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Massive Parallelization of Laser Beams with Diffractive Optical Elements for High Speed Two Photon Polymerization

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Abstract

Repetitive patterns were fabricated by parallel two photon induced photopolymerization (TPP) on Ormocomp® photoresist. Large patterns were created in one single step of microfabrication by dividing the original laser beam into 51×51 and 101×101 parallel beams using Diffractive Optical Elements (DOEs). A femtosecond pulsed laser, with a wavelength of 515 nm, was used in order to provide enough peak power to induce TPP within every single parallel beam. In this way, arrays of micron-sized cones were successfully fabricated in the resin using 0.3 W. However, the proximity effect limited the maximum number of parallel structures that could be fabricated simultaneously. Still, a very high fabrication throughput was achieved.

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1. Introduction

It has been already demonstrated that two-photon polymerization (TPP) is a reliable technique for the fabrication of complicated 3D structures in photosensitive materials. This technique has been successfully used for the fabrication of different structures for different applications (Serbin et al., 2003; Waheed et al., 2016) as for example the fabrication of 3D scaffolds for applications in tissue engineering (Ovsianikov et al., 2011).

One of the main advantages of TPP is the full flexibility for freeform fabrication, but at low rates. Parallelization through the use of Diffractive Optical Elements (DOEs) seems a valid method for the enhancement of TPP throughput. In this way, splitting the laser beam into multiple parallel beams promotes

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reaching fabrication speeds orders of magnitude faster than conventional TPP, specially for the fabrication of repetitive patterns which are of great interest for some photonic applications like metalenses (She et al., 2018).
In this work we report on the fabrication of different repetitive structures by using different DOEs providing over 10^4 parallel beams, as an effective method for the enhancement of TPP throughput.

2. Experimental details

All the samples were fabricated with a Laser micromachining workstation from OPTEC. The pulsed radiation from the second harmonic of an Amplitude Satuma HP^2 laser (280 fs, 515 nm), first expanded and then splitted into multiple parallel beams by a DOE (Nguyen et al., 2017), was focused inside the resin with an Olympus microscope objective (40×, NA 0.93). The DOEs that were used in this study, optimized to produce 3×3, 11×11, 51×51 and 101×101 parallel beams were provided by IMT-Atlantique, as part of a collaboration within the frame of the H2020 PHENOmenon project.

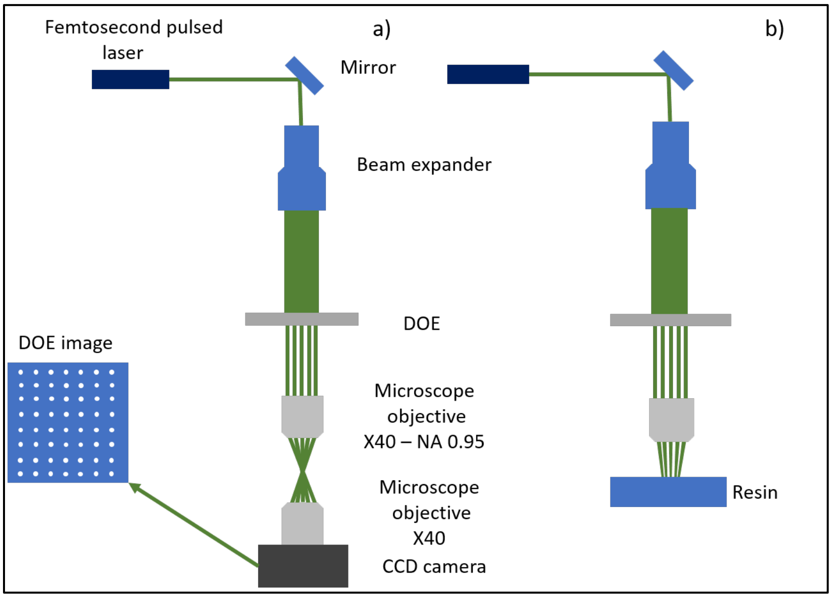

Fig. 1. Optical setup for the a) characterization of the DOEs and b) microfabrication inside the resin.

Prior to the microfabrication experiments, the image projected by the DOEs was characterized with the help of an additional microscope objective and a CCD camera (See Figure 1a), in order to assure that the DOE image was correctly projected through the optical system. After the DOEs characterization, conical microstructures were fabricated by scanning the focused multiple parallel beams along helicoidal trajectories with a decreasing diameter (bottom-up). In order to test the microfabrication feasibility with the parallel beams, all the experiments were carried out with a well-known commercial resin from Micro Resist Technology (OrmoComp$^©$), with the addition of a commercial photo initiator (1,3,5-Tris(2-(9-ethylcabazyl-3)ethylene)benzene, Sigma Aldrich). The development process used for this resin, once cured with the laser, involved its immersion in two solvents: first 30 minutes in a Methyl isobutyl ketone bath and then 30 minutes in isopropyl alcohol bath. After such process, the samples were air dried.

