Optical Micromachining Tool: Fabrication, Manipulation and Assembling of Complex Microstructures Applying Holographic Optical Tweezers

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"Don’t let them dim your light simply because it’s shining in their eyes."

To my beloved Mam and Dad.
Danksagung


Vor allem aber danke ich meiner Mam und meinem Dad. Ich danke Euch dafür, dass ich durch Eure bedingungslose Liebe die beste Version von mir selbst werden konnte. Ich danke Euch von ganzem Herzen für Euren unerschütterlichen Glauben an mich, die Unterstützung in jeder Sekunde meines Lebens und Euren uneingeschränkten Rückhalt. Ihr seid das Beste, was mir in meinem Leben passieren konnte und mein ganzer Stolz. Ich bin der glücklichste Mensch der Welt, weil ich Eure Tochter sein darf.
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<td>°C</td>
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<td>LCOS</td>
<td>liquid crystal on silicon</td>
<td></td>
</tr>
<tr>
<td>LG</td>
<td>Laguerre Gaussian</td>
<td></td>
</tr>
<tr>
<td>LMA</td>
<td>laser microassembling</td>
<td></td>
</tr>
<tr>
<td>LOPA</td>
<td>low one photon absorption</td>
<td></td>
</tr>
<tr>
<td>$M^2$</td>
<td>beam quality factor</td>
<td></td>
</tr>
<tr>
<td>$N$</td>
<td>particle density</td>
<td>m$^{-3}$</td>
</tr>
<tr>
<td>$n$</td>
<td>refractive index</td>
<td></td>
</tr>
<tr>
<td>$n_S$</td>
<td>refractive index of surrounding medium</td>
<td></td>
</tr>
<tr>
<td>$n_P$</td>
<td>refractive index of particle</td>
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<tr>
<td>OMM</td>
<td>optical micromachine</td>
<td></td>
</tr>
<tr>
<td>OMMT</td>
<td>optical micromachining tool</td>
<td></td>
</tr>
<tr>
<td>OT</td>
<td>optical tweezer</td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>power of laser beam</td>
<td>W</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure</td>
<td>N m$^{-2}$</td>
</tr>
<tr>
<td>$Q$</td>
<td>energy of a laser pulse</td>
<td>J</td>
</tr>
<tr>
<td>$r$</td>
<td>amplitude reflectivity</td>
<td></td>
</tr>
<tr>
<td>rot</td>
<td>rotation operator</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>SA</td>
<td>streptavidin</td>
<td></td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
<td></td>
</tr>
<tr>
<td>SLM</td>
<td>spatial light modulator</td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>Name</td>
<td>Units (SI)</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
<td>K</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
<td>s</td>
</tr>
<tr>
<td>$u$</td>
<td>speed of light in a medium</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$w$</td>
<td>beam radius of the Gaussian fundamental mode</td>
<td>m</td>
</tr>
<tr>
<td>$w_0$</td>
<td>beam radius locally in beam waist</td>
<td>m</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>absorption coefficient</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Laplace operator</td>
<td>m$^{-2}$</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>absolute permittivity of vacuum (8.8542 · 10$^{-12}$)</td>
<td>A s V$^{-1}$ m</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength m</td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>magnetic permeability</td>
<td></td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>absolute permeability of vacuum (4\pi · 10$^7$)</td>
<td>N</td>
</tr>
<tr>
<td>$\mu_r$</td>
<td>relative permeability</td>
<td></td>
</tr>
<tr>
<td>$\pi$</td>
<td>Pi (3.14159)</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td>fluence</td>
<td></td>
</tr>
<tr>
<td>$\varphi$</td>
<td>relative rotation angle</td>
<td>rad</td>
</tr>
<tr>
<td>$\omega$</td>
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<td>rad m$^{-1}$</td>
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Chapter 1

Introduction

Laser based manufacturing technologies comply with the demand of fast and effective processing in industrial production. The trend in miniaturization together with an increasing complexity requires new innovative, flexible production technologies. Recently, generative or additive processes have been further developed with regard to the transition from rapid prototyping to small series production. Well established technologies, like stereolithography, are limited in the geometrical structure due to the layered production process. This is where the full three-dimensional (3D) writing abilities of the two-photon polymerization (2PP) process are deployed. This additive manufacturing (AM) process can generate tiny microelements in the range of 3-50 μm directly from CAD-files.

Building up more complex microsystems, however requires disruptive techniques for assembling of these 2PP-generated microelements. Holographic optical tweezer (HOT), in this context, enables a new assembling technique to be integrated. This optical manipulation and assembling technology is highly flexible to integrate and works with highest precision. Using a spatial light modulator (SLM) allows to rearrange the incident laser beam into flexible light patterns in order to simultaneously generate multiple movable spots. Every optical trap can be modified to specific beam profiles with a frame rate of several tens of Hertz.

A possible combination of the 2PP manufacturing together with the contactless HOT manipulation would enable the production of individual complex 3D microsystems. Therefore, an innovative approach for manufacturing, manipu-
lation and assembling of microstructures with well defined manipulation forces, which should be free of any adhesion effects, is essential. For an evaluation of the manipulative capabilities for microstructures, the interaction between light and matter needs to be analyzed for these specifically manufactured microelements. Only if the 2PP generated structures exhibit a high geometrical accuracy assembling to microsystems is conceivable, especially with regard to an interlocking connection. Further, the conception needs to be completed by storage and transportation solutions for the microstructures utilizing optical forces.

Those fabricated structures could be applied in microbiology and -fluidics as well as for industrial applications like microelectromechanical systems (MEMS). In these fields such microdevices could be implemented to control fluid or particle flow as well as microsensors or actuators. Assemblies for medical applications could e.g. be injected intravenously for analysis or removal of atherosclerosis inside a human vein, as a future vision for this developed assembling technology. Thus, assembled microsystems could be used e.g. for the substitution of minimal invasive surgery treatments. Furthermore, it would enable temporary assembling of microelements for future disassembling processes or replacement of defective microparts within a deficient microsystem.

Previous work solely deals with the permanent assembly of spherical structures utilizing biochemical binding technologies. There are some unique advantages by using light as generation tool for microfabrication and manipulation of microcomponents. Hence, this thesis includes developments and solutions for the following requirements, resulting in an 'optical micromachining tool' (OMMT) as a basis for a highly sophisticated interlocking assembling technology:

- production of complex microstructures by an appropriate direct laser writing (DLW) technique
- investigations of optical manipulation possibilities
- strategy for building larger structures by assembling individual microcomponents
- contact-free trapping and fixation of the microcomponents
• no adhesion of the microcomponents to manipulation tool
• flexible moving and positioning of the microstructures as well as joining
• manipulation of structures of different size and shape
• simultaneous manipulation by multiple traps
• assembling technique for non-spherical components and an appropriate storage or provisioning solution for several different microstructures
• idea for miniaturization within a demonstrator for industrial usage
• integration into one optical platform
• definition of component transfer points including all necessary technologies
• analysis of useful assembling techniques at the microscopic level as well as the development of a targeted delivery processing for provision of a plurality of different microelements

The main advantage of this new technology is individual assembly of microcomponents to complex microsystems, which makes it more suitable than other micromanufacturing and -assembling technologies like micro robots or micro-grippers. Moreover, the capability of disassembling microsystems complements the need of replacing defective microelements as a second outstanding feature.

The final aim is the implementation of an ’all-optical micromachine’ (AOMM) in just one integral system. With such a technology, arbitrary components are fabricated and manipulated within only one setup. This development results in a faster process flow by the elimination of all storage and transport procedures between manipulation and assembling.

Starting with an introduction including motivation, aim of research and general requirements for the OMMT, the second chapter of this thesis gives a fundamental physical background of optical microfabrication, as well as manipulation of non-spherical microstructures. Basic physical principles along with the experimental setups are described in detail. Herein, not only theoretical basics of two-photon polymerization and optical trapping are given,
along with the experimental setup, but also a summary of the current state of technology with focus on fabrication and manipulation procedures of 3D microcomponents for complex assembling processes. Chapter 2 also includes a short description of the interaction between light and matter within all HOT processes.

Chapter 3 gives an overview of previous assembling techniques for spherical structures, followed by assembling techniques for 3D microstructures both with spherical ports and without any ports, along with existing storage and transport methodologies for complementary microparts.

Chapter 4 describes the concept developed in this investigation for an all optical micromachining tool. Followed by a process adaptation of the AM procedure the sample preparation and fabrication of freely movable microcomponents with geometrical interlocking characteristics are realized. In particular, fabrication accuracy and quality enhancement of complementary microelements are analyzed. Furthermore, an alternating writing process is implemented with analysis of repeatability and quality of the interlocking microelements. Afterwards, the storage-, development-, and transport processes are analyzed and adapted for usage of freely movable microelements. Followed by assembling techniques with application examples for vertical and horizontal alignment, translational and rotational movement, as well as full 3D control of non-spherical microcomponents. The entire process flow is given in the end of these investigations. The all-optical micromachining draft is presented in the end of chapter 4. A detailed description of the integral system is given, as well as the process flow adaptations, first results of fabricated microstructures and the miniaturized models for industrial usage.

Chapter 5 gives a summary and an outlook of the developments and its implementation for an all-optical micromachine. Attached files contain further detailed information on design data and applied hardware.
Chapter 2

Optical microfabrication and manipulation

Within this chapter, several microfabrication and manipulation techniques are described regarding the single development processes of an OMMT. The idea of a micromachining system combines two independent optical laser processes. In the manufacturing part, 2PP is used. This process is then adapted to the main system, the HOT, for further manipulation and assembling. HOT have the advantage, that multiple optical beam paths can cross each other, while the optical trap remains unimfluenced. Mechanical micro-grippers conversely cannot be overlapped without mutual destruction. Hence, HOT represents a non-destructive and gentle alternative to mechanical manipulation techniques with exceptional capabilities regarding e.g. 3D-control applying small forces in the range of pN.

In the following, the interaction between light and matter is briefly presented, with respect to the optical forces on non-spherical microstructures. The goal is the production of complex microstructures with geometrical joining characteristics, in order to build up complex 3D microsystems. Therefore, an optical tool for processing, positioning and fixation of microstructures is needed using multiple beams for assembling microstructures without interference. Disassembling of microstructures is another very important requirement for all assembling methods presented in this work. Additionally, the generated structures need to meet the specifications, which would be a complementary shape with interlocking demountable characteristics.
2.1 Optical fabrication: Two-Photon Polymerization (2PP)

2.1.1 Definitions and physical principles

Micromanufacturing of complex components can be realized utilizing different generation techniques. In detail, laser based AM processes apply partial melted metallic powders [SHI99] for selective laser melting, polyamides for selective laser sintering or photopolymers for the generation of more complex structures [LIN03]. Another powder based AM process, direct metal deposition, is also able to generate 3D geometries for assembling procedures. A focused laser beam is used for the generation of a melt pool. The metallic powder is then added to the melt pool layer by layer. Additionally, stereolithography (SLA) represents an AM technique for generating 3D-printed prototypes applying photopolymerization. These 3D parts are fabricated layer by layer by exposing the surface of the polymer, which immediately cures. Theoretically, SLA is equal to one-photon polymerization (1PP). Here, the polymer material also completely cures within the exposed area.

Thus, 2PP is implemented as an advanced 3D printing technology for micromanufacturing. 2PP allows the fabrication of structures with highest flexibility and precision compared to other micromachining techniques, with a higher resolution. Two photons need to be absorbed almost simultaneously. This is why high intensities are required for this processing method. For this purpose, an ultrashort laser pulse is applied, in the range of femtoseconds with extremely high intensities within the focal region. At specific locations, where the laser beam power density is high enough for two-photon absorption (2PA), the structure locally polymerizes. The material densities of the monomer and the hardened polymer material are almost identical, allowing processing in liquid without any contact to the surface. After the illumination the ambient material is washed out by a developer. Thus, the resulting microstructures freely float in the fluid, if not written with contact to the cover glass. In this context the process generates individual components, which are used by the subsequent process by HOT for assembling into more complex microsystems. 2PP describes the simultaneous absorption of two photons by a molecule, which
thereby is excited into a higher energy state. Due to the low energy of a single photon at the chosen wavelength 780 nm, two photons are required to start the polymerization of the photosensitive material. This chemical reaction, triggered by irradiating with pulsed laser radiation, is utilized in this specific application. To start a 2PP process the energy of the absorbed photons must be equal to the energy between the molecular states, which is described by \( h \) the Planck’s constant and the frequency of the photon’s oscillation \( \nu \).

Within radiation-induced polymerization of the 2PP process, the laser beam is only absorbed within the focus volume and not along the whole beam path. The regions outside the laser focus remain unaffected, because the photore sist only hardens in regions of high laser intensities, where 2PA occurs. The photocrosslinking of the mono- or oligomers is initiated by free-radical photoinitiators. Therefore, hybrid polymers, such as OrmoCore, Femtobond 4B or SU8 are highly suitable for increasing the quantum efficiency of the applied reactive molecules. 2PP bases on the absorption of the energy of two photons by the photoinitiator. 2PP consists of three individual process steps. First, the photoinitiation process absorbs a photon with the energy \( E_{\text{photon}} = h\nu \), resulting in a radical, which is able to initiate a chain reaction. The symbols for the photoinitiation are the photoinitiator \( I \), the radical \( R^- \) and \( I^* \), which is the intermediate state after the absorption of a photon and is described by

\[
I \xrightarrow{hv} I^* \longrightarrow R^- .
\]  

(2.1)

This is followed by a reaction of the radicals with mono- or oligomers \( M \). The resulting chain propagation is given by

\[
R^- + M \longrightarrow RM^- \xrightarrow{M} RMM\ldots \longrightarrow RM_n^- .
\]  

(2.2)

The macromolecule with the number of monomeric or oligomeric units are described by \( M_n \) and \( M_m \), resulting in the termination. This is when two radicals react with one another given by

\[
RM_n^- + RM_m^- \longrightarrow R M_n + R M_m
\]  

(2.3)

Afterwards, the polymerization process is completed by a development process.
A distinction is made in the 2PA in principle between the resonant and non-resonant absorption. In the resonant absorption, it is the first photon energy $\Delta E_1$ which stimulates a temporary intermediate state, followed by the absorption of the second photon energy $\Delta E_2$ given by

$$E = \Delta E_1 + \Delta E_2 = h\nu_1 + h\nu_2$$  \hspace{1cm} (2.4)

The resonant excitation ends at end state $E$, whereas the individual energies do not need to be identical. This is schematically illustrated in Fig. 2.1.

