From Lab to Fab – High-Precision 3D Printing

Towards high throughputs and industrial scalability

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The demand of sophisticated components is continuously increasing, driven by big data, IoT, and Industry 4.0. Reducing process cost is impacting all levels in a vast majority of products. 3D printing is typically restricted to additive fabrication within one material class, structures are limited in size, shape, surface finish, requiring supporting structures. This prevents high quality photonic components. High precision 3D printing is utilizing a multiphoton process which is a powerful tool for prototyping of miniaturized designs in automated, scalable processes for products in photonic or medical packaging. While most of the 3D systems are still working rather on a lab than on an industrial scale with typically very long fabrication times ranging from minutes to hours for a single microlens, the process can be boosted significantly to a fabrication time in the range of seconds per lens using different fabrication strategies, resulting in microlenses with high optical quality. This saves more than 90 % of the fabrication time compared to standard fabrication, and 1 cm² lens arrays with high filling factors can be fabricated within only a few hours – a big step towards high throughput and industrial scalability.

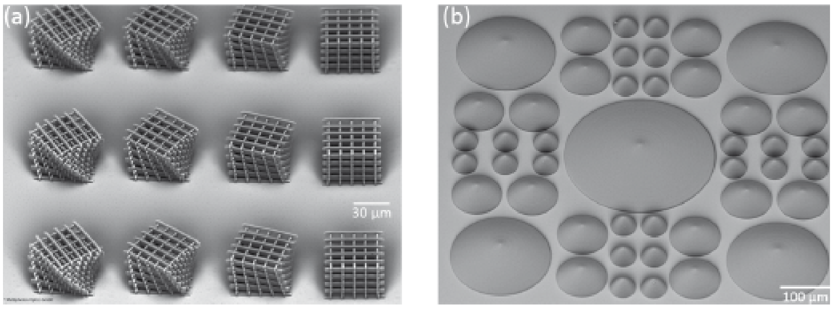

Fig. 1 Special scaffold structures (a) and set of differently shaped microlenses generated using high-precision 3D printing (b).

Company

Multiphoton Optics
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Multiphoton Optics GmbH offers a 3D printer platform, software, and prototyping & engineering support for high-precision 3D printing of many materials. Additive and subtractive fabrication are integrable into standard 2D process work flows, providing high-precision 3D prototyping of miniaturized designs in automated, scalable processes for products in information & communication technology, IoT, photonic or medical packaging.
Multiphoton Optics has won a start-up award in 2017, was a finalist in the Prism Award 2015 and 2017, and a finalist in the Querdenker Award 2015.

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The processing of metals and polymers by 3D printing, for example via selective laser sintering (SLS), selective laser melting (SLM), or by stereo lithography (SLA), has become very prominent for rapid prototyping in the last decade. Prevalent techniques enable a layer-by-layer fabrication of workpieces in additive working steps, resembling a 2D bottom-up deposition method. However, limits are reached wherever high-precision and high surface quality is required with an industrial scale throughput, for example for photonics packaging and microlens fabrication for imaging, illumination, and sensor purposes, respectively.

Fabrication without limit

High-precision 3D printing via non-linear two-photon absorption (TPA) provides a unique real 3D technique based on femtosecond laser pulses [1], suitable for the fabrication of optically smooth surfaces [2]. Due to the nature of the non-linear process, the intensity is only high enough in the strongly confined focal volume to initiate a reaction in a material. Structures are created in an additive mode in photo-responsive materials such as polymers, hybrid polymers, or special glasses. In most of the setups used so far, typically high-*NA* oil-immersion objectives are used to focus the pulsed laser light into a photochemically reactive material's volume to initiate an organic cross-linking.

Dependent on the underlying material to be processed, this confinement cannot only be used for additive, but also for subtractive fabrication for positive photoresists. On the other hand, metal can be directly structured subtractively, making use of conventional ablation processes to create structures in metals with very high precision. This particularly allows to integrate high-precision 3D printing using additive and subtractive fabrication into industrially relevant 2D process work flows.

