sample holder inside the machine (left), representation of the sample setup and writing strategy (right)

The workstation uses the manufacturing software SCA to set the process parameters and to slice the structures. The most crucial parameters, for fabrication a structure with good resolution, are the laser power *P*, the pulse density *PD* (pulse[p]/mm), the speed *S*, the layer height D_z and the hatch width *HW*. The following table lists the parameter sets that are suitable for utilizing the two different materials in the FemtoLAB workstation.

Table 1 parameter sets for structures written with a 50x objective, P= laser power, PD= pulse density, S= speed, Dz= layer height, HW= hatch width

Resin	P [mW]	PD [p/mm]	S [mm/s]	D_z [nm]	HW [nm]
OrmoComp	498,75	20000	15	500	500
OrmoCore	498,75	30000	15	500	500

2.2. Test structure

The optical system that is described in this work consist of three functional assemblies, a coupling structure, a waveguide and an illuminating structure. The coupling structure serves for the purpose to redirect the light that strikes orthogonally to the glass slide surface by 90°. The input lens collimates the incoming light. The 45° surface serves as a total reflection surface and redirects the light (see Figure 2), while the output lens focusses the light on a waveguide.

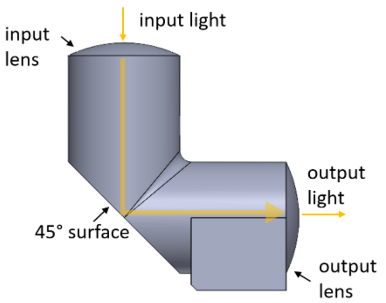

Figure 2. schematic presentation of the coupling structure and the functionality

The waveguide is radial designed as multimode with step-index. For a better coupling of the incoming light, the waveguide has a funnel-shaped side. Three columns beneath the waveguide support the structure. The usages of support structures can lead to light losses in the structure [5]. For the further tests this circumstance is neglected. The illuminating structure purpose is to be illuminated by the diverted light; the design is not relevant in this work.

3. Results

The manufacturing of optical components requires a trade-off between the resolution of the structure and the time consumption. Especially the layer height and therefore the slicing distance of the structure is crucial for the surface quality. A hight value (e.g. 1µm) for the layer heigh can result in a surface with visible steps, seen in Figure 3.

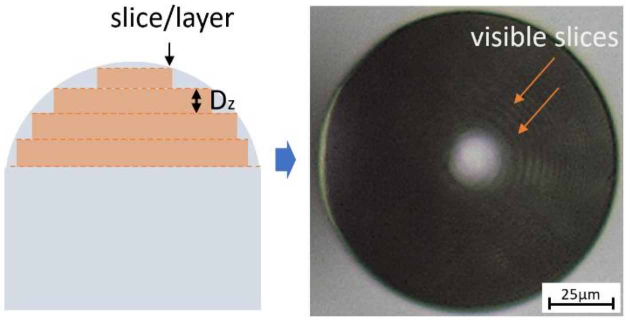

Figure 3. schematic of the slicing of the coupling structure and the result of the layer heigh in the end product

Therefore, printing tests were performed to determine suitable parameter sets that allow a smooth surface with the highest possible layer height values. The value for the layer height D_z was changed while the other parameters stayed constant. The Table shows the used parameters and the time that was needing to print the coupling structure with OrmoComp©.

Table 2 Parameter sets for the test fabrication of the coupling structure and the time consumtion

Dz [µm]	Time [h]
0,001	1,5
0,00075	2
0,0005	3
0,0003	4,5
0,0001	13,5

The measurements of the coupling structure were taken with a VK-X3000 Series laser microscope from Keyence and analysed with the multi file analyser provided by the company. According

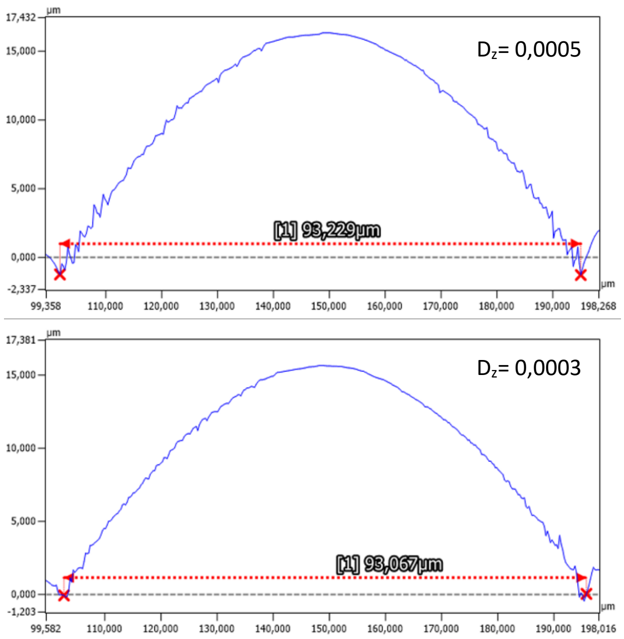

Figure 4. Comparison of the surface between two fabrications, on top Dz=0.0005, beneath Dz= 0,0003