![Diagram](image)

Figure 2.1: Photon energy $\Delta E_1$ stimulating an intermediate state, followed by the absorption of the second photon energy $\Delta E_2$ ending in state $E$. Energy levels given by $E_0$, $E_1$ and $E_2$.

Within the interaction between the absorbing medium and the photon for the realization of a 2PA process, the use of a fs-laser is indispensable. Generated 3D microstructures can subsequently be used to manufacture e.g. interlocking parts for microassemblies. To improve this microprocessing method, 3D structures are optimized in geometrical quality and processing time. For different application examples various writing processes are utilized. Based on the activation of a photosensitive material with laser light, the microstructures are generated with arbitrary shape and any desired geometry.

### 2.1.2 Experimental setup

The utilized 2PP system consists of a Titan Sapphire (Ti:Sa) laser (see Table A.7) with a central wavelength of 780 nm, a pulse duration of 80 fs, and a rep-
etition rate of 82 MHz, pumped by a 532 nm solid-state laser (see Table A.6). For the 2PP writing process a negative-tone photopolymer is used. The wavelength of the chosen Ti:Sa laser is twice the polymerization wavelength of the applied photoresists, which are all highly transparent in the NIR wavelength range.

![Diagram of experimental setup for 2PP with a Ti:Sapphire laser with 780 nm, 82 MHz and 80 fs.](image)

Figure 2.2: A schematic illustration of the experimental setup for 2PP with a Ti:Sapphire laser with 780 nm, 82 MHz and 80 fs.

The power control unit includes a λ/2-plate and a polarizing beam splitter. An acoustooptic modulator (AOM) is used as a shutter. A galvanometer scanner (see Table A.2) is utilized to move the laser beam in the x- and y-direction, whereas the positioning stage (see Table A.3 and A.4) moves the z-axis and the sample. An immersion objective (see A.5) with an numerical aperture (NA) of 1.4 is integrated into this setup to focus the beam into the photoresist. The higher the NA of the objective, the better the resolution of the generated microstructures within the photoresist. The polymerization process is monitored with the aid of a CCD camera (see Table A.1). Schematically the start and end position of the writing process within the photoresist are given by the focus position with a defined distance above the cover slip. A schematic illustration
of the 2PP setup is given by Fig. 2.2.

The non-spherical microstructures are designed in a CAD environment, resulting in a STL file. The file is then imported in the 2PP software algorithm, illustrated by Fig. 2.3.

Figure 2.3: Left: Sliced model of a 3D prism as STL file. Right: CAD file uploaded in 2PP software.

After uploading of the CAD data the micromanufacturing process is started. Thus, 3D microstructures are generated within the photosensitive material, shown (after the development) by Fig. 2.4.

Figure 2.4: SEM image of micromanufactured structure by 2PP.

The first fabrication processes are implemented with a hybrid polymer OrmoCore and the solvent Ormodev. OrmoCore by micro resist technology GmbH (Berlin, Germany) is a UV-curable negative hybrid polymer with a refractive index of 1.543 at 780 nm and belongs to the group of organically
modified ceramics (ORMOCER). OrmoDev is specifically applied for OrmoCore development processes and removes uncured material. However, the volume shrinkage of OrmoCore of 2-5 % results in non-combinable interlocking ports for microstructure assembling. Thus, the more suitable successfully tested negative polymer Femtobond 4B by Laser Zentrum Hannover e.v. (Hannover, Germany) and SU8 by MicroChem Corp. (Massachusetts, United States of America) with the solvents Ormodev and Mr. Dev 600 (solvent based) are implemented after system optimization and tests for all following fabrication processes. The material shrinkage is lower than the shrinkage of OrmoCore. The materials both need to be developed under yellow light conditions, because of its spectral sensitivity to UV exposure and high transparency to visible light. The geometrical voxel size increases with the increasing amount of absorbed laser power, exposure time and a decreasing NA of the objective [SER03]. For a high manufacturing accuracy of the interlocking ports, all processing parameters have to be considered, like the distance between two voxels, the sensitivity of the photoresist as well as the writing speed.

2.2 Optical Manipulation: Holographic Optical Tweezer (HOT)

With reference to the objective to develop an AOMM an OT setup is applied for the manipulation of 3D structures in the micrometer range. In this case a spatial light modulator (SLM) is used for the manipulation process to generate desired light fields and thus to enable the manipulation of non-absorbent complex microstructures e.g. puzzle components for interlocking assembling procedures. To understand the interaction between laser radiation and matter, the following sections describe the physical principles of optical manipulation, as well as momentum transfer within a microcomponent with spherical and non-spherical shape.

2.2.1 Optical forces on microstructures

As a general assumption for all following descriptions the structures to be manipulated will be larger than the laser wavelength. The interaction between
laser light and spherical particles by OTs is well investigated. Especially the optical forces on transparent spherical objects are analytically described in detail. In the 1980s, Arthur Ashkin first trapped spherical objects with optical forces only [ASH+86, ASH70, ASH78, ASH92]. Since its first development, this technology has not only revolutionized many fields of research in cell biology, but also had significant impact in microtechnology. OTs cannot only trap and manipulate spherically shaped microstructures, but also non-spherical microstructures. In the manipulation of non-spherical objects, the basic research for spherical structures can be considered, even though the optical forces model needs to be adjusted to non-spherical microstructures.

To understand the generation of the optical forces, a geometrical optics based model can be applied. Here, each ray can be interpreted as a flow of photons carrying a momentum \( \vec{p} = \hbar \vec{k} \), shown by Fig. 2.5.

![Figure 2.5: Schematic description of radiation pressure: The laser emitted photon flux \( \frac{\partial N}{\partial t} \) results in a force \( \frac{\partial \vec{p}}{\partial t} \) on the matter.](image)

The corresponding energy flow is described by the radiation flux

\[
\phi = \hbar \omega \frac{\partial N}{\partial t}
\]

with the number of photons \( N \). Each photon stream is connected to a momentum flux leading to a force \( \vec{F} \)

\[
\vec{F} = \frac{\partial \vec{p}}{\partial t} = \hbar \vec{k} \frac{\partial N}{\partial t} = \frac{\phi}{\omega} \vec{k} = \frac{n\phi}{c} \vec{k}.
\]
\( \omega \) is the angular frequency, whereas \( \vec{k} \) represents the wave vector and \( \hat{k} \) is a unit vector. When the light ray impinges on the surface of an object, it is partly reflected and refracted. This leads to a change in momentum, and results in a corresponding force

\[
\vec{f} = \frac{n_S \phi_i}{c} \vec{k}_i - \frac{n_S \phi_r}{c} \vec{k}_r - \frac{n_P \phi_t}{c} \vec{k}_t.
\]  
(2.7)

Here, the index \( i \) denotes the incident, \( r \) the reflected and \( t \) the transmitted part. The negative signs of the outgoing parts origins from the fact, that momentum is carried away from the surface, the resulting change in momentum is then opposite to the direction of the ray. The reflected and the transmitted radiation flux are connected to the incident radiation flux by the reflection (\( R \)) and transmission (\( T \)) coefficients, given by

\[
\phi_r = R \phi_i
\]  
(2.8)

and

\[
\phi_t = T \phi_i = (1 - R) \phi_i.
\]  
(2.9)

The coefficient \( R \) can be calculated by use of Fresnel's formulas on reflection and refraction according to the polarization of the electric field

\[
R_\parallel = \frac{\tan^2(\vartheta_i - \vartheta_t)}{\tan^2(\vartheta_i + \vartheta_t)},
\]  
(2.10)

and

\[
R_\perp = \frac{\sin^2(\vartheta_i - \vartheta_t)}{\sin^2(\vartheta_i + \vartheta_t)},
\]  
(2.11)

with the angle of incidence \( \vartheta_i \) and the corresponding angle for the transmitted ray, \( \vartheta_t \) which can easily be derived by Snell's law. Only objects which are large compared to the wavelength are considered. Therefore Fresnel's formulas can be used even though they are strictly valid only for plane waves incident on an infinite plane surface.
Figure 2.6: Optical forces acting on radiation with resulting acting force $F_{\text{sum}}$. Left: Light with a Gaussian intensity distribution impinges on a transparent microsphere. According to the angle of incidence the refraction of the light (given by a and b) at the boundary between surrounding medium and microsphere changes the direction of the light propagation, resulting in a momentum change into the direction of $F_{\text{sum}}$. Right: Light on microsphere with a different angle of incidence, resulting in a different momentum change into the direction of $F_{\text{sum}}$, which acts antagonistic to $F_{\text{sum}}$ with propagation characteristics. If these force effects occur simultaneously, the microsphere is trapped by OT and can be manipulated in three dimensions. Refraction of light interacting with the microsphere is given by beam path a and b.

Each change of a momentum flux leads to a corresponding force. The total force can be subdivided into two parts. The gradients a and b from the refraction (see Fig. 2.6) of the rays at the surface of the particle, which pushes the particle in the direction of the highest intensity. The scattering force, caused by the reflected rays, leads to a light pressure and acts along the beam axis. The force, which is caused by the refraction of the laser beam within the spherical structure, is higher than the force, which is caused by the reflection. As a result the light pushes the particle along the same direction of
the beam. The force component, which pushes the particle into the direction of the propagation of the radiation focus, is higher than the acting force by the inner reflection [DR07]. Thus, the trapping of objects using optical forces is possible only if the gradient force $F_a$ is larger in the axial direction than the scattering force $F_b$ [ZWI10]. Each photon of the laser light has the energy $E_{\text{photon}}$ with the Planck's constant $h$ and the frequency of light $\nu$. The momentum's direction changes as a result of the refraction within the irradiated medium. Following, the forces due to refraction and reflection are shown referred to the gradient forces and acceleration of the particle to the point of its highest intensity. As shown in Fig. 2.6 the center of the irradiated microstructure is marked with the starting point of all acting forces $F_a$, $F_b$ and $F_{\text{sum}}$. According to the entrance angle of the applied objective with a specific NA, the acting force on the microstructure results in $F_{\text{sum}}$. NA is defined as the product of $\sin \Theta$, representing the beam divergence, and the refractive index of the medium between the specimen and the objective.

$$\text{NA} = n \sin \Theta$$  \hspace{1cm} (2.12)

The lateral and axial intensity gradients increase with NA and, therefore the force increases. Monochromatic light is essential, in order to prevent chromatic aberration and thus allow a strong focusing into the polymerized microstructures. As beam profile a Gaussian mode is applied for all manipulation procedures. The Gaussian beam exhibits a rotational symmetrical transversal beam profile and allows a coherent irradiation of the specimen. Such a collimated laser beam is tightly focused, resulting in an optical trap with a focus size $d$.

$$d = \frac{1.22 \lambda}{\text{NA}}$$  \hspace{1cm} (2.13)

The application of a LaGuerre-Gaussian beam enables the manipulation of ring-shaped bodies and enables the trapping of highly reflecting particles. In this case the beam has a donut intensity distribution [ASH70]. Usually, a Gaussian beam is applied for generating optical traps for tweezer applications. Optical forces can be determined by measuring the particle displacement relative to the trap. The beam path through a spherical microstructure is given by Fig. 2.7. Here, spherical microstructures can be utilized as single microspheres.
or spherical trapping ports for microassembly processes. The simulations are realized with exact the same data used for the manufacturing process.

Figure 2.7: Left: Simulation of the ray path within the microsphere. Right: Simulation of the ray path within non-spherical microstructure with spherical ports. This non-spherical microstructure is trapped with two optical traps, which act on the spherical ports of the microstructure.

Optical forces on non-spherical microstructures are calculated equally to the forces and momentum acting on spherical particles. The functions are also based on the gradient and scattering force described above in equations. As can be seen from Fig. 2.8, the path of the rays inside the microstructure strongly depends on the shape and so does the resulting force. Depending on the geometry of the trapped microstructure, torques act on the microstructure, as well as torsion resulting in possible unintentional movements in the direction of the torque. In summary, it can be concluded, that the geometrical shape of a microstructure defines the direction of the acting forces on the non-spherical microstructure. For this reason, the forces can be deduced by assuming the total force density over the whole microstructure without taking a precise force allocation into account [SIM15]. Therefore, the trapping behavior of non-spherical microstructures need to be taken into consideration, regarding its size and direction of the induced forces. Depending on the shape and the laser beam profile, the light is refracted and reflected differently within the non-spherical microstructure, like shown in Fig. 2.8.
2.2.2 Experimental setup

Micromanipulation can be realized by HOT. Here, 2PP-fabricated microstructures, described in the previous chapter, can be introduced, manipulated and assembled to more complex microsystems. For the manipulation and assembling processes, a fiber laser with a wavelength of 1064 nm is applied from Manlight (see Table B.1) with a fiber optical output (collimator connector). By combining an OT setup with a SLM (see Table B.2) any light fields can be generated, thereby the number of traps and the beam profile can be freely selected. The individual optical traps are independently controllable and movable in three dimensions. The laser can be focused to a spot of less than 2μm – 3μm for manipulation processes. The SLM control of the laser beam is based on phase only modulation. By locally changing the phase of the incident laser beam, the light field is modulated and can be used to manipulate the beam profiles. After the modulation of the laser beam, it is reflected by a dichroic mirror into a microscope objective (see Table B.4) with a 100x optical magnification and an NA of 1.45. The beam is focused on trapping (assem-
bling) ports of the microstructure by the objective for further manipulation operations. A detailed description of the single hardware components is given by Fig. 2.9.

![Diagram of the objective setup](image)

**Figure 2.9: Outline of the objective within the experimental setup of the HOT.**

With such an OT setup, it is possible to trap microstructures and manipulate these in the size range of a few nm up to trap pins of complex components. The laser emits a laser beam with a diameter of 2.2 mm, which is expanded to 8.6 mm for an exposure of the narrow edges of the SLM. Afterwards, the laser beam is collimated to 4.3 mm before the entrance into the objective.

The relevant power for manipulation processes is given in Appendix D. It gives the measured power before and behind all mechanical components within the HOT system. The results introduce the optimal manipulation specifications for the applied radiation, which is given in current of 0.1 to 0.4 A, depending on the shape and size of the microstructure. Microstructures with a diameter over 20 µm need higher trapping intensities and thus the current of the laser needs to be at least 0.4 A. All manipulation procedures are implemented with low power of several mW behind the objective. Fig. 2.10 also shows the measuring points of the applied laser power (a-d).