In the additive fabrication mode (AFM) using polymers or inorganic-organic hybrid polymers, the laser pulses initiate a radical cross-linking of the C=C bonds or a cationic cross-linking of epoxide bonds, respectively. If the

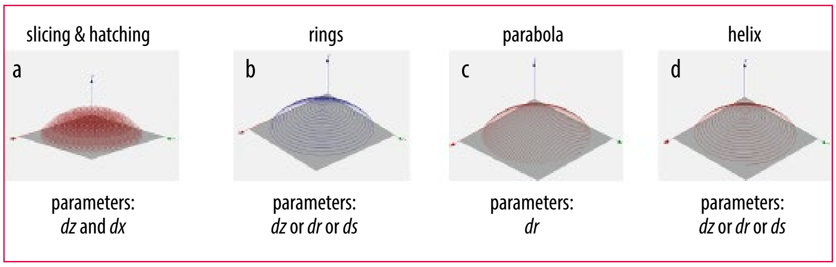

Fig. 2 Exposure strategies to fabricate microlenses. Slicing and hatching typically used by scientists (a), combination of contouring via TPA and UV flash using various strategies (circle, parabola, and helical path, b-d).

focal volume of the laser is scanned in 3D through the material, it is directly cross-linked in 3D along the path of the focal volume. This enables users to fabricate arbitrary 3D structures in a true 3D fabrication mode in the volume or on a surface of a material with highest precision directly, fast, and reliably from a CAD file or from files generated with a special software (Fig. 1). The degree of cross-linking in a polymer or hybrid polymer and thus the chemical and physical properties of the created material structures can be precisely controlled by a variety of accessible process parameters [3].

By varying these parameters, material properties can be altered to create gradient structural properties which are interesting for many different applications in photonics or biomedicine. This is used for years already, nowadays referred to as 4D printing.

For example, the mechanical stability of additively fabricated structures can be modified such that their Young's modulus or mechanical strength differs within the structures or mechanically differently stable structures can be created [4]. This is of particular interest in tissue engineering, since the cells prefer to adhere, differentiate, and proliferate on non-toxic structures which resemble the natural tissue in its mechanical properties.

Optical properties such as refractive index profiles can be also altered in the process, resulting in refractive index gradients particularly beneficial in the fabrication of in situ fabricated waveguides for optical data transfer [5]. In the following, light will be shed on the fabrication of microlenses and the corresponding fabrication strategies ensuring high throughput and industrial scalability.

Speed-up fabrication

Many products in illumination or imaging require specially shaped microlenses to enhance their performance which need time-consuming and costly processes. For spherical microlens arrays, there are standardized processes available to create microlens arrays at low cost, for example by UV replication.

For high precision 3D printing, however, standard processes for high surface qualities are not yet available on an industrial scale. As there are many different equipment used for mainly academic purposes yielding nice results with strong limitations in either accessible structural sizes or substrate formats or processable materials, a comparison of the individual properties concerning throughput and precision is hard to achieve.

To create comparability of different fabrication strategies, microlenses were defined which are used as suitable benchmark structures. The uniqueness of TPA fabrication originates from its freedom in design, particularly enabling aspheric or free-form optics and combinations thereof. The exposure was carried out using an air objective ($NA = 0.6$, $WD = 3.3$ mm) which is very useful for industrial scale fabrication.

3D structures, as shown in Fig. 1, can be build up by scanning the focal volume using a corresponding pathway. Bulky structures like microlenses are typically fabricated in a slicing and hatching mode by scientists and scientific companies, scanning the complete volume layer by layer as shown in Fig. 2a. This is suitable to create all kinds of structures with arbitrary shape. Accessible parameters are the slicing distance *dz* (vertical distance between adjacent layers) and the hatching distance *dx* (horizontal distance between two lines in one layer). To speed up the process, either *dx* or *dz* can be increased, but the optical quality of the fabricated microlens is decreasing if these parameters exceed about 300 nm. Depending on the fabrication parameters, an optical surface quality with an rms roughness of less than 10 nm can be easily achieved using, e.g., inorganic-organic hybrid polymers [2]. The fabrication time for an individual microlens, however, is very high compared to other fabrication strategies (see below).

In contrast, contouring of a microlens' shell in combination with a subsequently applied UV flash after a development step analogously to conventional 2D processing to remove the non-exposed material is an alternative fabrication strategy, making use of the full potential of materials and processes with a high impact on lowering fabrication times. Particularly hybrid polymers are very process-stable, providing a TPA cross-linked outer shell upon light absorption which is stable to be used in this process. After a subsequent UV flash for only a few seconds, the liquid material inside the TPA-written lens surface is also polymerized [6].

There are different fabrication strategies applicable for shell writing, like contouring by circles, helices, and parabolas (Fig. 2). In the following, the fabrication via consecutive circles will be discussed. The corresponding number of circles and position of each circle depends on the writing parameter of either *dr, ds,* or *dz*. This parameter, set to be constant, defines the position of consecutive circles with respect to the shell. Additionally, the shape of the voxel – resembling an ellipsoid with a minor diameter *dr* and an eccentricity ε – can be used.

