

Scalable Multilayer Architecture of Assembled Single-Atom Qubit Arrays in a Three-Dimensional Talbot Tweezer Lattice

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We report on the realization of a novel platform for the creation of large-scale 3D multilayer configurations of planar arrays of individual neutral-atom qubits: a microlens-generated Talbot tweezer lattice that extends 2D tweezer arrays to the third dimension at no additional costs. We demonstrate the trapping and imaging of rubidium atoms in integer and fractional Talbot planes and the assembly of defect-free atom arrays in different layers. The Talbot self-imaging effect for microlens arrays constitutes a structurally robust and wavelength-universal method for the realization of 3D atom arrays with beneficial scaling properties. With more than 750 qubit sites per 2D layer, these scaling properties imply that 10 000 qubit sites are already accessible in 3D in our current implementation. The trap topology and functionality are configurable in the micrometer regime. We use this to generate interleaved lattices with dynamic position control and parallelized sublattice addressing of spin states for immediate application in quantum science and technology.

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Rapid advances in experimental platforms for quantum science and technology propel progress in a wide range of forefront research: exploiting the laws of quantum mechanics, experiments promote quantum chemistry [1], quantum interferometry [2], quantum metrology [3,4], and quantum information science [5–8]. One of the signature architectures are arrays of neutral atoms in optical tweezers [9], which constitute a versatile experimental platform with comprehensive coherent control of quantum states and tunable interactions at the single quantum level. Their spatially resolved trapping sites are adaptable to hold individual atoms [10–12] and can be composed of multiple colors of laser light [13–16]. Straightforward dynamic position control facilitates the coherent transport of quantum states [17–21] and the seminal assembly of defect-free subarrays [9,22–25]. Thus, arrays of individually controlled microtraps lend themselves to the bottom-up engineering of quantum systems with configurable tunnel coupling [9,19,26–28] and on-demand Rydberg interactions [9,16,22–25,29–34].

For future progress, scalability is pivotal. In this Letter, we resolve this issue with a configurable large-scale implementation using a novel platform for quantum simulation and computing: we harness the Talbot effect [35–38] to extend a microlens-array (MLA) generated 2D periodic configuration of single-atom microtraps to a multilayer architecture in the third dimension (Fig. 1). This Talbot tweezer lattice unlocks a new class of 3D atomic arrays with excellent scalability as it is built in parallel from a microfabricated source element with tens of thousands of lenslets [39,40] and the self-imaging effect that extends the 2D tweezer array to 3D at no additional costs.

Figure 1(a) visualizes the experimental platform: the source element is a quadratic-grid MLA that is illuminated by a trapping laser beam with a Gaussian profile and produces a 2D periodic spot pattern in its focal plane. This is the origin of a 3D Talbot lattice, which exhibits integer and fractional self-images of the generating pattern in the axial dimension, referred to as Talbot planes [41]. The separation of integer self-images is given by the Talbot length $z_T = 2a^2/\lambda$, which is a quadratic function of the spatial period a of the generating pattern. In our setup, the MLA's focal plane with a pitch identical to the pitch of the MLA is reimaged and demagnified by the use of relay optics, which renders the trap size w_0 , trap pitch a , and the associated Talbot length configurable. Individual planes T_i are labeled according to their axial position normalized to z_T with T_0 being the reimaged focal plane. An important modification due to reimaging is the appearance of negative indexed Talbot planes before the focal plane T_0 that complete the symmetric 3D structure of the resulting Talbot tweezer lattice. Principal planes, such as $T_0, T_{\pm 1/2}, T_{\pm 1}, \dots$, show the same in-plane trapping geometry and pitch as the focal plane and are separated by $z_T/2$. The planar arrays in consecutive principal planes are shifted by $a/2$ in the x and y direction. A typical MLA, as used in the realization shown in Fig. 1, consists of $166 \times 166 = 27556$ refractive lenslets with a pitch of $30.0(3) \mu\text{m}$ (see figure caption for experimental parameters). Figure 1(b) shows a 2D projection of the simulated Talbot tweezer lattice in the relevant region along the optical axis.