to the manufacture, the laser scanning microscope has a height resolution of 0,01 nm even for transparent or reflection surfaces. The light intensity is auto corrected for reflective objects. The repeatability is defined as 12nm for z and 40nm for x and y axes. The laser scanning microscope is suitable to evaluate the surface quality of the fabricated structures. Because of the nature of the measurement method the evaluation of the radius is subject to tolerances and artefacts. Further investigations have to be done to define the radius of the lenses. The results indicated that a layer height of 500 nm is sufficient to produce smooth slightly curved surfaces (see Figure 4).

After defining the suitable parameters for the manufacturing of the coupling structure, the optical system can be printed in OrmoClad©. To ensure that the alignment of the structure is precisely a base is added to the system. This provides additional stability to the systems and prevents the displacement of single structures. The results can be seen in Figure 5.

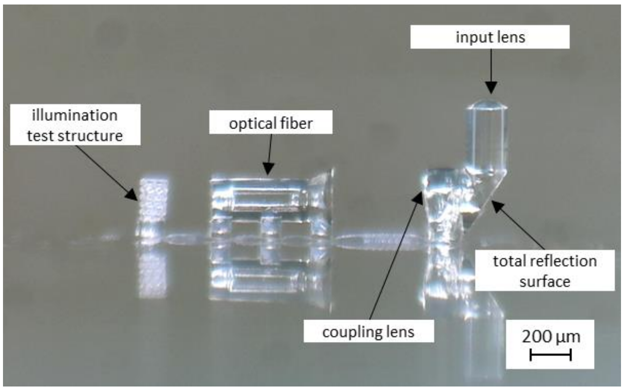

Figure 5. manufactured optical system in OrmoCore

To determine the functionality of the optical system an experimental setup was development to couple an external light source into the system and to record the light transmission by observing the illumination test structure. The positioning of the external light is realized by an x-y stage and a manual adjustment. This adjustment prone to errors, since the process is depending on the subjective decision of the user. The test indicated that the coupling structure and the waveguide fulfil their task by redirection and forward the incoming light (see Figure 6).

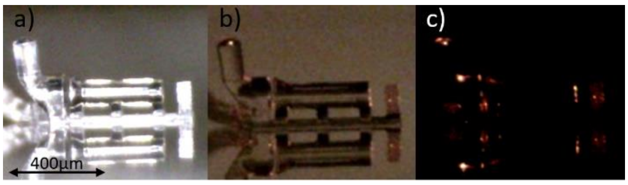

Figure 6. functionality test, a) without light source and with room light, b) with source light and back light, c) with source light and in the dark

4. Summery

The manufacturing of optical components with the two-photon lithography opens new possibilities for the design of such components as well as the requirements. The structure and surface quality depend on various different parameters, that can be adjusted. Parameter sets differ for other system configurations or materials. Therefore, it is necessary to determine suitable parameter sets for different applications.

This work developed an optical system to redirect light that strikes orthogonal to the glass slide surface, to use optical systems that are completely or partially manufactured with the two-photon lithography. Different parameter settings were analysed to find a sufficient trade-off between surface quality and fabrication time. The functionality test of the optical system proofs the ability of the system to redirect the incoming light and to illuminate a structure.

The fabricated structures have to be further investigated to evaluate all functional surfaces. The next step is to measure the radius of the input lens, therefore different comparative measurement method has to be carried out. These numerical results will give an indication on the form fidelity of the optical components.

To further improve the resolution and the functionality of optical systems, other adjustments of the manufacturing process are necessary. In this case study only the input lens was taken into account for the definition of suitable parameter sets. The surface of the 45° surface and the output lens were neglected. These features should be considered in the interpretation of the parameter sets, since they are crucial for the optical properties of the system. The functionality of the waveguide needs to be analysed and the light loss determined to ensure a sufficient light transmission. Another point that should be improved in future work is the functionality test of optical systems, they are still prone to errors. A trustworthy and reproducible measurement system for the functionality test is needed to advance in the manufacturing of optical systems.

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