Regarding conventional full volume writing, slicing and hatching distances are typically in the range of 0.1 to 0.3 µm. The corresponding fabrication time for a single spherical microlens with a diameter of 25 µm and a radius of a curvature of 20 µm using this fabrication strategy is dependent on the writing speed and is at best about 14 s for $dz = dx = 0.2$ µm, as depicted in Fig. 3.

Although galvo-scanners inherently possess a high, but still limited acceleration, the fabrication time is not simply reduced by increasing the writing speed (fabrication using a velocity of

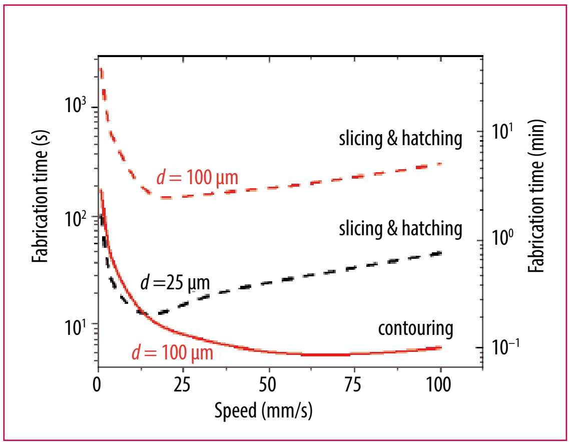

Fig. 3 Comparison of the fabrication times for slicing and hatching of the full volume of microlenses and contouring using circular slices of model microlenses of 25 and 100 µm diameter, respectively.

100 mm/s is easily possible). In order to ensure homogeneous polymerization in the exposure process, randomized starting points with included acceleration pathways are implemented for the fabrication process. Thus, there is an optimum scanning speed in terms of fabrication time for every structure. For larger microlenses with a diameter of 100 µm and a radius of curvature of 100 µm, the fabrication time increases to 150 s for the slicing and hatching mode.

For prototyping of individual lenses, a fabrication time of 150 s for an individual microlens might be considered to be acceptable. For industrial scale prototyping and production, this fabrication time is by far too high to account for a reasonable throughput. Novel exposure and fabrication strategies allowed to further increase the throughput tremendously.

With respect to fabrication time, contouring the shell results in a pronounced reduction of the fabrication time of an individual microlens with 100 µm diameter and 100 µm radius of curvature to only 5.5 s (distinct parameter *dr*) compared to a fabrication time of 150 s when using slicing and hatching as method to create the lens. This corresponds to a saving of approximately 95 % of the fabrication time, and the resulting rms roughness in the range of 20 to 30 nm is even appropriate for applications in the visible.

The fabrication of a microlens can, in principle, be further accelerated by increasing the corresponding fabrication parameter *dr, dz* or *ds*, thereby decreasing the number of circles, provided that an increase in surface roughness can be tolerated to some extent. With the exposure strategies depicted in Figs. 2b to 2d, rms roughnesses of 20 to 30 nm were easily achieved, with still potential for further improvement.

Fabrication of 1 cm² microlens arrays

Regarding industrial applications, the total processing time for a 1 cm² lens array which is the typical size of chips for sensor applications is evaluated for the slicing and hatching method as well as for the shell writing technique. As previously, a microlens with a diameter of 100 µm and a radius of curvature of 100 µm is used as example structure.

In the fabrication process, the position of the interface is usually determined by an autofocus (AF) procedure in the writing step of each lens. As the substrate tilt is not very pronounced, a unit cell of (3 × 3) microlenses was defined with one single AF (time t_2) in the center of the unit cell as shown in Fig. 4. The times t_1 to t_6 are associated to the individual times for moving the focal volume via stages and scanner, and the movement only needs 0.4 % of the total fabrication time (without taking into account t_4, which is the fabrication time for an individual lens itself and considered separately, cf. Table 1). The definition of a unit cell reduces the amount of AF executions by a factor of nine, directly effecting the total processing time.

As discussed, the fabrication by slicing and hatching yields a fabrication time of 150 s for a single, high-quality microlens. Taking into account all necessary steps included in the fabrication process as schematically shown in Fig. 4a, the fabrication of a 1 cm² lens array with a filling factor of η = 50 % (6,400 lenses) takes approximately 270 hours, i.e. more than eleven days. This is not acceptable on an industrial scale, and it does not take advantage of the full potential of this technology.