Furthermore, there are several techniques for beam shaping, which are se-
Figure 2.10: Beam expansion and collimation within HOT setup [HEY12]: 1064 nm CW fiber laser, variable beam expander, mirror (M), SLM, lens-

system L1 and L2, dichroic mirror (DM), objective 100x with NA 1.45, stage

and a transmitted white-light illumination source (TL), camera (see Table

B.3), joystick and computer for hologram provision.

lected depending on the application case. Within this work, a phase-only light

der modulator by Holoeve GmbH is utilized. In the following manipulation pro-
cedures, phase modulating devices are applied. Programmable SLMs consist of

a reflective LC on silicon (LCoS) microdisplay with full HD resolution. The

LCoS display basically consists of 7 layers [HEY12], shown in Fig. 2.11.

The glass layer protects the underlying layers, followed by a layer containing

transparent electrodes. The electrical circuit is closed between liquid crystal

(LC) layer and silicon layer. The following LC layer holds the nematic LCs,

embedded within an alignment layer. The liquid allows a polarization change

of the incident light. The alignment of the crystals to modulate the desired

beam profile depend on the applied voltage. Finally, the light intensity is

controlled by this effect. The reflective layer reflects the incoming light and

transmitted light and finally combines the light beams to an hologram. The

silicon layer with transistors modulates the light at its specific pixel on the
Figure 2.11: LCoS display with single layers: 1. Glass layer, 2. Transparent layer, 3. Alignment layer, 4. Liquid crystal layer, 5. Reflective layer, 6. Silicon layer with transistors, 7. Control layer.

LC layer. The higher the voltage on a certain area (pixel), the more light transmits through the LC layer. Thus, voltage-controlled phase modulation is achieved. The individual transistors are addressed by the control layer. LCoS displays allow a local retard of the light wave front by applying a voltage on the pixels. This voltage causes a change of the optical density within the pixel medium, as the containing LC molecules orientate with the imposed electrical field. Each pixel (8 \( \mu \text{m} \)) of such an 0.7" active area device can induce a phase modulation to the irradiated laser light between 0 to 2\( \pi \). The filling factor of the SLM is 87%, which represents the quality and efficiency. Computer-generated holograms (CGH) generate and control multiple traps for simultaneous micromanipulation procedures with tightly focused laser light. For the manipulation of non-spherical parts and digital addressing a gratings and lenses (GL) algorithm is applied for beam modulation, which is a very simple method for the generation of independent controllable laser traps. For a description of the modulated EM fields with a SLM, the properties of EM waves are assumed. Particular algorithms allow calculating the necessary local phase retardation to obtain the desired laser intensity pattern. HOT are able to trap microstructures simultaneously by such modulated light fields. Additionally to the trapping of multiple particles, HOTs also offer the control of non-transparent structures by generating beam shapes different from
the Gaussian beam. For instance, doughnut shaped beam profiles can be applied to trap reflecting structures, which otherwise would be pushed out of the beam center, when using a simple Gaussian profile. In contrast to other optical manipulation techniques, HOTs also enable the generation of traps in the 3D plane, while scanning techniques only allow for planar arrangements of traps. The holographic diffraction in HOTs, allows the 3D manipulation of trapped preassemblies of spherical or non-spherical shape, whereas the annual beam only 2D manipulation. Thus, spherical particles and non-spherical 2PP microstructures can be trapped without damaging the surface or the inside of the microparts. The conventional setup of a simple OT with a laser allows the creation of one or two traps.
Chapter 3

Optical Assembling

3.1 Assembling of spherical microstructures

Different assembling techniques for spherical microstructures are reported in the literature [GHA+12, GHA14, GLU+13, GLU14, GRI+06]. Previous researches successfully demonstrate, that HOT can be used as a powerful tool in different fields of engineering with applications both as force actuator and sensor, as well as microfabrication tool for planar, 3D and hybrid microstructures made of spherical microstructures. Thermal and photothermal induced melting assemblies, as well as biochemical assembling technologies were used for generating arbitrary spherical structures in desired quantities. Biochemical or melting based assembling technologies without disassembling characteristics have already been analyzed and implemented within the fabrication and manipulation systems in previous researches [GHA14]. Thus, previous investigations and the results of the developments only deal with biochemical connectable microspheres, which have the key advantage of being easy to trap with optical tools and are much easier to manipulate and assemble because of their spherical shape, than non-spherical microstructures. Up to that point, the assembling process of 3D complex or even complementary microstructures is entirely unexplored, but would of course lead to new applications in microrobotic development, MEMS technologies and microprocessing in general. Microstructures with spherical shape cannot be disassembled because of their permanent binding affinity. Thus, spherical coated particles are joined by HOT and stably connected by use of streptavidin biotin (SB) interactions.
This biochemical approach exploits the high affinity between SB, which is the strongest non-covalent binding. Therefore, purchased SB-coated microspheres are applied for 3D assembling processes within HOT processes. The particle binding through reactive coating, which is the strongest non-covalent binding with a force of >100 pN, is generated by a thin particle coating layer of 10 nm. Until now only biochemical assembling technologies with permanent assembling results are applied. This assembling technology is appropriate for structuring chains of microspheres e.g. for assembling microrotors consisting of microspheres. This joining technology has no disassembling characteristics. Such hybrid structures, like magnetic structures can be manipulated by HOT, as well as actuated by setting up an external magnetic field for generation of a laminar fluid flow. Microrotors are generated with magnetic actuation [GHA14]. The electromagnets are installed around the probe to induce the alternating magnetic field. The microrotor experiences the magnetic actuation by the alternating field and reacts with a rotational movement of the assembled microsystem. Microfluidic system are generated in different ways e.g. biochemical assembling technologies for microspheres [KOE+14, KOE+14_2]. Nevertheless, this biochemical assembling method has its limits. A disadvantage is, that 3D microstructures cannot be disassembled, because the used optical forces are not strong enough. Using light to control liquid motion is a new paradigm for the actuation of microfluidic systems. The different principles and strategies to induce or control liquid motion using light include the use of radiation pressure. This approach is done to control using light for many kinds of microfluidic operations and can be used to sort or control fluid flows in microchannels. A generation of complex microsystems by assembling spherical structures using biochemical coatings is the basis of all previous developments without disassembling characteristics. Thus, the manufacturing of complex microsystems applying spherical microspheres is limited.

3.2 Assembling of non-spherical microstructures

Previous works solely deal with permanent assembling utilizing biocompatible microstructures with spherical shape. The experimental results for the assembling and manipulation processes for non-spherical microstructures apply
SLA processing techniques for microstructure microfabrication and use spherical binding ports as connection between the single microstructures [GLU+13]. But to realize microrobotics in e.g. medical technology non-permanent assembling methods are required. Therefore, a suitable micromanipulation technique with an appropriate binding method is required to join non-spherical microstructures complementary and stable even if the laser source is switched off, but also a separation of the assembled microstructures has to be possible if necessary e.g. for replacement of defective microstructures within chain-like microsystems. Therefore, photopolymerization is suitable for generation of such non-permanent bindings with high stability.

3.2.1 Assembling technique for microstructures with spherical ports

The generation of complementary shaped microstructures serves to the implementation of a reversible assembling technology. Spherical ports are often integrated into complex shaped microstructures for simple optical trapping, because trapping characteristics of spheres are well known. 3D non-spherical microstructures written by 2PP have to be trapped each with multiple spots. Hence, complex shaped 2PP-microstructures need a different handling, e.g. specific beam shaped profiles for arbitrary alignment and movement of the microstructures. Different techniques were developed and validated in the setup of the OT by Glückstad [GLU+13]. Laser-based process manufactures specific shaped microstructures with spherical ports and spherical complementary characteristics. The use of spherical ports simplifies the handling of the structures and is realized by utilizing the beam profile, such as the Gaussian beam profile. By trapping spherical ports, which are trapped analog to spherical particles, there is no beam modulation required to realize trapping and assembling. Glückstad realized a reconfigurable microsystem, manufactured with stable mechanical assemblies using optical traps and 2PP produced structures. Complementary components are linked over dumbbell-like connecting elements as interlocking structures. Fig. 3.1 shows the generated interlocking microstructures. The spherical ending ports, which are trapped by multiple OTs, are applied as connecting elements. With this, temporary interlocking
assembling, as well as disassembling is possible at any time.

![Microstructures written by 2PP, using spherical ports. The dumbbell-ports are joint permanent for assembling and disassembling procedures. (a) Trapping of microstructure and dumbbell with spherical ports. (b) Alignment of trapped microstructures. (c) Assembling of dumbbell. (d) Movement of microsystem 16 traps [GLU+13].](image)

The manipulation procedures are realized with the utilization of counter propagating (CP) beams, which allow a control of microstructures in all directions, as well as a rapid interlinkage of all components. Further, the alignment of the entire assembly is possible. With this approach, a mechanically stable system is produced, which can easily be disassembled and reconfigured. This method requires a much higher quantity of the desired microstructures, because of a very complex and time-consuming writing and relocation of the produced microstructures within 2PP processing.

### 3.2.2 Assembling technique for microstructures without spherical ports

Assembling microstructures without spherical ports has theoretically been analyzed in previous researches by using interlocking shaped microstructures. Therefore, releasable microstructures are fabricated by 2PP for HOT manipulations utilizing spatial light modulators. Kim et al. published these results for manipulation of microstructures by applying a microtip within the HOT process [KIM13]. This method necessitates a microtip to release the microstructures from the surface to receive freely movable microstructures within the solvent. This strategy avoids relocation problems of the generated structures.
in the fluid. The microrings can be moved afterwards with multiple traps. The whole assembling process is completed by positioning the microring on a complementary microrod by applying the microtip as fixation tool for this assembling process. In this approach, a different number of optical traps control the alignment for the manipulation process of the microring on the microrod. This is realized by two optical traps, whereas the microgear assembling is implemented by four optical traps on the tiny microrod, given by Fig. 3.2 [KIM13].

![Diagram of manipulation procedures applying a microtip for releasing microstructures from glass substrate](image)

Figure 3.2: Schematic illustration of the manipulation procedures applying a microtip for releasing the microstructures from the glass substrate [KIM13].

To avoid relocation problems of the generated structures in the fluid, the manipulative microrings are manufactured directly on the glass substrate. Alignment verification is shown by rotating the assembled micro-gear with a single trap on the microrod.

Fig. 3.3 illustrates the experimental system [KIM13]. Additional SB coatings are used to remove unwanted adhesion of the microstructures on the glass substrate and to prevent, that the single microstructures stick together. Non-spherical complex structures such as e.g. manipulative microrings require, multiple optical traps or the use of non-Gaussian beams to realize trapping for translative or rotating movement [KIM13]. Kim et al. apply LaGuerre-Gaussian (LG) beams for all manipulation processes and utilize a mechanical microtip. Hence, this system does not work with optical tools only. Fur-
Figure 3.3: Schematic diagram of the manipulator and side view of the system, as well as composition of the microtip, inverted objective lens and side objective lens on the sample plane [KIM13].

Furthermore, this method of assembling has no disassembling possibility, not only because of the SB doping, but also because of the non-interlocking shape of the structures. Besides provision and storage of the microstructures for assembly processes, a multiple quantity of different microstructures needs to be realized. With these research results, the problem still remains the same, because of a non-stable configuration. The freely movable microgears could be lifted up by the developer so that a relocation of the microstructures is not possible.

### 3.2.3 Storage and transport of complementary microstructures

First research results, for a relocalization of 2PP generated components, as well as a basic idea for storing 3D structures, was developed in 2012 [KIM12]. This
kind of modular system has been implemented containing structures stored as single elements in boxes. The use of multiple optical traps is essential again in this type of storage solution. Here, stockpiling of microstructures is shown theoretically, but was not realized in practical experiments. However, this modular system is available only on the retention in separated compartments, thus always requires multiple optical traps for the transportation from the components to the assembling area. The idea of placing the manipulative microstructures into separated boxes is shown in Fig. 3.4 below. Here, specific U-shaped structures are generated theoretically and stored within the manipulation platform.

Figure 3.4: Storage ideas based on Kim et. al 2012. Left: (a) Microstructures. (b) Manipulation platform. (c) Storage for assembled microsystems. Right: Previous storage solution ideas for microstructures: (a) shows the initial state of the 2PP-generated microstructures: Respective components in boxes. (b) illustrates the removal of a components and its placing on the manipulation platform. (c) deals with the manipulation of two components. (d) shows the final state after the manipulation [KIM12].
Chapter 4

Optical Micromachining Tool (OMMT)

4.1 Process flow

Manufacturing of complex microsystems also necessitates specific assembling techniques. Special interlocking microstructures can provide movable connectivity. The introduced assembling methodology works without mechanical impact on single microstructures. Thus, a high surface quality for interlocking parts with low roughness is inevitable for such assembling procedures with optical tools. For this purpose, fabrication by 2PP and manipulation by HOTs are combined appropriately. Furthermore, the new assembling technology is implemented to enable a temporary assembling of microstructures to enhance permanent assembling of microstructures. This process can comply the need to manufacture hybrid multi functional assemblies by combining different materials for future applications. Therefore, a new production technology resulting in an OMMT with the following capabilities is developed:

- fabrication method for microsystems engineering
- contactless manipulation (and thus free of any adhesion effects)
- chemical development process for dispersed polymeric microstructures
- storage of microstructures
- transport of microstructures into manipulation system
• assembling of microstructures

• disassembling of microstructures

Schematically, the complete process chain from fabrication of microstructures to assembling of these elements is shown in Fig. 4.1, including transport, storage, as well as the assembling processes.

Figure 4.1: Theoretical process flow of optical micromachining tool with fabrication, transport, storage, transport to the assembling area and assembling of the microstructures.

The new optical manufacturing technique is based on the integration of two technical installations. The HOT offers a tool for a very precise and contact free manipulation of tiny objects. The 2PP technology provides a flexible method for the production of individual, arbitrary shaped microstructures. For movable parts, corresponding interlocking connections have to be developed. Particular attention has to be payed on the post fabrication process. The cleaning of microstructures after the fabrication process for dispersed microstructures is e.g. with a specific solvent, explained within the following investigations. Different solvents have already been proven feasible for this application.

