High-Speed 3D Direct Laser Writing of Micro-Optical Elements

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Abstract: We demonstrate high-speed diffraction-limited 3D direct laser writing using pivoted galvo mirrors. High photoresist curing speeds and stitching of individual scan fields allow for the fabrication of diffractive and refractive micro-optical elements on large areas.
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Three-dimensional direct laser writing (DLW) based on two-photon polymerization allows for versatile fabrication of micro- and nanostructures for a large variety of applications [1,2]. While DLW has become a working horse in many scientific laboratories all over the world, the transfer of applications to industrial products has not taken place yet. Here, we demonstrate the combination of our recent technical advances (i)-(iii) of DLW in order to fabricate arbitrarily shaped micro-optical elements on areas in the square-centimeter range.

(i) High-speed fabrication has been enabled by scanning the laser beam [3,4] instead of using a fixed-focus configuration. Diffraction-limited spot size of oil immersion objectives has been achieved using pivoted mirrors ensuring highest spatial resolution. Specially designed imaging optics allow for very small vignetting over the entire scan field. Residues of lateral aberrations are compensated by synchronous power adjustments. (ii) Recently, we have introduced 3D dip-in optical lithography to overcome the problem of axial aberrations [5]. Using laser-scanning dip-in lithography we demonstrate 3D patterning with processing times reduced by orders of magnitude. (iii) To achieve large-area patterning, we employ a stage concept to stitch adjacent writing volumes. By this, we have patterned areas in the cm^2 range on a variety of substrates and with high spatial resolution.

We have combined these developments to demonstrate the applicability of our DLW system for demanding optical elements, i.e., 3D woodpile photonic crystals, 2D diffractive photonic-color materials, and 3D free-form microoptics.

3D woodpile photonic crystals are well-studied optical materials that can exhibit a complete photonic band gap for sufficiently high refractive index contrast of the constituent material. To tune the Bragg reflection bands to optical frequencies, rod spacings of a few hundred nanometers are necessary, i.e., highest accuracy of the fabrication process is required. Therefore, woodpile photonic crystals often serve as benchmark structures for 3D DLW. With our high-speed DLW setup, we have achieved rod spacing as low as 500 nm with a high numerical-aperture objective (NA = 1.3). To further confirm the quality and functionality of the fabricated photonic crystals we present transmittance and reflectance spectra measured with a Fourier-transform microscope-spectrometer (Bruker Tensor 27 with Hyperion 1000 microscope).

As second application example, we have fabricated a multitude of photonic color materials [6] which are built up by 10s of millions of nanodots on reflective silicon substrates (depicted in Figure 1). By varying the dot spacing the diffracted color is tuned from blue to red. Then, we have mapped dot spacings to the colors of a picture (e.g., jpg or png) to fabricate large-area colored nanomaterials. These diffractive optical elements can potentially be used for security labels or sensors.

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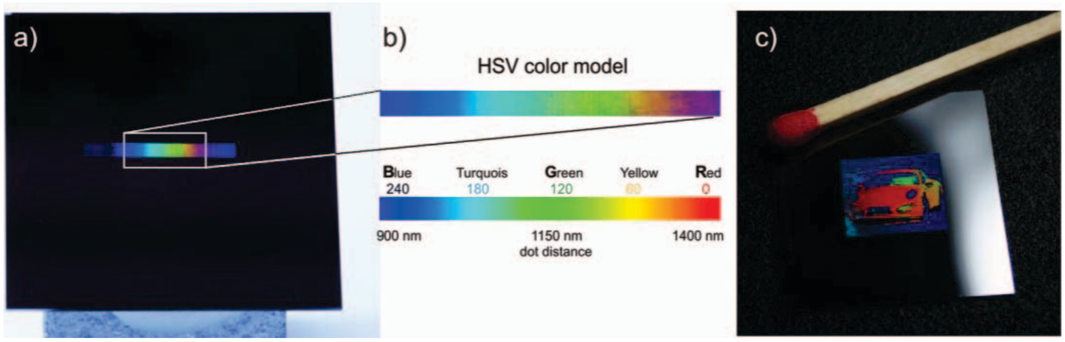

Fig. 1: a) Photograph of fabricated 10 mm × 1 mm rainbow made of dot arrays with varying dot distance. b) Mapping of dot distance to HSV color model. c) Example of a 10 mm × 8 mm photonic-color structure on a silicon substrate.

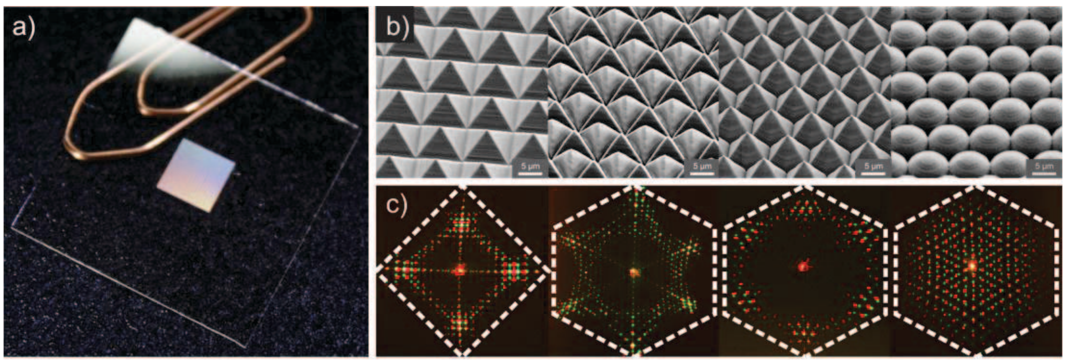

Fig. 2: a) Photograph of fabricated 5 mm × 5 mm array of pyramids. b) Gallery of scanning-electron micrographs of different microoptics. Note that there is no "dead zone" between the fabricated elements. The input can easily be created using commercial CAD programs. c) Corresponding diffraction patterns of the microoptics in b).

Finally, we demonstrate 3D free-form microoptics. Figure 2 a) shows a photograph of a fabricated 5 mm × 5 mm array of pyramids that has been stitched by using a mechanical stage. Arbitrary CAD files can be programmed (e.g., with the software "Blender") and directly be fabricated using DLW. Figure 2b) depicts electron micrographs of selected microoptics. The geometrical parameters of the pyramids and hemispheres are all about 10 µm. Note that there is no "dead-zone" between adjacent elements and that the fabrication process is not limited to periodic arrays. Using the simulation software "Light Trans Virtual Lab" we have calculated the far-field patterns (not depicted) of all arrays shown in Figure 2b). To validate the optical properties of the fabricated structures we use collimated laser diodes at green and red wavelengths in a forward-scattering setup. The diffraction patterns are then photographed from a screen and compared with theoretical results. The qualitative agreement between approximate calculations and experiments is good. However, the immense demand on computer memory for more rigorous calculation so far prevents quantitative comparisons.

In conclusion, we have demonstrated high-speed DLW at the diffraction limit and, simultaneously, on areas in the square-centimeter range. As an application example, we have fabricated and characterized high-quality micro-optical elements. We argue that the combination of laser-scanning lithography and stitching opens new routes for free-form optics that are not accessible with other fabrication techniques. Accordingly, DLW technology in its current state is already appealing for industrial applications.

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