The characterization of the fabricated structures was carried out with an inverted optical microscope from Zeiss before and after developing. Additionally, the 3D characterization of the microfabricated structures was performed with a confocal microscope (SensoFar S Neox) after their development process.

3. Results and discussion

Figure 2 shows the projection image on the CCD camera of the different DOEs used in this study (3×3, 11×11. 51×51 and 101×101). As can be seen in the image, the parallel beams arrive separately to the CCD camera, indicating that the DOE effectively divides the beam into multiple parallel beams with enough distance between them, even if this distance is much shorter for the largest DOEs (51×51 and 101×101). On the other hand, there seems to be a slightly intense contribution from the zero order in the case of these latter DOEs, more relevant in the case of the 101×101 DOE, as noticeable by the stronger intensity of the central beam of the parallel beam array (see Figure 2c and 2d). Despite this small zero order effect, the DOEs seem to provide an optical resolution good enough for the fabrication of repetitive structures inside the resin with parallel beams.

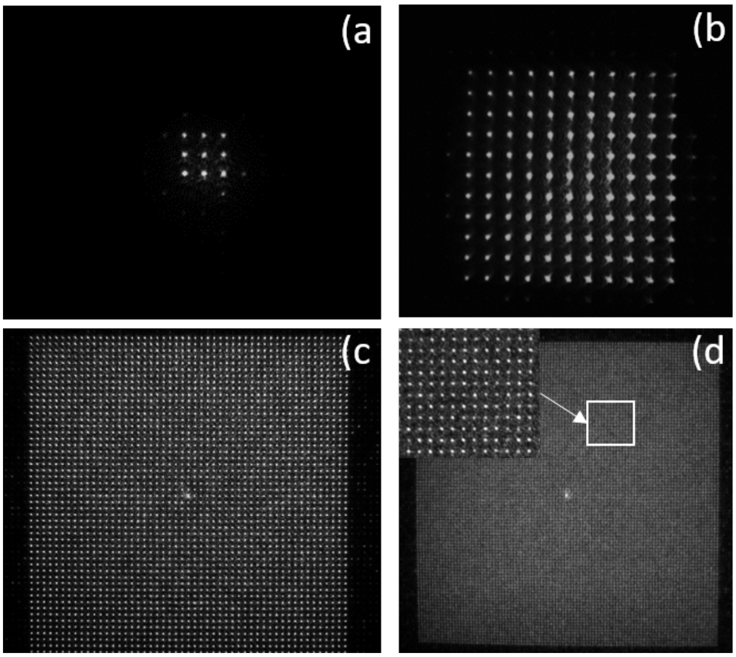

Fig. 2. Images of the a)3 ×3, b) 11×11, c) 51×51 and d) 101×101 DOEs obtained with the CCD camera.

Figure 3 shows optical image of conical microstructures fabricated with the 3×3 and 11×11 DOEs (Figure 3). In these two cases, the cones were fabricated in parallel with a similar, well defined, shape and with the separation given by the optical projection of the DOEs. Confocal imaging (Figure 4) is in agreement with the results obtained by optical microscopy. For both the 3×3 DOE and the 11×11 DOEs, the cones are well separated (12 µm in the case of the 3×3 DOE and 25 µm in the case of the 11×11 DOE), presenting a similar shape with an aspect ratio > 3. The fact that the distance between adjacent cones is larger in the case of the 11×11 DOE is related to the larger angular separation between individual focii, and it is a consequence of this particular DOE's fabrication. Additionally, this separation allows the fabrication of structures with a larger lateral size, which could be of interest for the fabrication of different optical elements, like microlens arrays or microprisms.