Transport from the fabrication process into the assembling and joining process are controlled by manual joystick operation. The processes combine storage and stocking inside of compartments, so that the second transport can be eliminated. This also reduces the process time. The storage solution, as well as the transfer method for the microstructures are analyzed in detail within the following chapters. Optical conveyor belts as transfer tweezers are not
taken into consideration. Furthermore, it has to be noted that all transport procedures must keep the functionality of the microstructures and shall not adversely affect their quality. To establish the requirements for the system a theoretical analysis of the optical micromachining tool has to be done. Fig. 4.2 includes the state of the art, as well as the main concept, which is to be investigated on a feasible assembling methodology for interlocking microstructures. Fabrication of non-spherical microstructures in combination with an manual transport is minimal required. A storage solution has to realize not only supply, piling, but also moving and organizing of non-spherical microstructures. The assembling solution for non-spherical microstructures has to be able to assemble not only 2D microelements, like puzzle jigsaws, but also 3D more complex microstructures with non-spherical assembling ports. Therefore, complementary assembly of these microstructures is utilized. Applying complementary microstructures offers the possibility to release assembled microsystems in a disassembly process.

Figure 4.2: General description of all processes for the developed main processes fabrication, transport, storage and assembling including all sub functions, needed to be analyzed and solved within the analysis of the following investigations.
All necessary processes and junctions for the implementation of the integral process chain are given. The entire analysis and researches deal with non-spherical microfabrication processes. Storage of microstructures is to be realized for supplying, piling, moving and organizing of microstructures, generated within the 2PP procedure. Finally, an assembling method for interlocking microstructures is to be implemented for 2D and 3D assembling of non-spherical complex microstructures. It also has to be taken into consideration, that a positive side effect, which is the possible disassembling of microstructures, can give this research another unique selling proposition.

4.2 Generative Micromanufacturing (GMM)

Optical microrobotics have growing impact as a basis for all-optical workstations where spherical and non-spherical microstructures are to be generated, trapped, manipulated, and assembled in one process. Therefore, the developed processes are optimized and described in the following sections. An application example for organizing interlocking components and storage of microstructures is investigated with the intention to shorten the processing time of the tiny microstructures and their storage systems.

4.2.1 Sample preparation

This section describes the sample preparation. A drop of Femtobond 4B is given on a cover glass, which a glass thickness of approximately 130-160 μm. A prebake process is done for at least 30 minutes at 60 °C. The prebake process is indispensable to evaporate the solvent and thus to reduce the shrinkage of the utilized resin. Fig. 4.3 illustrates the prebake process of Femtobond 4B on glass substrate. After the prebake process, the immersion oil (Immersol 518 N by Carl Zeiss Microscopy GmbH) is applied on the other side of the glass substrate, so that the probe can now be rotated by 180° to place the substrate with the Femtobond 4B drop on the sample holder for the 2PP fabrication process. After the preparation the sample is clamped into the operating area. It should be taken into account that the resin drop needs to be located on the bottom side of the glass substrate.
Figure 4.3: Left: Prebake process of Femtobond 4B drop on glass substrate. Hotplate temperature is 60°C for approximately 30 minutes. Right: Glass substrate with Femtobond 4B drop is placed on 2PP sample holder within fabrication process.

The laser is then focused into the resin with a distance of 2-3 µm above the glass substrate to generate microstructures with freely movement characteristics. Consequently, the microstructures can be developed with an appropriate solvent and, if always kept in fluid, being used as dispersed microstructures for a vertical, horizontal or rotational alignment, as well as full 3D control.

4.2.2 Fabrication of interlocking microstructures

In initial experiments, microstructures are generated with 3D shape in order to analyze how complex structures can be trapped, manipulated, assembled and disassembled. The difference compared to spherical structures is emphasized, because non-spherical interlocking microstructures are not available for purchase. Until now, complex elements are joined by utilizing biochemical bonding techniques or by applying thermal connectivity treatments without disassembling possibilities. The microstructures are therefore generated from a STL file programmed within a specific CAD tool, shown by Fig. 4.4. Exemplary, complex test components for accuracy investigations are shown below.

Figure 4.4: Variety of 3D test microstructures, which are utilized for repeatability and quality characteristic tests [MAT14, KUE15].
Microstructures generated for scanning electron microscope (SEM) analysis are written directly on the substrate surface. Fig. 4.5 shows complex 3D components generated as application examples and tested on its complementary assembling capabilities and assembling quality.

![Microscopic analysis of complementary microstructures written by 2PP for manipulation processes with HOT [KUE15].](image)

The distance to the cover glass needs to be taken into account, because levitated elements can only be manipulated, when their surfaces have no direct contact to the glass surface, because of adhesion effects. The structures, produced within the resin are built layer by layer in a 2PP bottom-up procedure. Afterwards, the fabricated microstructures are available dispersed inside the solvent, like shown in Fig. 4.6. This fabrication process results in an efficient and writing process tool for freely floating microstructures.

### 4.2.3 Alternating and linear writing method

The combination of microfabrication by 2PP and assembling by HOTs offers numerous advantages and capabilities for microprocessing of complex microsystems. High manufacturing accuracy and quality is crucial to assemble two microstructures. Analysis with the alternating writing (AW) method is implemented (see appendix C.2) for investigating the positive effect on the edge quality of the written microstructures. Within the following investigations, micron sized microstructures are written with two different writing techniques for
Figure 4.6: (a-b) SEM analysis of developed complementary microstructures written by 2PP for manipulation processes with HOT [KUE15].

achieving a higher shape quality and thus a better matching accuracy for the following manipulation and assembling steps within the HOT setup. AW requires STL files sliced into layers and organized into an alternating order. This process turned out to be very time-consuming, which is why an automated solution was needed. Within the 2PP algorithm first the center position of the layer is calculated. After this calculation the objects can be written into the resin. Thus, a time counter for a controlled hardening process of the microstructures within the photoresist, calculates the current layer thickness. After a successful fabrication of one layer, the next layer is generated. The algorithm adjusts the objects writing function, so all other functions of the existing program can still be used completely. Thus, the quality of the more complex interlocking structures is improved substantially for precise assembling by HOTs. For the optimization of the structure quality of the microstructure surface, different writing processes are analyzed, along with the linear and alternating procedures. As a consequence of the fabrication of components within the resin with a distance between the structure and the cover glass surface, the quality of the microstructures is worse compared to those microstructures, which are written directly on the surface. With this alternating processing it is possible to find a remedy for shape quality variations in comparison to the CAD data. The peculiarity of these 2PP components is their interlocking shape, which offers the possibility of joining them in a HOT process. The modular
design of the microstructures and the diversity of enhancement options offer numerous capabilities to combine these structures to very long chains in 3D plane. Furthermore, several parameters for 2PP manufacturing, such as laser power, distance of the single layers, which is the so-called hatch, is compared within runtime investigations. Above all, the sequence of the writing process is important to realize a high manufacturing accuracy of interlocking 2PP components. An AW process of the single layers is more effective and leads to high quality 2PP structure. An linear or aligned writing process, leads to a lateral deformation of the whole microstructure and thus a deterioration of the 3D structure quality. The 2PP parameters for the generation of dispersed microstructures require specifications like the quantity (number) of layers, layer thickness, edge length, as well as writing options like contour and filling of the layers. The linear writing (LW) method is analyzed by writing microstructures into the photosensitive material (see appendix C.1), rinsed with the suitable solvent Ormodev and 2% of the surface-active agent. The dispersed specimen is enhanced for the alternating and linear writing process, which are the above mentioned hatch and the layer sequence of the 2PP structures. The higher the quality of the microstructures, the better the matching accuracy for all manipulation and assembling experiments. The central layer is written first, all of the following layers are written alternately on top and below the central layer, until the full thickness is fabricated for both the linear and alternating writing method. A fixed element (mounting) in combination with a dispersed component (T-bar) is written in a 2PP process, for comparison of linear and alternating writing procedures. Fig. 4.7 illustrates a comparison of both structures with their different shape qualities. 2PP structures with a pivot axis e.g. are written with unintended convex deformations, whereas structures with a laser power of 20 mW and writing speed of 1.8 m s⁻¹ are written with a better quality, when utilizing the AW.
Table 4.1: Writing parameters for linear and alternating writing method of dispersed structures with T-bar shape.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>writing speed</td>
<td>1.6 m s(^{-1})-2.2 m s(^{-1})</td>
</tr>
<tr>
<td>power</td>
<td>16 mW-24 mW</td>
</tr>
<tr>
<td>layer thickness</td>
<td>0.05(\mu)m-1(\mu)m</td>
</tr>
<tr>
<td>filling</td>
<td>(x/y)</td>
</tr>
<tr>
<td>writing distance (x)-direction</td>
<td>0.1 (\mu)m</td>
</tr>
<tr>
<td>writing distance (y)-direction</td>
<td>0.1 (\mu)m</td>
</tr>
</tbody>
</table>

Figure 4.7: Left: LW sequence. The quality of both structures (a+c) is compared because of their different shape quality. (a-b): 2PP structure with a pivot axis which is written with a length of 43\(\mu\)m, showing unintended convex deformations. (c-d): Optimized structure written with the AW. The central layer is written in a first step and subsequent layers are written alternating, i.e. one layer above and the next layer below the central layer, until the full thickness is achieved. It is shown that the layer sequence is important for a high quality. Right: AW sequence.

All samples are generated with varying writing parameters for both the linear and alternating processing with a writing speed of 1.6, 1.7, 1.8, 1.9, 2.0, 2.1 and 2.2 m s\(^{-1}\), as well as varying writing intensities starting with 16 mW in single steps up to 24 mW. The layer thickness is adjusted in the same way, starting with 0.05, 0.1, 0.5. up to 1.0 \(\mu\)m.

Comparing linear and alternating writing of non-spherical microstructures leads to the following results. Identical microstructures are generated in vertical and horizontal orientation within the resin, because high aspect ratio microstructures are produced rather inaccurate in general. These manufacturing inaccuracies depend on the process flow, which is analyzed by changing
the fabrication orientation. Vertical linear written microstructures structures have a clear contour and a very good reproducible structure quality. However, the edges of the dispersed microstructure are rounded in z-direction. Whereas, alternately generated structures reveal contrasting properties, resulting in very straight edges. The x/y-edges are fabricated with a very poor quality utilizing alternating writing procedures, due to the manufacturing precision of the scanner within the 2PP process.

4.2.4 Quality optimization for linear writing method

Non-spherical components are fabricated in Fentobond 4B and SU8. In practical applications the polynomial runtime needs to be considered for a successful process. In the following experiments, considering only the highest exponent, the runtime depends on the number of layers (n) as well as the waiting time (t), which is the time between the fabrication of two single layers within 2PP processing. When a 3D structure is generated linearly, the stage proceeds incrementally with a constant time t between the generated layers. The runtime for n layers is the product of time t and layers n. A calculation for an alternating polymerization process is more complex, because the waiting time increases with every single written layer. The waiting time can therefore be calculated by:

$$\sum_{i=0}^{n-1} i \cdot t = \frac{n^2 - n}{2} \cdot t. \quad (4.1)$$

Though, a linear time development is essential, because a quadratic development of the processing time would have a contra-productive effect on the processing time. When doubling the number of layers, the time increases four-fold, so that a very long processing time arises. Between the generations of two layers, a short specific processing stop is inserted. In that way, the sample table is adapted more precisely. The result of the tests with additional time intervals makes clear, that with increasing length of the intervals, manufacturing defects by LW, like in 4.7 (left), get smaller or disappear completely.

These result suggest to use time interval adaptations not only in the AW processes, but also to analyze the shown behavior for a LW process, where the structures are written in an aligned process. Additionally, the microstructure
Table 4.2: Optimal writing parameters for combined dispersed and fixed microstructures in one processing for a simultaneous fabrication.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>writing speed</td>
<td>1.8 m s$^{-1}$</td>
</tr>
<tr>
<td>power</td>
<td>20 mW</td>
</tr>
<tr>
<td>layer thickness</td>
<td>0.1 μm</td>
</tr>
<tr>
<td>filling</td>
<td>$x/y$</td>
</tr>
<tr>
<td>writing distance x-direction</td>
<td>0.1 μm</td>
</tr>
<tr>
<td>writing distance y-direction</td>
<td>0.1 μm</td>
</tr>
</tbody>
</table>

quality is improved by the implemented time interval. This can be noticed by the fact, that rounding at the bottom of the microstructure is reduced. These results are reproducible, resulting in a stable fabrication process. With a rising time interval between fabrication of the single layers the polymerized structures quality is enhanced, as well as the contour of the microstructure. This additional interval is added within the 2PP programming for linear fabrication procedures. Furthermore, edge roundings are eliminated. Polymerization without edge roundings is possible with enhanced quality of the structure by AW. This process indicates an mechanism within the control software of the 2PP process. The communication between galvo scanner and piezo stage can be controlled. Microstructures fabricated along the z-axis are generated almost identical to the uploaded STL file. Microstructures which are written in x- and y-plane are fabricated 14% clinched compared to the STL master file. By shortening all objects written in z-axis about 14%, the 2PP fabrication process is adjusted to the interacting piezo stage and galvo scanner, so that all microstructures can be fabricated proportionally. This is realized by integrating a scale factor into the 2PP control software. Thus, also rotational alignment is simplified and an adaptation of the single axis is substituted.

The following analysis shows, that the linear fabrication of dispersed microstructures is preferable to AW. Furthermore, the three items are generated simultaneous. Therefore, a STL file is created instead of three separate files. Fabrication of vertical generated microstructures still shows excesses and unintended deformations, so that vertical fabrication of linear microstructures is
inapplicable for fabrication of dispersed elements. Solely the mountings, which represent the fixed 2PP element, are polymerized clearly without deformations. Further experiments have shown, that the generated microstructures can differ depending on its point of origin within the CAD model.

![Image](image.png)

Figure 4.8: (a) Vertically generated microstructures in general show deformations. (b) Horizontally written microstructures exhibit a rounding at the bottom of the movable element, which shows the anisotropy of the generated microstructures in 2PP processing [BOE16].

The anisotropy of microstructures generated by 2PP processing necessitates a program adaptation. Therefore, the waiting time is adapted to the processing conditions (see Appendix C.). After comparing linear and alternate writing performance further parameters are analyzed like the dynamic waiting period for the alternate writing processing (see appendix C.3). Previous experiments have shown, that a waiting time of 1000 ms between each layer can be assumed as a good orientation for alternate writing of microstructures. As an example the T-bar structure is built by 500 single layers. Thus, the waiting time starts with 2 ms increasing by 2 ms per layer, so that the waiting period is 2, 4, 6, 8, ..., and 1000 ms respectively in the end of the T-bar processing. Further experiments with waiting periods of 5 ms per layer starting with 5 ms via 10, 15 ms up to 2500 ms, respectively, per layer have been carried out to investigate, if the waiting period between the single layers has an effect on the structure quality.

