Micro-optical systems for quantum technologies with laser-trapped neutral atoms based on rapid prototyping by 3D direct laser writing

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We present recent work with a microlens array fabricated by 3D direct laser writing. This micro-optical system is used to produce an array of optical tweezers dedicated for trapping individual neutral rubidium atoms. By employing a digital mirror device, we obtain dynamic control of the light field incident on the microlens array, allowing us to generate versatile trap patterns.

1 Introduction

The seminal invention of optical tweezers [1] has paved a way for a broad range of applications [2]: Optical tweezers can be used to investigate mesoscopic particles just as biological objects and individual neutral atoms. Ultra-cold atoms in 2D arrays of optical tweezers provide an excellent platform for quantum technologies since efficient quantum simulation, quantum information processing, and quantum metrology require scalable architectures that guarantee the allocation of large-scale resources of quantum systems. Our work is based on micro-optical elements for providing the necessary hardware: We use microlens arrays (MLA) to create 2D registers of individual ^{85}Rb atoms [3]. This implementation benefits from a high stability due to the inherent alignment of the optical tweezers and from an extensive scalability since there are MLAs with tens of thousands of lenses available [4]. However, there is still a demand for flexible geometries and dynamic reconfiguration of the tweezer arrays. Within the recent years, 3D printed micro-optical systems have gained tremendous complexity and accuracy [5]. Here, we report on the realization of tweezer arrays with flexible multisite geometries based on MLAs fabricated by 3D direct laser writing. The combination with a digital mirror device (DMD) allows us to dynamically configure the light field illuminating the MLA and thus the tweezer pattern.

2 Design and fabrication

We use 3D dip-in direct laser writing with a femtosecond lithography system (Nanoscribe Photonic Professional GT) to fabricate an array of 97 spherical lenses with a diameter and a pitch of 110 µm. The lenses are written sequently on a fused silica substrate with a writing speed of approximately 10 lenses per hour.

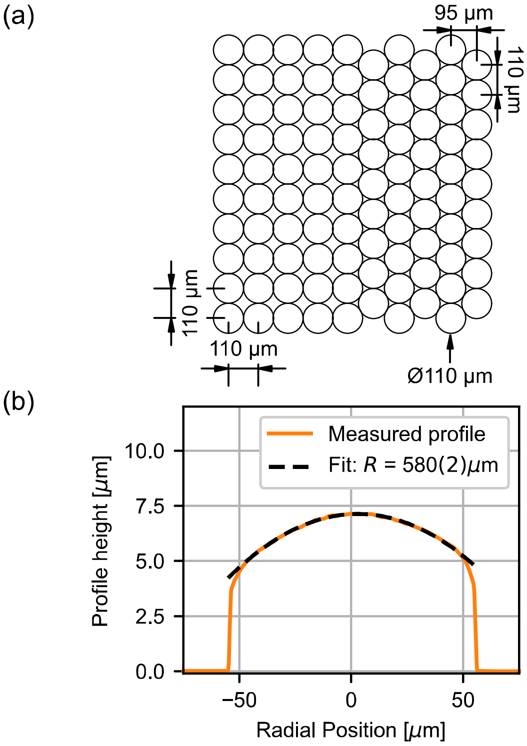

Fig. 1 *(a) Design of an MLA for fabrication by 3D direct laser writing. (b) Surface profile of a typical lens of the manufactured MLA with a radius of curvature* $R = 580(2)$ *µm.*

The layout in Fig. 1 (a) illustrates the nonstandard design of the MLA which features a central transition from a quadratic pattern (left) to a hexagonal pattern (right). The surface of the manufactured MLA is inspected with a confocal microscope. A typical lens profile is depicted in Fig. 1 (b). We retrieve a spherical surface with a radius of curvature of 580(2) µm and a rms-deviation of 0.03 µm from the sphere within 90 % of the lens diameter. Note that the curved lens structures are shallow compared to their diameter. This puts high demands on the writing resolution and on the acceptable sur-

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face roughness. We use the photoresist Nanoscribe IP-S (index of refraction 1.505 for a wavelength of 796 nm [6]) which has been designed for this purpose. The obtained surface roughness is negligible compared to the profile height. Each lens is printed on a pedestal to compensate for wedging and surface imperfections of the substrate.

3 Optical tweezer setup

Fig. 2 (a) shows a schematic of the optical setup used to generate an array of optical tweezers. A DMD (Texas Instruments Lightcrafter EVM) is used in order to render the microlenses selectively addressable. This device features 608×684 quadratic mirrors that can be tilted individually between two distinct positions of ±12° relative to the DMD surface. Laser light at a wavelength of 796.7 nm illuminates the device. The DMD plane is mapped onto the MLA using a confocal telescope with a demagnification of 0.45 such that each microlens is spatially correlated to 730(8) mirrors on the DMD. The MLA creates a regular pattern of focal spots with a $1/e^2$-waist of 6.5(3) μm. In order to serve as an optical tweezers array the focal plane is relayed and demagnified by a factor of 0.094(3).

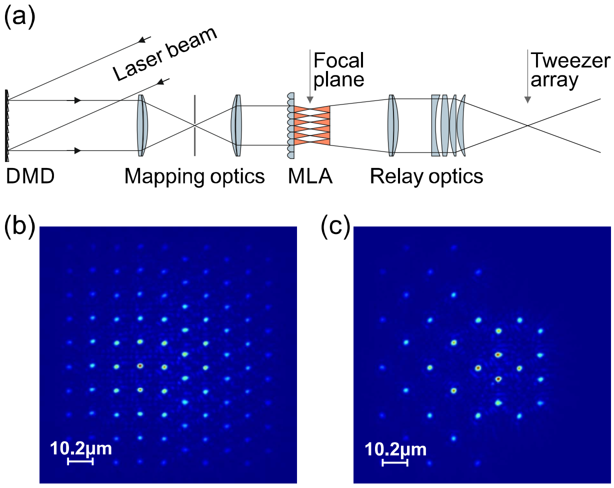

Fig. 2 *(a) Optical setup used to generate an array of optical tweezers. (b) Full tweezer array with all lenslets illuminated. (c) A DMD is used to generate arbitray tweezer patterns dynamically.*

Fig. 2 (b) shows an image of the full tweezer array recorded with a charge-coupled device camera (CCD). Well defined optical tweezers with a distance of 10.2(3) μm and a diffraction-limited $1/e^2$-waist of 1.33(6) μm are generated. The peak intensities of the spots show a Gaussian envelope caused by the Gaussian beam with a waist of 1.2 mm illuminating the DMD. In Fig. 2 (c) several tweezers are deactivated by flipping the corresponding sets of mirrors on the DMD. We obtain a high extinction ratio that is consistent with the noise floor of this measurement while there is negligible influence on the activated tweezer traps.

4 Conclusion

We have presented an optical tweezer array generated by a micro-optical system fabricated by 3D direct laser writing in a rapid production cycle. This method allows us to produce microlens arrays with versatile geometries on demand. Additionally, the design of each lenslet can be adapted to match an existing optical setup. The obtained tweezer array is suitable for trapping individual atoms when compared to state-of-the-art experiments [7]. A novel combination of a digital mirror device and the microlens array allows us to deactivate individual traps dynamically granting access to arbitrary tweezer sub-arrays.

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