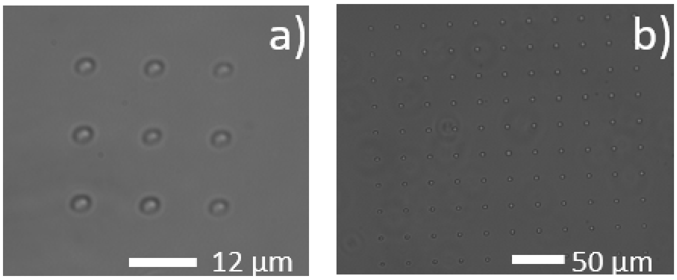

Fig. 3. Cones fabricated with the a) 3×3 and b) 11×11 DOEs

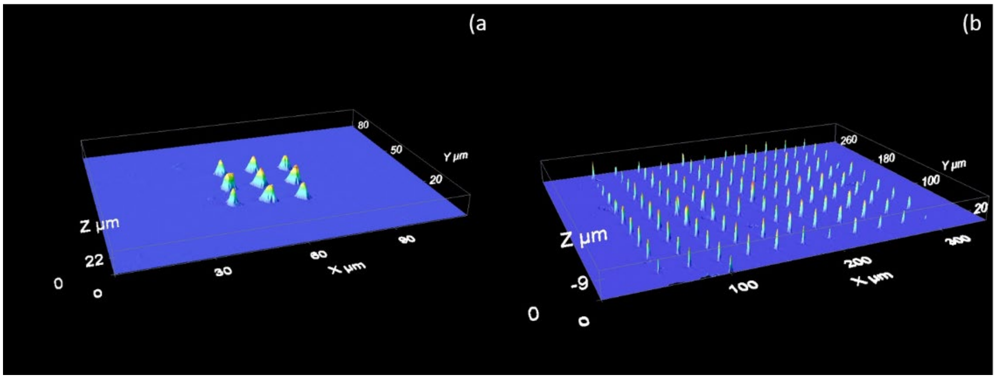

Fig. 4. Confocal images of the fabricated cones. a) with the 3×3 DOE and b) with the 11×11 DOE.

The cones fabricated with the 51×51 DOE present a similar shape as the cones fabricated with the smaller DOEs, as expected due to the fact that the cones were fabricated following similar trajectories. Moreover, as a result of the smaller distance between the parallel beams, the distance between adjacent cones (approximately 5 µm) is much smaller than in the case of the structures fabricated with the smallest DOEs (12 and 25 µm for the 3×3 and 11×11 DOEs, respectively). However, in this particular case noticeable differences between the cones fabricated with central and lateral beams can be observed (Figure 5). The fabrication of well-defined conical structures seems to require a smaller power within the central beams, while the fabrication of the same structures produced with the beams located closer to the edge of the DOE projection required of a higher power. This issue can be explained by the proximity effect, where the power needed for the photopolymerization of a single beam diminishes due to presence of other beams interacting with the resin in their surroundings. Such effect becomes relevant in the case of the 51×51 DOE due to the large number of parallel beams and the small distance between them, making difficult the fabrication of structures with the parallel beams closer to the edge. This effect is even more pronounced in the case of the 101×101 DOE, where the proximity effect becomes more evident as a consequence of the smaller distance amongst parallel beams, making extremely difficult to fabricate with all the parallel beams and producing isolated structures in the central area at the same time. In addition to the proximity effect, the fabrication with the 101×101 DOE is affected by its zero order, which could be already observed through its projection on the CCD camera.

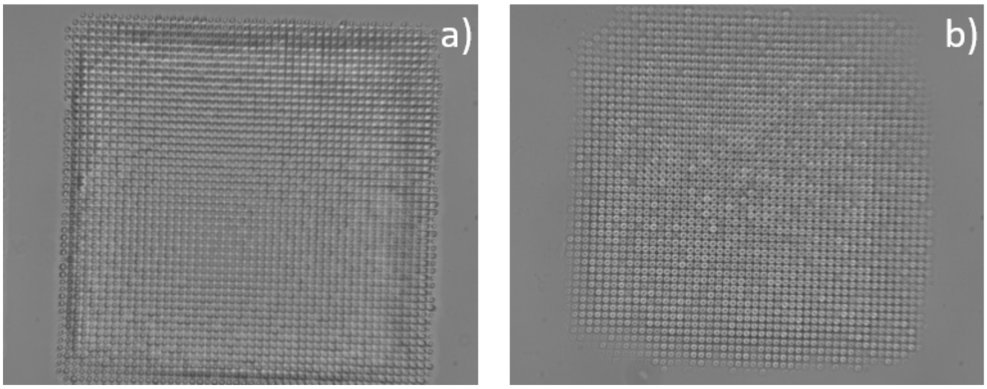

Fig. 5. Image of the cones fabricated with the 51x51 DOE with a) 320 mW and b) 192 mW.

4. Conclusions

Parallel two photon polymerization can be successfully achieved through the use of DOEs splitting the laser beam into multiple parallel beams, over 2600. Large fields of high aspect ratio structures can be fabricated with this technique, increasing dramatically its throughput through parallelization. However, massive parallelization induces the appearance of a strong proximity effect and an increasing zero order effect. Despite this drawback, a very high fabrication throughput could be achieved through parallel TPP.

Further research must be dedicated to the correction of the proximity effect through the design of DOEs producing parallel beams with different intensities to compensate such effect. Moreover, the reduction of the zero order for massive parallelization DOEs must be also investigated in the future.

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