These results show that the layer sequence is important for getting a high quality. Therefore, optimal writing parameters for dispersed microstructures are chosen, as can be see in Tab. 4.2. These parameters can be considered for both writing techniques, alternating and linear procedures for low aspect ratio and for high aspect ratio. Previous calculations and settings result in
an enhancement of the microstructures quality by implementing the optimal
waiting period (see appendix C.4 and C.5). The sample quality is improved
with 100 ms latency for a 100 nm film thickness (as test layer for Femtobond 4B
and SU8 photoresists). With this calculation, the latency for 2PP processing
of microstructure for arbitrary layer thickness is defined. Subsequently, the
latency per micron can be specified, along with the latency per layer thickness
L, which is

\[
\frac{100 \text{ ms}}{100 \text{ nm}} \cdot L = 1 \text{s} \mu\text{m}^{-1} \cdot L. \tag{4.2}
\]

From this, the total processing time \( t_p \) is given, depending on the number
of layers \( n \), by

\[
t_p = 1 \text{s} \mu\text{m}^{-1} \cdot L \cdot n. \tag{4.3}
\]

Vertically and horizontally written dispersed microstructures (T-bar) in
combination with fixed microparts (mounting), shown in Fig. 4.9, need to
be analyzed for a selection of an appropriate alignment for the CAD files for
2PP manufacturing.

![Figure 4.9: Left: Horizontally written T-bar. Right: Vertically written T-bar [MAT14].](image)

As an application example for fabricated fixed and dispersed microstructures
the mountings with a width of 48 \( \mu \text{m} \) and the dispersed T-bar with a length of
50 \( \mu \text{m} \) are written by 2PP and measured with a SEM.

Further system optimizations for 2PP are implemented by introducing the
algorithm adaptations for vertically and horizontally fabricated dispersed mi-
crostructures. A deviating layer thicknesses results in 14% smaller microstruc-
tures, according to its writing direction in z-direction, but must only be taken
Figure 4.10: Comparison of vertically fabricated microstructures generated by 2PP processing measured for 2PP program adaptations. (a-b) Structure oriented vertical (parallel to the z-plane) with same parameters. (c-d) Microstructure fabricated in horizontal (parallel to xy-plane) alignment [BOE16].

into consideration for high aspect ratio structures. Thus, the real dimensions of the fabricated microstructures deviate from nominal dimensions. A algorithm is adjusted by a reduction in z-alignment to 86 % to generate accurate geometric objects in accordance with the designed specifications.
4.3 Transfer of microstructures

2PP-generated microstructures need to be transferred or conveyed into the OT setup. The integration of the 2PP structure into the OT setup is realized by developing the structure in the 2PP installation and then manually transfer the microstructures in the solvent to the manipulation process. As a result, the 2PP microstructures are dispersed in the solvent solution. It is helpful to generate more than just one microstructure within the photoresist, but rather 10-20 microstructures, so the structures are easier to be found in the solvent liquid. Furthermore, it is inevitable to define the quantity of the liquid in μL, so that it can be completely poured into the manipulation area of the OT system. The liquid, containing the generated 3D structures, is depleted in the manipulation area of the HOT for all following processes. The developed 2PP pattern is taken from the test tube and positioned on the cover slip for manipulation and assembly reasons. Another cover slip covers the manipulation area for the following OT process. The entire process flow for processing without compartments using Femtobond 4B is illustrated in Fig. 4.11.

![Fig. 4.11](image.png)

Figure 4.11: Entire process flow for processing without compartments with Femtobond 4B. The process starts (a) by applying of the resin to the glass substrate holder. The prebake process (b) of the resist is followed by (c) the fabrication process with exposure of the resin. (d) comprises the cutting of the glass substrate with a glass cutter for inducing the cover glass into the solvent which carries the 2PP microstructures. The solvent containing the 3D microstructures (e) is transported into the HOT process with a pipet directly. After awaiting the specific developing time (f) the manipulation process is started. Assembled microstructures (g) are now available within the liquid solvent.
After the 2PP fabrication process the cover glass with the microstructures written into the resin is developed and the fluid is transported with a pipette into the OT setup. To close the sample chamber, containing dispersed microstructures, a 20 mm × 20 mm glass is applied on the top of the sample chamber. In the following, the microstructures within the solvent can be moved and assembled by HOTs for approximately 3 weeks until the elements descend and stay fixed to the cover glass surface. This manipulation time could be increased by applying a surface-active agent.

4.4 Storage of dispersed microstructures

Manipulation of microstructures in general requires dispersed microstructures. Thus, after the development process the microstructures have to be available dispersed inside the solvent. The relocation of the microstructures is very time-consuming, if the microstructures are not even rinsed out completely of the manipulation area. Relocation of dispersed microstructures is one of the challenging tasks, regarding an efficient microassembling process. Thus, surrounding compartments must keep the microstructures in its defined volume for a rapid relocation of the elements inside the solvent. Furthermore, any mechanical microtip [KIM13] can be replaced by this approach.

4.4.1 Storage in separated compartments

A key challenge was, among the development and stockholding transfer, the installation and storage unit of the system. First examinations by writing microstructures directly into the resin, without any surrounding compartments or relocation possibilities, result in significant losses of microstructures. The microstructures cannot be relocated after the developing process within the large solvent volume. Thus, freely floating microstructures are removed with a pipet in the solvent, so that a later relocation of the structures only works in very rare cases. This makes this kind of structuring without storing compartments to a very ineffective and irreproducible method of microstructure fabrication for OT manipulation procedures. Consequently, a storage system or storage unit for the microstructures has to be developed, which not only offers the possibility of keeping generated dispersed microstructures inside, but
especially simplifies the relocalization of the multiple microstructures. Relocalization is possible utilizing storage systems with separated compartments, shown in Fig. 4.12. Due to the small size of the microstructures in relation to the perforated compartment, the microstructures cannot be fabricated directly within the resin, as they cannot be detected or they may completely washed away during the development process. Time-consuming relocalization and the detection of very few microstructures inside the solvent lead to the idea of fabricating compartments containing interior dispersed microstructures.

![Diagrams](image)

Figure 4.12: (a-c) First CAD models and validation within a HOT setup for the generation of provisioning of microstructures using separated compartments [PRU14].

The provisioning of different microstructures is implemented by fabricating the desired microstructures directly within the storage compartments. Therefore, sufficient space within the storage compartments is essential for assembling procedures with HOTs. Thus, if a number of about 10 microstructures is written into the photosensitive material at a distance of 2μm to the cover glass inside such compartments facilitates the detection or relocalization immensely. The design of such complex storage systems is presented within the following illustration. Time-consuming processing about 6 hours for each compartment shows the drawback of such complex storage chambers. The assembly platform comprises three separated compartments, each is perforated. Without perforating the compartment, a development of interior microstructures is not possible. First experiments show a very low quality of the microstructures
and the surrounding compartments. For an optimal 2PP writing processing all parameters like power, scan speed and thickness of the microstructures need to be analyzed more precisely. Support struts, like shown in Fig. 4.13, might be eliminated by parameter optimizations.

![Image of microstructures](image.png)

Figure 4.13: (a) Interior microstructures within the compartment separated by floatgates. (b) Defects in the form of support struts. The larger the microstructure, the more support struts occur.

The following table introduces all necessary parameters for microfabrication of surrounding compartments and interior microstructures. For a realization of high quality microstructures written inside the storage systems the repeatability of the structure quality is analyzed by the following parameter studies. The best structure quality can be achieved with a laser power of 1.8 mW and a scan speed of 20μm s⁻¹, with a layer thickness of 0.1μm, but a x+y filling and contour. Using these parameters the assembling platform can be written on the cover glass including, in this example, the applied 2PP microrings dispersed in the solvent. The perforation of the storage compartment permits the solvent to flow into the interior of the compartment to chemically develop the 2PP microstructures inside the compartment. After the development of the pattern and the 2PP structure sedimentation process, the modular assembling platform is integrated in our OT system for further manipulation processes. As a result, platform generated microstructures are available in separated chambers in multiple quantity for HOT manipulations or assembling. Fig. 4.14 also shows a SEM image and different microscopic views to illustrate the operation compartment and the containing interlocking 2PP microstructures.
Table 4.3: Optimal writing parameters for linear writing procedures for 3D dispersed microstructures for HOT manipulation processes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>writing speed</td>
<td>1.8 m s⁻¹</td>
</tr>
<tr>
<td>power</td>
<td>20 mW</td>
</tr>
<tr>
<td>layer thickness</td>
<td>0.1 μm</td>
</tr>
<tr>
<td>filling</td>
<td>x + y</td>
</tr>
<tr>
<td>writing distance x-direction</td>
<td>0.1 μm</td>
</tr>
<tr>
<td>writing distance y-direction</td>
<td>0.1 μm</td>
</tr>
</tbody>
</table>

Figure 4.14: (a) SEM image of the assembling platform, containing 2PP microstructures. (b) Shape of the storage compartment (20x optical magnification). (c) Storage compartment with floodgate (20x optical magnification). (d) Microscopic picture of the operation compartment with 2PP components separated by the floodgate and one assembled structure in the center without covering by way of illustration (20x optical magnification). (e) Assembling area (white triangle) generated within a 2PP manufacturing process (100x optical magnification) [KSO+13_2].

Another example, see Fig. 4.15 (a-h) shows also the compartment containing microstructures, which are trapped and moved from the chamber to the assembling area. The transportation of the ring-shaped microstructures is realized by utilizing a two trap 10 mW tweezer. The single 2PP microstructures can also be rotated at an angle of 90° by using one trap, so that the structures can be viewed from the front.

For multiple traps, a SLM is applied for rotation and alignment of the microstructure, which is described in the following sections. Utilizing these kinds of assembly platforms as transfer and storage method for individual mi-
First manipulation experiments within compartments of generated 3D structures (white circle): Moving of one particle from the left bottom compartment to the left top compartment is shown (a-h) (all 100x optical magnification) [KSO+13_2].

Microstructures optimizes the whole process and minimizes the processing times. This method is transferable into a miniaturized demonstrator for future industrial usage. The laser beam can usually be seen after switching on the laser light for manipulation procedures of the structures with the optical traps. The perforation layer on top of the storage compartment changes the appearance of the laser beam, so that the focus appears unclear. Herein, the microrings are trapped by using a Gaussian beam. These first experiments with dispersed microstructures within relocalization compartments demonstrate that especially the quality of the 2PP-microstructures has a major impact on manipulation procedures. The more complex the structure, the more complex is the assembling process, which is why especially the quality of the interlocking components plays an essential role. Nevertheless, refill of microstructures proves another problem to be solved. The compartments still need to be fabricated directly on the cover glass. Thus, the microstructures are isolated from the surrounding fluid, as well as the replacement or exchange of microstructures is not possible. To be able to connect the production and manipulation process, a manual feed option can be developed for future provisioning procedures of microstructures. Solely the perforation on top of the compartment facilitates the pouring of the compartment and thus, the development of these.
Figure 4.16: (a) Single compartment with 2PP component flower 3μm separated by the floodgate to the assembling area, as well as (b) the ring diameter 6μm separated by the floodgate to the assembling area and (c) with 2PP component ring 4μm after the sorting process. (d) Ring 6μm manipulated by two optical traps for being tilt at an angle of 90° (all 100x optical magnification) [KSO+13_2].

### 4.4.2 Selection of appropriate compartments

Microassembling of microstructures requires not only precise fabrication but also a fast localization of the 2PP structures. The process ensures the optimum availability for the subsequent manipulation processes using strategies for supplying and storing of microstructures for complex assembling applications. In the following different variants are analyzed for storing 3D microstructures. Selection and enhancement of the storage system is required, because complex three-chamber assembly platforms result in time-consuming fabrication processes of several hours, not compatible with procedures for future industrial usage. The compartments have been taken into account, because of the simultaneous writing process of microstructures and compartments within only one 2PP process. Additionally, the geometric characteristics are adapted to fast processing requirements of the 2PP processing as well. Especially complex, fast producible storage compartments with optimized shape are demanded in order to reduce the processing time for the relocation storage units. Therefore, simple compartment units are designed with slim walls and a wafer-thin perforation as cover of the interior dispersed microstructures. Within parameter studies optimal writing parameters for the appropriate storage compartments are tested, shown by Fig. 4.17.
Figure 4.17: Overview of storage compartments with variable filling distances from 0.9 to 4.0 μm with "only filling" function within 2PP using optimal writing parameters for compartments of 4.0 μm and 3.0 μm filling distance [MAT14].

Writing the 3D microstructures into compartments makes it possible to write 3D microstructures dispersed inside the enclosure. Additionally, relocalization is easier, given by Fig. 4.18.

Figure 4.18: 2.0 μm filling with interior microstructures.

The contour of the box as well as only one single layer in the x- and y- direction as cover of the structure has to be written for fabricating the complex
scaffold as shown below. Furthermore, the sequential process with analyzed fabrication time is introduced into the program. The compartments have dimensions of 50 µm × 50 µm × 30 µm. The fabrication takes 2-3 minutes only and can be reduced substantially by applying an appropriate sequential procedure. Here, a low laser power of 20 mW but high writing speed of 1.8 m s⁻¹ is used for generating an appropriate structure with a grid as cover. The interior complex microstructures are successfully fabricated with the same parameters like the surrounding assembling platform given in table 4.4. Usable assembling platforms are given in Fig. 4.19. The perforation grid is generated very precise with cover-only function in 2PP.

Figure 4.19: Assembling platform loaded as a full cuboid for dispersed 2PP microstructures. 1: Overview of written 2PP enclosure with same laser power and scan speed, but different writing distance of the single layers. 2: Platform quality compared. All structures are written with a laser power of 20 mW and a writing speed of 1.8 m s⁻¹, but with different writing succession. 3: Optimal structure containing dispersed 2PP microstructures written with alternating method. 4: Grid structure with openings in the cover for the developing process. Lateral surfaces are written without grid structure [KSO14].