Contrary, if only the outer shell is written for the same (3 × 3) unit cell with 5.5 s per lens (at constant *dr*), the fabrication time is already significantly reduced to about 12 h, i.e. by a factor of more than twenty. This seems to be acceptable, however, using another exposure strategy by also considering the ellipticity of the focal volume ε in combination with *dr* results in a fabrication time of a single microlens with the chosen layout of approximately 1 s, thus further reducing the fabrication time of the total 1 cm² microlens array down to about 3.6 h. The resulting rms roughness of 20 to 30 nm is well suited for application wavelengths of 850, 1310, and 1550 nm, and also acceptable for selected applications in the VIS.

In terms of mass manufacturing, parallelization of the writing process via multiple focal points can be implemented by diffractive optical elements (DOEs) or spatial light modulators (SLMs). Thus, contouring of microlenses in combination with parallelization provides fabrication with high throughput enabling the testing of different lens designs on a very short time scale. For example, using this fabrication strategy with an adapted layout and a 2 × 2 DOE, where four lenses can be written at a time, would result in a to-

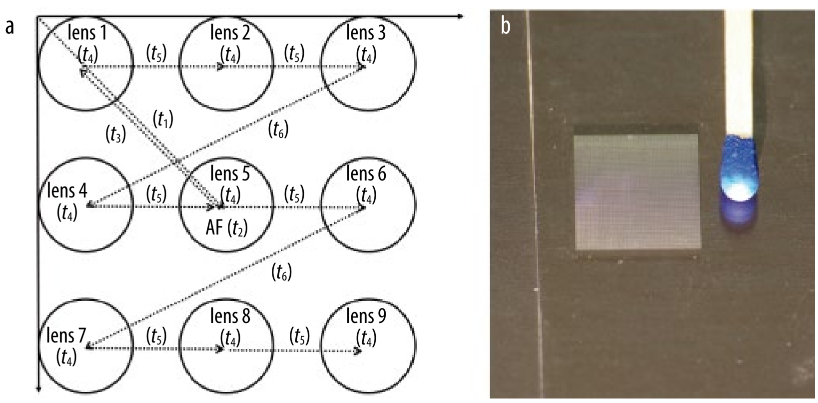

Fig. 4 Unit cell of (3 × 3) microlenses with one single autofocus procedure in the center (a). 1 cm² microlens array with a filling factor of 50 % (b).

1 cm² µlens array	slice & hatch benchmark	contouring (serial)		contouring (parallel: 2 × 2)
time single lens	150 s	5.5 s	1 s	0.25 s
roughness Ra	< 10 nm	20 – 30 nm		
time array	270 h	12 h	3.6 h	< 60 min

Table 1 Fabrication times of a 1 cm² lens array with a filling factor of 50 % consisting of 6,400 microlenses, each 100 µm in diameter, and with a radius of curvature of 100 µm. Conventional slicing and hatching fabrication strategy is compared to rapid contouring processes.

tal fabrication time of less than 1 h for the given 1 cm² microlens array. Table 1 summarizes the different strategies with their fabrication times.

The technology not only allows the fabrication of individual prototypes on a short time scale, but it particularly also enables mass manufacturing of aspheric and freeform optics by creating a master tool for replication, combining classical fabrication methods with high precision 3D printing. This enables industrial scale manufacture with arbitrarily shaped optical elements, among others.

Summary and conclusion

High-precision 3D printing using TPA provides a maskless real 3D laser direct writing process with the capability to create arbitrary and complex 3D structures that are not feasible with conventional methods. However, due to long fabrication times induced by the slicing and hatching writing strategy that is conventionally used by scientists, this technology is up to now only used for prototyping. For industrial purposes, novel strategies like contouring of bulky objects as microlenses enable a tremendous decrease of fabrication time by more than 90 %. By the implementation of parallelization, high throughput and scalability can be achieved thereby providing a fast and reliable technique with plenty room for design.

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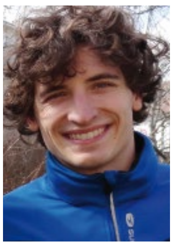

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Ruth Houbertz
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Houbertz owes more than ninety patents and received several awards, among them the COWIN Award of Entrepreneurship in 2014, the Green Photonics Award in 2013, the Joseph von Fraunhofer Award 2006, and the Stifterverbandspreis 2002 (cf. Company Box for more awards).

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