The compartments fulfill their function as storage unit and by perforating each compartment, but do not facilitate a refill of microstructures into the compartments. Thus, a floatgate is not required any more to separate the microstructures. Interior structures are developed extensively. All storage compartments localize the microstructures on an area of about 40 × 40 µm for a fast relocalization within the HOT processing. The compartments are simply generated with wafer-thin cover, with tiny holes in the cover for development of interior elements. With a "cover-only" writing process the manufacturing of the compartments takes only 6 minutes.
4.4.3 Dispersed microstructures in storage units

For microassembling procedures, dispersed complementary microstructures are fabricated within storage units for a faster relocalization of the microstructures. In the following, non-spherical microstructures are tested on their movability and manipulation characteristics within 2PP-generated storage units. A corresponding CAD file with compartment and interior microstructures is loaded to the 2PP algorithm. The STL file contains the information about shape and size of the components generated from CAD data, modeled in SolidWorks. Next, the STL data are sliced in various layers and subsequently written by applying a galvo scanner as beam controller. With the multi-photon absorption process, the volume pixel can be polymerized below the surface allowing direct writing of 3D structures inside the volume of the material. The individual microstructures are fabricated inside chambers with varying geometry and size. Complementary puzzle pieces, along with 3D microstructures with complementary shape are generated within the compartment. Thus, the development process with the solvent Ormodev works as expected for this application. In the following, microstructures are processed by 2PP and integrated into an HOT process. Here, simple planar microstructures are processed dispersed in the solvent within specific compartments. Firstly, several writing processes are done with previously used parameters.

Figure 4.20: Dispersed microstructures within HOT process visualizing the movability of complex microstructures written in a 2PP process. (a) Microstructures within storage compartment with perforation. (b) Storage unit with wall thickness of 2μm.
The structures need to be released from the glass surface in order to allow optical micromanipulation in the subsequent assembly process. Trapping, lifting as well as moving along x, y- and z-axis must be feasible. Dispersed microstructures are shown as application example in Fig. 4.20. Of course, the structure needs to be ensured for all assembling procedures. Writing parameters for non-spherical complex microstructures can be found in the following table for the resin Femtobond 4B.

Table 4.4: Optimal writing parameters for linear writing procedures for 3D dispersed microstructures with Femtobond 4B for HOT manipulation processes.

<table>
<thead>
<tr>
<th>writing speed</th>
<th>1.8 m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>power</td>
<td>21 mW</td>
</tr>
<tr>
<td>layer thickness</td>
<td>0.1µm</td>
</tr>
<tr>
<td>filling</td>
<td>$x + y$</td>
</tr>
<tr>
<td>writing distance x-direction</td>
<td>0.1µm</td>
</tr>
<tr>
<td>writing distance y-direction</td>
<td>0.1µm</td>
</tr>
</tbody>
</table>

Possible defects are shown in Fig. 4.21 for illustration. Air bubbles within compartments occur quite frequently after development procedures of the 2PP samples. The incoming solvent rinsing into the compartment can lead to such blistering. These microcompartments cannot be used for manipulation procedures after inadequate development processing.

Figure 4.21: (a) Blistering within compartment after developing process with Ormodev. Manipulation with HOTs is technically not feasible any more. (b) Microstructures are available in solvent for HOT manipulation [MAT14].

Manipulation of interior microstructures is realized by utilizing a SLM, which can generate multiple laser spots with simultaneous actuation. Following application examples are given for interior microstructures generated in
Femtobond 4B. Non-optimized fabrication parameters for the GMM processing result in microstructure defects like displacement of microstructures around the compartments. A successful and productive manufacturing by 2PP of arbitrary microstructures within storage units with good pouring and development procedures is illustrated in Fig.4.22. In this case, separated compartments are filled with different microstructures dispersed for HOT assembling procedures. Using an optimal laser writing speed of 1.8 m s⁻¹ and a laser power of 21 mW, microstructures as well as surrounding compartments are manufactured with a very high accuracy within a processing time of 3 min per compartment without structures. Processing with interior microstructures takes 7-10 min, in accordance to the complexity of the microstructure.

Figure 4.22: Generation of different microstructures within separated compartments in the HOT setup (20x magnification). Storage compartments with perforation and inlying 3D microstructures fabricated using a 2PP process in Femtobond 4B and developed in Ormodev. (a+c) Complementary 2D puzzle jigsaw pieces. (b) 3D hole plate with cylindrical microstructure. (d) 2D complementary microelements.

4.5 Development process for dispersed microstructures

Dispersed microstructures need an adapted development process to be utilized within the following manipulation processes based on HOTs. An adaptation of the process flow must also be made so that the transfer of microstructures can be transferred into the manipulation setup. Therefore, a drop of Femtobond 4B, in the first processes, is placed on the cover glass, so that the droplet is seen from above, through turning the sample by 180°. The sample holder is
fixed by utilizing silicone paste around the small hole inside the aluminum plate. The development process is started by applying the solvent Ormoclear to the sample chamber, when working with a non-postbake photoresist material like Femtobond 4B.

Immediately after filling, the developing compartment is closed by a glass to reduce the evaporation of the solvent and to keep all microstructures inside the fluid, shown by Fig. 4.23. The fabrication and development is done under yellow light and the transfer after a period of about 20 minutes into the HOT setup is followed. There, the sample holder is clamped on the positioning table, on which further manipulation processes are accomplished. For evaluation of the structure quality or further SEM procedures, the pattern can also be
attached on a metal platelet and can be clamped on a microscopic mounting, given by Fig. 4.24. After drying of the structure, HOT manipulation or assembling procedures is not possible any more. Drying of the microstructures leads to sudden fixation of the microstructures on the glass surface.

4.6 Micromanipulation and -assembling

Existing joining technologies are usually represented by adhesive bonds resulting in durable and inflexible structures. Joining different microstructures can also be realized by using complementary microstructures, which can be released if necessary. Geometrical joining of microstructures by complementary assembling also offers new possibilities, e.g. movable systems. As a result, an assembling technology for geometrical joining of complementary microstructures is implemented. A temporary assembly of microstructures with full 3D control is realized for future manufacturing processes of highly complex microrobotic systems. The components can be controlled in their vertical (in z-direction) and horizontal alignments (in x-/y-direction) as well as they can be moved in translation and rotation. For the assembling of complementary microstructures, a method based on the so-called pick and place technique is utilized. Here single microstructures are trapped and can be positioned arbitrarily. This technique also can be used in micromanipulation of non-spherical 2PP generated components, shown schematically by Fig. 4.25.

![Figure 4.25: Assembling steps for single 3D microstructures. First, the preform is generated by 2PP and then integrated into the manipulation process for the following assembling process using multiple single parts, which are available in the solvent. The structures can be assembled and disassembled by using multiple optical traps simultaneously.](image-url)
Specific applications require individual handling of microstructures regarding their shape and size, because of the non-spherical geometry. Thus, arbitrary shapes also demand adapted optical forces and multiple traps for an implementation of optical handling. In the following, the analyzed application examples are introduced. Firstly, the challenge is the high degree of surface adhesion, because of the large planar shape. In general, it can be noted that structures with large contact surface on the cover glass are more difficult to manipulate as a structure with a smaller contact area less than 3µm. Secondly, more complex complementary elements are introduced into the 3D process. Assembling of the microproducts can also be realized based on chemical or complementary connectivity. The presented assembling type of positive assembling not only allows the installation, but also the dismantling for a resolving 3D microstructures from an assembled microsystems. Within the following sections, 3D alignment along with rotational movement is implemented for optical manipulation procedures. By applying a combination of the HOT algorithm "Blue and Red Tweezers" by School of Physics and Astronomy at the University of Glasgow as software controller and the adaptation to the process chain, HOTs are utilized as micromachining manipulation and assembling tool.

4.6.1 Translational / horizontal alignment (in xy-direction)

By trapping non-spherical components with two optical traps within a stable position, the object automatically aligns itself into the trap along the z-axis. Horizontal alignment in x- and y-direction is possible by utilizing 1-4 optical traps homogeneously distributed on the microstructure for a constant force. By applying only one optical trap with a Gaussian beam profile, the microstructure is trapped, lifted and moved on the x- and y-plane. No matter, if the microstructure is of 2- or 3D geometrical shape, up to a size of 20 µm × 20 µm × 20 µm the microstructure can be moved with a Gaussian beam and a single optical trap. Well-directed handling of complex microstructures is shown by implementing an application example for horizontal alignment in Fig. 4.26. For controlled alignment of non-spherical objects, more than just one laser spot for each 2PP microstructure is needed, to realize a stable trapping and manipulation process. This Fig. shows a more complex application of OTs.
Figure 4.26: Translational movement in the x- and y-directions with 3D-microstructures without spherical trapping ports. Micromanipulation of 2PP manufactured microstructures with a non-spherical complementary geometrical shape. Horizontal alignment is feasible by applying 2 optical traps. The zeroth order can be recognized as a bright spot. (a) Starting position of manipulation with 2 optical traps. (b) Rotation of upper microstructure horizontally about 45°. (c) Rotation of upper microstructure vertically about 90°. (d) Microstructures are aligned to their complementary ports.

Here, translational movement of 3D elements is given, to illustrate trapping and translational movement.
4.6.2 Vertical alignment (in z-direction)

Trapping a non-spherical microstructure with only one optical trap leads to the case, that the object is torn in the direction of the highest intensity, as physically explained in chapter 2.2. In general, vertical alignment is achievable by implementing one trap with a simple Gaussian beam profile. Fig. 4.27 illustrates the controlled tilting at an angle of 90° around the z-axis of complex 3D microstructures.

![Figure 4.27](image)

Figure 4.27: Vertical alignment process of 2PP microstructure by utilizing one optical trap using a Gaussian beam profile. Trapping a non-spherical microstructure by OT results in vertical control with tilting movement in z-axis direction. (a) Starting position parallel to glass surface. (b-d) Lifting and tilting of microstructure into z-plane. (e) 90° tilted microstructure in OT.

Dispersed 3D microstructures available inside the solvent can be vertically manipulated as well, shown exemplary in Fig. 4.28.

![Figure 4.28](image)

Figure 4.28: (a-c) Dispersed 3D hole plates with cylindrical microstructures available within OrmoDev (100x magnification) in HOT setup for piling and 3D manipulation processes. Manipulation and assembling procedures of these microstructures is given Fig. 4.29.

The following application example describes multiple trapping for vertical alignment by controlling multiple microstructures piled up one above each
other. Therefore, 3D microstructures need to be levitated within the solvent. A dimensioned CAD image of the manipulated microstructure is given by Fig. 4.29 (a). By this, it is demonstrated that also piling and manipulation in two superimposed levels on the z-axis are possible with non-spherical components with optical tools only. Here, 3 laser spots have to be utilized to trap the exterior components and manipulate the smaller structure parallel to the cover-slip plane through the hole of the quadratic hole plate. By lifting the microstructure, as shown in the Fig. 4.29 below, a generated 3D microstructure is lifted up vertically about 90° (along the z-axis) by applying two optical traps.

![Figure 4.29: (a) CAD file of the generated 3D microstructures. (b-e) Hole plate with superimposed optical traps. Overlapping of OTs could have been realized by trapping a non-spherical structure. The optical force acting on the cylindrical microstructure does not affect the position of the hole plate. Vertical alignment can be used for tilting procedures as well as manipulation processes, where multiple microstructures are superimposed.](image)

The laser beam is used for trapping not only the 3D element, but also the cylindrical element, which is led through the hole plate to demonstrate controlling of microstructures through a polymeric element.

### 4.6.3 Rotational movement

For rotational movement and generation of multiple optical traps again the SLM is applied. Thus, tiny microstructures can be manipulated in a contactless manner with precise manipulation forces and thus free of any adhesion effects. Investigations and Fig. 4.30 show, that simple Gaussian micromanip-
ulations can realize rotational alignments, but need to be positioned correctly. The acting forces on microstructures result in circular movement, when the structure is fixed with 2-3 optical traps in a parallel position to the cover glass.

![Image](image.png)

Figure 4.30: (a-d) Rotational movement about 180° with multiple optical traps with Gaussian beam profiles.

### 4.6.4 3D control

Full 3D control of the movement and generation of multiple optical traps again necessitates a SLM. Furthermore, interlocking structures can be trapped and rotated into each other to cause connection. 3D control of the interior microstructures is possible by applying one to four optical traps for manipulation and assembling procedures with HOTs. The 2PP microstructures are available dispersed in the solvent solution. Two different structures with the shape of a puzzle are fabricated by 2PP as an application example of geometrically complementary microstructures. The peculiarity of these 2PP components is their complementary shape, which offers the possibility of joining them together. The modular design and the diversity of enhancement options offer numerous capabilities to combine these structures to very long chains. In the experiments, complementary 3D microstructures with a size of $4\mu m \times 4\mu m$ are assembled. Geometrically linked microstructures are assembled for demonstrating optical joining of complex complementary microstructures. For the manipulation and assembling of the written 3D structures HOTs prove themselves as an outstanding optical tool to position and control the orientation of complex components in micrometer range from 3-20 $\mu m$.

First, an complementary microstructure is positioned in the manipulation area of the OT. In this approach, each single microstructure is trapped by two
Figure 4.31: (a-d) Unassembled dispersed single structures in OrmoDev after transport into HOT setup. Movability demonstration of dispersed 2D microstructures with planar geometry in HOT setup with 100x magnification. (e-f) Assembling process of puzzle structure by utilizing multiple traps simultaneously focused with 100x magnification.

focused laser beams, positioned near the circular edges. Then the microstructure is assembled with its interlocking element. Therefore, the microstructure with a length of 17μm has to be lifted single-sided at an angle of 45° and be moved into the complementary element. Therefore, the position of the laser focus has to be elevated by 15μm. The complementary element has a length of 20μm and remains fixed by the tweezers. For more assembling processes, multiple complementary microstructures can be brought into the manipulation area. As the first element is stably linked with its complementary part, the traps can be loosen for all following manipulation processes. Using these universal microstructures, long chains of multiple microstructures can be assembled. By using precisely fabricated 2PP microstructures, structures that are more complex are available for the following assembling process.

Figure 4.32: (a-d) Alignment of 2D microstructures by applying a single trap with a laser power of 10 mW.

Thus, more flexibility in designing the desired microsystem is given. By taking this combined process, a tailored method for the allocation of microsystems becomes possible. Flow control in microfluidic applications can be realized by
this technique. The OT technique can be used to manipulate or connect single structures with more complex 3D elements or the tweezer can also be used to loosen a assembling. In the following experiments, interlocking 3D microstructures with a size of $4 \mu \text{m} \times 4 \mu \text{m}$ are assembled, presented in Fig. 4.32. Fig. 4.33 (1-3) shows application examples of geometrically linked microstructures within HOTs, fabricated in advance with optimized 2PP processing parameters. The structures are assembled by utilizing multiple traps simultaneously focused with 100x magnification. For 3D control, two traps per microstructure are applied. Within these analysis for 2PP processing, the mentioned additional time interval between each layer is adjusted, resulting in a significant improvement of the accuracy and a high level of reproducibility. To illustrate the mounting of microstructures the following application example is shown, as two planar microstructures can be assembled with HOTs.

Figure 4.33: HOT assembling of 2PP microstructures with multiple traps. (a) Single 2D microstructure in OrmoDev. (b) Multiple single parts aligned to each other by applying two optical traps in OrmoDev. (c) Assembly of microstructures.

The performed manipulation procedures validate the findings within the investigations. The reciprocal interactions and acting physical effects on the non-spherical micron sized components influence the microstructure. Asymmetrically formed microstructures without spherical ports need two optical traps for parallelization of the structure to the surface plane. Multiple traps by HOTs are applied to control and position the arbitrary microstructures. For the purpose of assembling and disassembling of complementary 2PP components a very high precision of the structures generated is realized. Any distortion or deviation from the designed shape may result in problems during the assembling phase. In addition, interlocking 3D puzzle microstructures with a size of $5 \mu \text{m} \times 5 \mu \text{m}$ can be assembled. Fig. 4.34 gives another application
examples of geometrically linked microstructures within HOTs. With these examples it can be shown, that planar as well as spatial complementary parts can be controlled or assembled in three dimensions by HOTs.

Figure 4.34: (a) 3D CAD model of microstructure [KUE15]. (b-d) 3D control of assembled microstructures. Generated single components by 2PP and assembled with HOTs can be controlled in a subcomponent assembling process using multiple microstructures. Multiple HOT traps simultaneously control is required with 6 traps.
4.6.5 Entire process flow for fabrication, manipulation and assembling (FMA) of complex microstructures

All developed and combined processes are shown theoretically in Fig. 4.35:

Figure 4.35: Entire process flow for processing with Femtobond 4B. With a higher laser power of 50 mW, microstructures can also be loosening afterwards by using the thermal effect, when the elements are not movable directly after the developing process. All processing steps from (a) applying of the sample to the glass substrate holder to (g) the storage of the dispersed Microsystems in fluid are given within Fig. 4.35. Processing with the optical micromachining tool starts with (a) applying of the sample to the glass substrate holder, (b) the prebake process of the photoresist, (c) the fabrication process with exposure into the resin, followed by (d) the removing and attaching of the probe to the aluminum holder for integration into the HOT process. The resin containing the 3D microstructures is developed with a solvent (e) directly after integrating the sample into the HOT setup. After pouring, the developing compartment with the solvent and awaiting the specific developing time (f) the manipulation process is started afterwards. Compartments with the interior microstructures (g) are now available fabricated by 2PP.
4.7 All-optical micromachine (AOMM)

In order to develop microrobotic systems for industrial applications, miniaturization and assignment of a future, all-optical micromachine is necessary. Thus, the mentioned manufacturing techniques, manipulation and assembling methods are analyzed. Thus, multiple micromanipulations and assembling are feasible with complex microstructures, resulting in tiny microsystems. Combinations of single microstructures to hybrid microsystems are feasible. But, for industrial usage, the innovation potential must be increased. Therefore, the implementation of fabrication and manipulation within one integral system requires a process adaptation. By applying all previous analysis for the all-optical micromachine, these investigations on process combinations give an answer to the following process requirements:

- one tool for processing, positioning and fixation
- selection of appropriate direct laser writing processing
- selection of appropriate CW laser source for fabrication and manipulation
- high resolution for GMM processing (also non-multi-photon absorption)
- CAD import via STL-file format
- processing for fabrication of tiny microstructures
- integration into one platform for miniaturization within a demonstrator
- camera for real-time observation of the fabrication and manipulation process

The selection of an appropriate laser source for a system miniaturization requires the understanding of the correlation of resulting focus diameter $D$ and corresponding laser spot within the resin. $M^2$ describes the beam quality, depending on the chosen laser source, and $\lambda$. The focus diameter is given by the following equation.

$$D = 2M^2 \frac{0.62\lambda}{NA}$$  \hspace{1cm} (4.4)
The structure size interrelates on the size of the focus diameter \( D \) of the laser spot. Utilizing the low photon absorption (LOPA) processing with a voxel size of 190 nm (NA: 1.3, \( \lambda \): 532 nm), manufacturing of microstructures results in a microstructure line width of approximately 2.4 \( \mu \text{m} \). Thus, structuring and fabrication of microstructures is possible with a CW laser system. The combined system is constructed as a miniaturized version of the OMMT. Thus, the system is reduced not only in size, but also in functions. The writing process here bases on a 1PP process, generating microstructures in the range of several micrometers as well and is like 2PP, fabricated under specific working condition. Basic researches for 1PP shows, that microstructures can also be generated by applying an efficient resin, which polymerizes when using the wavelength 532 nm. Thus, a 532 nm laser with a 1.3 NA objective is applied for a miniaturized AOMM. First investigations approve, that 2D elements can be generated with 1PP processing, which is sufficient for microstructures in the range of 10 \( \mu \text{m} \) – 50 \( \mu \text{m} \). With this finding for manufacturing, two separate processes can be combined, resulting in the substitution of the manufacturing pulse laser.
4.7.1 Process flow adaptations

The process optimization for the AOMM is illustrated in Fig. 4.36:

![Diagram of process flow adaptations](image)

Figure 4.36: Process adaptation for FMA. Entire process flow for FMA of elastic microstructures for AOMM (D3). The process optimization for AOMM start with (a) applying of the sample to the glass substrate holder, (b) the spin-coating process, (c) the prebake process of the spin coated photoresist, (d) the fabrication process with exposure of the resin, followed by (e) the generated probe on the sample holder. The removing and attaching of the probe to the aluminum holder for integration into the HOT process is shown in (f). The resin containing the 3D microstructures is developed with a solvent (g) directly after integrating the sample into the HOT setup. After pouring, the developing compartment with the solvent and awaiting the specific developing time (h) the manipulation process is started afterwards. Compartments with the interior microstructures (i) are now available fabricated by 2PP within the liquid solvent.

4.7.2 Probe preparation

Miniaturizing the micromachine requests an adapted probe preparation, starting with a spin coating process with 2500 revolutions per minute, result in a 25 μm SU8 layer.
Figure 4.37: Spincoating process of SU8 drop on glass substrate at 300 rpm/s for 30 s. (a) Positioning of the sample holder with a drop of SU8. (b) Evacuated processing area with SU8 sample holder.

Excess SU8 material on the sides is removed with isopropyl alcohol. This process is followed by a prebake for 10 minutes with 95 °C. The prebake process is necessary to reduce the shrinkage of SU8.

Figure 4.38: Prebake process of SU8 drop on glass substrate. Hotplate temperature is 95 °C for approximately 10 minutes.

After prebake procedures, the glass substrate is given inside the polymerization processes. Localization of the glass surface on the substrate, as starting point for the writing process, is done with a laser power of 40 mW.

Microfabrication investigations with SU8 are done with a laser power of 12 mW and a writing speed of 1.2 m s⁻¹, resulting in optimal processing parameters given in the table 8. Fig. 4.39 shows the 2PP process. The spin-coated glass substrate is clamped into the installation for manufacturing of desired
Table 4.5: Optimal writing parameters for linear writing procedures for 3D dispersed microstructures with SU8 for HOT manipulation processes.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>writing speed</td>
<td>1.2 m s(^{-1})</td>
</tr>
<tr>
<td>power</td>
<td>12 mW</td>
</tr>
<tr>
<td>layer thickness</td>
<td>0.2 (\mu)m</td>
</tr>
<tr>
<td>filling</td>
<td>(x + y)</td>
</tr>
<tr>
<td>writing distance x-direction</td>
<td>0.2 (\mu)m</td>
</tr>
<tr>
<td>writing distance y-direction</td>
<td>0.2 (\mu)m</td>
</tr>
</tbody>
</table>

2PP microstructures inside the SU8 material.

Figure 4.39: (a) Positioning of spin-coated glass substrate on sample holder on 2PP stage. (b) 2PP manufacturing process with spin-coated SU8.

Postbake processing of SU8 drop on glass substrate is done again for 10 minutes with 95 °C. The process closes with a development process with the solvent Mr-Dev 600 for 10 minutes. With this process flow adaptations, writing and manipulation is realized.

The manufacturing procedure is followed by the probe preparation for HOT assembling with the 532 nm CW laser. First results with this processing method within in the AOMM are shown in the following chapter.
Figure 4.40: Preparation of aluminium sample holder for development process with Mr-Dev 600 for HOT usage. (a) Silicone paste is given on the aluminium substrate for (b) fixation of the glass substrate on the sample holder. (c) Developer is given inside the chamber and (d) closed with another glass substrate. (e) Immersion oil is applied for usage of (f) the oil objective and the high NA resolution.

4.7.3 Miniaturized model

The demonstrator for an AOMM integrates 2PP and HOTs with all interactions, transport and storage solutions, given within the following installation in Fig. 4.41. All requirements are compiled ensuring two procedural alternative methods for the production of 3D structures in polymeric solutions, as well as analysis of the LOPA method for HOT processing, resulting in the realization of an entire process in one integral system.

This miniaturized system includes both installations for the manufacturing and manipulation of individual microstructures. The system is tested by applying the 532 nm HOT laser for manufacturing and trapping of the generated structures. SU8 is applied as photosensitive resin, because of its exposing characteristics at the wavelength used. Micromanufacturing within the AOMM setup result in fine microstructures with a thickness of 2.4μm, shown in Fig. 4.42. Therefore, one-photon absorption (1PA) is applied. Within a 1PA only one photon excites a molecule from an energy level to a higher energy level. Thus, polymerization of SU8 is realized with 20 mW – 100 mW laser power, along with manipulating of the fabricated structures with 10 mW – 20 mW.
Figure 4.41: AOMM manufacturing and manipulation tool for complex microstructures with beam expander (BE) and spatial light modulator (SLM).

Figure 4.42: Microstructures with a line width of 2.4\,\mu m - generated with CW radiation within HOT setup for integrated fabrication and manipulation of microstructures within integral setup [SCH16].
Thus, a complex structure within a manual CW exposure is implemented by moving the x-axis manually and controlling the shutter within the HOTs simultaneously. The utilized mechanical shutter is opened for exposure of the SU8 polymer and closed to stop the radiation into the polymeric material. Adhesion effects on the substrate could not be noted. This procedure is repeated three times for a better line thickness and an improvement of the structure quality. It is to say, that the exposure time per volume element is limited to prevent formation of microbubbles. Such microbubbles are used as marker, which can be identified as starting position, in this combined process.

Furthermore, along with the fabrication, the development process of the manufactured structures is realized within the AOMM setup. A SLM is necessary for possible 3D radiation with computer-generated holograms. Such a complete new manufacturing technology can then be used for manufacturing and assembling of arbitrary complex microstructures. A final goal is to open up new areas of applications for this innovative manufacturing idea.
Chapter 5

Summary and outlook

5.1 Summary

This work shows how an optical micromachining tool is applied for manufacturing with 2PP and manipulation and assembling processes with HOT. Combination of both techniques opens up a complete new field for GMM, assembling and thus, generation of complex microsystems. Worth special mention, are the introduced assembling methodologies, which can also be applied for generating multi functional assemblies by combining different materials. This is still a challenging task for future applications.

Beginning with a brief introduction to the theoretical context, both applied technologies are described in detail for a scientific assessment and classification. Here, optical tools are applied for precise fabrication within a DLW process. Using the optical micromachining tool not only complex microstructures can be generated, but in addition to the manufacture of these, also be examined for their possibilities of manipulation. For 3D control by HOT of microstructures specific connection techniques are implemented in general, like biochemical, thermal and photothermal linkage or polymerized joining. These investigations are with main focus on interlocking techniques for complex microstructures. Hence, releasable joining of microstructures and thus, temporary assembling of microcomponents are accomplished. The assembling process of such complex microsystems necessitates not only precise vertical and horizontal movement, but also rotational alignment of the fabricated elements. Selected application examples demonstrate an overview for translational, vertical and rotational
movement and alignment of arbitrary non-spherical parts, along with 3D control. With the use of a single focused laser spot, 3D microstructures can be tilted (parallel to the z-axis) or with the help of two spots rotated stable by 90°. In general, one optical trap is utilized for translational or horizontal alignment of microstructures in x- and y-direction, analogous to vertical alignment in z-direction. Rotational movement is done by utilizing 3-6 optical traps. Depending on the structure and the number of tweezers used to join complementary elements, assembling is done within several minutes. The joining process is reversible by the positive geometry of the microstructures. The release of the individual components from one another is analogous to the described assembling, but in the reverse process sequence. Thus, replacement of defective microstructures is possible. The implemented assembling technique is feasible and optimized for microcomponents in microscopic range of 3 to 30 µm. Furthermore, the geometrical quality and processing time are optimized.

For 2PP, an additional time interval between each layer is adjusted, resulting in a significant improvement of the accuracy and a high level of reproducibility of the structures’ shape. This work contains all parameters adapted to the implemented alternating and linear writing method for bottom up and top down GMM for freely movable microstructures. Additionally, all storage and transport processes with its interactions, in accordance to the whole procedure from 2PP to HOT processing, are validated within these investigations.

Based on these researches, the results are transferred to development basics of microsystems for industrial and medical assignments. The findings can be applied for future applications, resulting in an economical miniaturized installation for functionalized arbitrary microstructures.

5.2 Outlook

Due to the complexity of optical micromachining applications and assignment, there are still challenges left for further investigations. Additionally, there are numerous techniques for beam forming, which have to analyzed in future approaches, regarding the use of complex modulation, amplitude-only modulators or continued usage of phase-only modulators. By changing complex modulation devices, both the phase and amplitude could be optimized, espe-
cially when time-varying beam shaping is required.

Along with an extension of the assembling technique for fabrication of elastic click connections with SU8, also snap connections are a possible future development. Thus, spherical and non-spherical microstructures could be applied for releasable microsystems, due to its elastic characteristics. Therefore, CAD based data could be utilized, again. Press-fittings and assembly operations need to be analyzed therefore in advance, for realizing a joining and disassembling of such complex elastic elements.

Additionally, further investigations regarding relocalization of microstructures are necessary. The linkage of functionalized single microstructures could result in multi-functional microsystems with hybrid functionalities. Thus, flow generation by magnetic actuators could be implemented with alternately constructed chains of single functionalized microstructures.

The idea of an AOMM can be extended to a theoretical future aim of a miniaturized model with roll-to-sample or role-to-role production system for industrial usage. This AOMM system could be a high-performance production technique with mass production capabilities of assembled microrobotics. The generation of microstructures with assembling is done between the heating processes with a CW laser. Fig. 5.1 shows a roll-to-sample production option integrating not only role-to-sample fabrication, but also punch processes of the silicon substrate holder, as well as the applied willow glass fixation (for the glass substrate). The process integrates all pre- and postbake procedures, analogous to the whole process given by Fig. 4.36 as well as the development process after post baking, along with the fixation of the cover willow glass, after generating the 3D microsystem into the resin. Afterwards, the probe can be punched as desired for the integration of a tiny microassembled system inside the resin. The integral system of course integrates the necessary requirements, like the high clearance fit of interlocking microstructures. A high level of reproducibility is inevitable here for e.g. future medical applications. Applying an AOMM to a mass production idea, complex microsystems are realistic with portable characteristics and in multiple quantities, but by virtue of this work and findings, with a very high quality. Applying a roll-to-sample system, shown in Fig. 5.2, allows manufacturing and provision of very complex microsystems e.g. for medical applications. With an AOMM microsystems
could not only be generated, but also be made available for industrial usage for specific microdevices or replace defective microstructures in MEMS.

Figure 5.1: Miniaturized model of AOMM with roll-to-sample microsystem production.
Figure 5.2: Miniaturized model of AOMM with roll-to-roll microsystem production.
Appendix A

Component specifications for 2PP

Table A.1: Camera: UIO-1545LE

<table>
<thead>
<tr>
<th>type</th>
<th>UI-1545LE-M-GL</th>
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<tbody>
<tr>
<td>interface</td>
<td>USB 2.0</td>
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<tr>
<td>sensor type</td>
<td>CMOS</td>
</tr>
<tr>
<td>frame rate</td>
<td>25 fps</td>
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<tr>
<td>resolution</td>
<td>1280 x 1024 (1.31 Mpix)</td>
</tr>
<tr>
<td>shutter</td>
<td>rolling shutter</td>
</tr>
<tr>
<td>optical class</td>
<td>1/2''</td>
</tr>
<tr>
<td>pixel size</td>
<td>5.2μm</td>
</tr>
<tr>
<td>IP code</td>
<td>IP 30</td>
</tr>
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</table>

Table A.2: Scanner: SCANLAB hurrySCAN II 14

<table>
<thead>
<tr>
<th>aperture</th>
<th>14 mm</th>
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<tbody>
<tr>
<td>wavelength range</td>
<td>750 nm – 850 nm</td>
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<td>typical scan angle</td>
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<td>accuracy repeatability</td>
<td>&lt; 2μrad</td>
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<tr>
<td>Positioning resolution</td>
<td>18 bit</td>
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Table A.3: Stage: Aerotech WafermaxZ

<table>
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<th>WafermaxZ -NC-LTAS</th>
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</thead>
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<tr>
<td>travel distance</td>
<td>5 mm</td>
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<tr>
<td>resolution</td>
<td>0.83 nm</td>
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<tr>
<td>accuracy</td>
<td>±1.5 µm</td>
</tr>
<tr>
<td>bidirectional repeatability</td>
<td>±0.3 µm</td>
</tr>
<tr>
<td>straightness</td>
<td>±2 µm</td>
</tr>
<tr>
<td>maximum speed</td>
<td>4 mm s⁻¹</td>
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Table A.4: Stage: ANT130-110-XY

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</tr>
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<tr>
<td>travel distance</td>
<td>110 mm</td>
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<tr>
<td>resolution</td>
<td>1 nm</td>
</tr>
<tr>
<td>accuracy</td>
<td>4.0 µm</td>
</tr>
<tr>
<td>bidirectional repeatability</td>
<td>±100 nm</td>
</tr>
<tr>
<td>unidirectional repeatability</td>
<td>±25 nm</td>
</tr>
<tr>
<td>straightness</td>
<td>±1.5 µm</td>
</tr>
<tr>
<td>maximum speed</td>
<td>350 mm s⁻¹</td>
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Table A.5: Objective: Nikon Plan Apo 100x/1.4

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<tr>
<th>type</th>
<th>plan apochromat</th>
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<tr>
<td>immersion liquid</td>
<td>oil</td>
</tr>
<tr>
<td>magnification</td>
<td>100x</td>
</tr>
<tr>
<td>numerical aperture</td>
<td>1.4</td>
</tr>
<tr>
<td>working distance</td>
<td>0.13 mm</td>
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Table A.6: Pumplaser: Spectra Physics Millenia Prime

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<tr>
<th>type</th>
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<td>output Power</td>
<td>15 W</td>
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<tr>
<td>wavelength</td>
<td>532 nm</td>
</tr>
<tr>
<td>mode</td>
<td>TEM00</td>
</tr>
<tr>
<td>beam quality (M(^2))</td>
<td>&lt; 1.1</td>
</tr>
<tr>
<td>beam diameter (1/(e^2))</td>
<td>2.3 mm ± 10 %</td>
</tr>
<tr>
<td>beam divergence</td>
<td>&lt; 0.5 mrad</td>
</tr>
<tr>
<td>polarization</td>
<td>&gt; 100 : 1 vertical</td>
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Table A.7: Laser: Spectra Physics Tsunami

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<th>type</th>
<th>3960-M3BB</th>
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<td>repetition rate (nominal)</td>
<td>80 MHz</td>
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<tr>
<td>mode</td>
<td>TEM00</td>
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<tr>
<td>beam diameter (1/(e^2))</td>
<td>&lt; 2 mm</td>
</tr>
<tr>
<td>beam divergence</td>
<td>&lt; 1 mrad</td>
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<tr>
<td>polarization</td>
<td>&gt; 500 : 1 vertical</td>
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Appendix B

Component specifications for HOT

<table>
<thead>
<tr>
<th>type</th>
<th>MAN-ML-5-CW-P-TKS-OTS GEVEL</th>
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<tbody>
<tr>
<td>nominal output power</td>
<td>5 W</td>
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<tr>
<td>laser wavelength</td>
<td>1064 nm</td>
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<tr>
<td>operation mode</td>
<td>CW-modulated</td>
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<tr>
<td>transversal mode</td>
<td>TEM00</td>
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<tr>
<td>beam quality ($M^2$)</td>
<td>&lt; 1.1</td>
</tr>
<tr>
<td>typical beam diameter</td>
<td>2.2 mm</td>
</tr>
<tr>
<td>beam divergence</td>
<td>&lt; 0.5 mrad</td>
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<tr>
<td>laser output configuration</td>
<td>Gaussian profile</td>
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<tr>
<td>output fiber length</td>
<td>3 m</td>
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<tr>
<td>vertical polarization</td>
<td>Linear &gt; 100 : 1</td>
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<tr>
<td>long term stability</td>
<td>&lt; ±2 %</td>
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<td>cooling</td>
<td>air</td>
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### Table B.2: SLM: Pluto - VIS Holoeye

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<tr>
<td>nominal output power</td>
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<tr>
<td>resolution</td>
<td>1920 x 1080 pixel</td>
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<tr>
<td>active area</td>
<td>15.36 x 8.64 mm</td>
</tr>
<tr>
<td>pixel size</td>
<td>8 μm</td>
</tr>
<tr>
<td>fill factor</td>
<td>87 %</td>
</tr>
<tr>
<td>frame rate</td>
<td>60 Hz</td>
</tr>
<tr>
<td>phase value</td>
<td>256 (8Bit)</td>
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<tr>
<td>maximum power</td>
<td>2 W cm⁻²</td>
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### Table B.3: Camera: USB UI-1225LE

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<tr>
<th>sensor-type</th>
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<tr>
<td>sensor chip</td>
<td>4.512 x 2.880 mm</td>
</tr>
<tr>
<td>pixel size</td>
<td>6 mm</td>
</tr>
<tr>
<td>frame rate</td>
<td>87 Hz</td>
</tr>
<tr>
<td>color depth</td>
<td>8 Bit (monochrome)</td>
</tr>
<tr>
<td>lens mount</td>
<td>C-Mount</td>
</tr>
<tr>
<td>port</td>
<td>USB 2.0</td>
</tr>
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</table>

### Table B.4: Objective: Zeiss Plan-Apochromat 100x

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<tr>
<th>magnification</th>
<th>100 x</th>
</tr>
</thead>
<tbody>
<tr>
<td>numerical aperture</td>
<td>1.4</td>
</tr>
<tr>
<td>working distance</td>
<td>0.17 mm</td>
</tr>
<tr>
<td>immersion liquid</td>
<td>oil</td>
</tr>
<tr>
<td>exit aperture</td>
<td>4.6 mm</td>
</tr>
<tr>
<td>focal length</td>
<td>1.64 mm</td>
</tr>
<tr>
<td>field of view</td>
<td>25 mm</td>
</tr>
<tr>
<td>transmission (λ = 532 nm)</td>
<td>≈ 70 %</td>
</tr>
<tr>
<td>transmission (λ = 1030 nm)</td>
<td>≈ 40 %</td>
</tr>
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</table>
Appendix C

Program codes for linear and alternating fabrication

C.1 Linear writing method

Achsen_verfahren( - Objekte[Objektnr]->x, Objekte[Objektnr]->y, Objekte[Objektnr]->z + Konstant->Z_Achsen_Nullpunkt , Konstant->Achsen_Standard_Geschwindigkeit, true, false);
for(long slicenumber=0; slicenumber < Objekte[Objektnr]->SchichtenListe->Count && fabflag; slicenumber++){   // Für jede Schicht in der SchichtenListe des aktuellen Objekts ...
    if (fabflag) Achsen_verfahren(0,0, Objekte[Objektnr]->Schichtdicke, Konstant->Achsen_Standard_Geschwindigkeit, 0, 0);

C.2 Alternating writing method

Achsen_verfahren( - Objekte[Objektnr]->x, Objekte[Objektnr]->y, Objekte[Objektnr]->z + Konstant->Z_Achsen_Nullpunkt , Konstant->Achsen_Standard_Geschwindigkeit, true, false);
for(long slicenumber=0; slicenumber < Objekte[Objektnr]->SchichtenListe->Count && fabflag; slicenumber++){   // Für jede Schicht in der SchichtenListe des aktuellen Objekts ...
    if (fabflag) Achsen_verfahren(0,0, Objekte[Objektnr]->Schichtdicke, Konstant->Achsen_Standard_Geschwindigkeit, 0, 0);
C.3 Alternating fabrication with waiting period

```c
int Mitte;
Mitte = (Objekte[Objektnr]
    ->SchichtenListe->Count - 1)/2;
Achsen_verfahren(-Objekte[Objektnr]
    ->x, Objekte[Objektnr]
    ->y, Objekte[Objektnr]->z + Konstant
    ->Z_Achsen_Nullpunkt + Mitte * Objekte[Objektnr]
    ->Schichtdicke, Konstant
    ->Achsen_Standard_Geschwindigkeit, true, false);
long slicenumber=0;
for(long a=0; a < Objekte[Objektnr]->SchichtenListe
    ->Count & fabflag; a++){
    // Für jede Schicht in der SchichtenListe
des aktuellen Objekts
    int Reihe;
    Reihe = Objekte[Objektnr]->y/100;
    Sleep(100*Reihe); //
    if ((a%2==0)/
        //%2 gibt den rest aus, wenn durch 2 geteilt wird
            {slicenumber=Mitte - a/2;}
        if ((a%2==1) && (Mitte+a/2 + 1 <= Objekte[Objektnr]
            ->SchichtenListe->Count)*/
            {slicenumber=Mitte+a/2+1 ;}
    ... 
    if ((fabflag) && (a%2==0))
        Achsen_verfahren(0,0, Objekte[Objektnr]
            ->Schichtdicke*(a+1), Konstant->
            Achsen_Standard_Geschwindigkeit, 0, 0);
    // Tiefe der nächsten Ebene anfahren,
eine Schicht unterhalb der Mitte wurde geschrieben;
daher höher fahren
    if ((fabflag) && (a%2==1) &&(a+1<Objekte[Objektnr]
            ->SchichtenListe->Count)*/
        Achsen_verfahren(0,0, -Objekte[Objektnr]
            ->Schichtdicke*(a+1), Konstant
            ->Achsen_Standard_Geschwindigkeit, 0, 0);
```

C.4 Linear fabrication with waiting period

Achsen_verfahren( - Objekte[Objektnr]->x, Objekte[Objektnr]->y, Objekte[Objektnr]->z + Konstant->Z_Achsen_Nullpunkt , Konstant-> Achsen_Standard_Geschwindigkeit , true, false); for(long slicenummer=0; slicenummer < Objekte[Objektnr]-> SchichtenListe->Count && fabflag; slicenummer++){ // Für jede Schicht in der SchichtenListe des aktuellen Objekts
    int Reihe;
    Reihe =Objekte[Objektnr]->y/100;
    sleep(Reihe)
    ...
    if (fabflag) Achsen_verfahren(0,0, Objekte[Objektnr] - >Schichtdicke, Konstant-> Achsen_Standard_Geschwindigkeit , 0, 0);

C.5 Final settings for linear fabrication

Achsen_verfahren( - Objekte[Objektnr]->x, Objekte[Objektnr]->y, Objekte[Objektnr]->z + Konstant->Z_Achsen_Nullpunkt , Konstant-> Achsen_Standard_Geschwindigkeit , true, false); for(long slicenummer=0; slicenummer < Objekte[Objektnr] - >SchichtenListe->Count && fabflag; slicenummer++){ // Für jede Schicht in der SchichtenListe des aktuellen Objekts
    sleep(1000* Objekte[Objektnr]->Schichtdicke)
    ...
    if (fabflag) Achsen_verfahren(0,0, 0,86* Objekte[Objektnr] - >Schichtdicke, Konstant-> Achsen_Standard_Geschwindigkeit , 0, 0);
    //nur 86% der Höhe verfahren ...

Appendix D

Power specifications for HOT
<table>
<thead>
<tr>
<th>current [A]</th>
<th>power before SLM [mW]</th>
<th>power behind SLM [mW]</th>
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<th>power before objective [mW]</th>
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References


Publications


10. Andreas Aumann, Sarah Isabelle Ksouri, Qingchuan Guo, Christian Sure, Evgeny L. Gurevich and Andreas Ostendorf: Resolution and aspect ratio in two-photon lithography of positive photoresist. J. Laser Appl. 26, 2022002, 2014. DOI: 10.2351/1.4857275


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