During a sequence of optical molasses, laser cooled ^{85}Rb atoms are prepared in the lattice traps with typical depths on

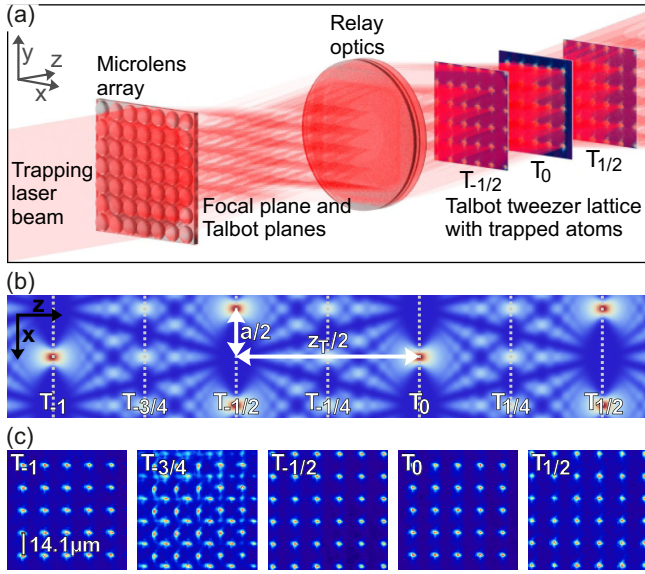


FIG. 1. Microlens-array generated Talbot tweezer lattice. (a) Schematic of the experimental setup. The MLA generates a 2D periodic spot pattern in its focal plane that is reproduced in Talbot planes. After reimaging and demagnification, these recurring self-images form a regular 3D multilayer lattice of 2D periodic optical microtrap arrays (for clarity, only three planes are drawn). (b) Detail of a 2D projection of the calculated intensity distribution (color coded) associated with a Talbot tweezer lattice created by an array of Gaussian beams. The principal planes $T_0, T_{\pm 1/2}, T_{\pm 1}, \dots$ are separated by $z_T/2$ and show a trap pitch identical to the one of the focal plane T_0 . Parameters are according to the experiment: $\lambda = 798.6$ nm, $a = 14.1(4)$ μm , $z_T/2 = 248(14)$ μm , $w_0 = 1.45(10)$ μm . (c) Averaged fluorescence images of single-atom arrays in integer and fractional Talbot planes (see text for details).

the order of $k_B \times 1$ mK. Because of the collisional blockade effect [10,11], each site is occupied by one atom at most. For the preparation and imaging of a 2D array of atoms in a selected Talbot plane, the imaging system is focused to the selected plane and the atoms in all other planes are removed with a resonant blow-away laser beam. Figure 1(c) exemplarily shows the averaged fluorescence images of individual atoms stored in the traps of the reimaged focal plane T_0 and of the Talbot planes $T_{-1}, T_{-3/4}$, and $T_{\pm 1/2}$. The trap positions are stable and optically resolved, which reveals the underlying periodic geometry. For the fractional plane $T_{-3/4}$, an increase in the number of trapping sites is observed. As expected, the trap pitch is reduced by a factor of 2, but the number of trapping sites with visible atomic fluorescence differs from a simple model: the signal is weaker and even vanishes for a subclass of sites at regular positions. We attribute the observed behavior to a modulation of the peak intensities within the plane resulting, for certain positions, in a reduction of the trap depth to the limit where atoms are no longer retained. This effect arises from interference of light transmitted by the lenslets and light transmitted through the interstices of

the MLA as well as from components of the light field that are not included in a simple paraxial description and originate in the spherical shape and limited aperture of the lenslets [36,54]. We do not observe these effects in the principal Talbot planes and thus limit our experiments to atoms within these principal planes.

The stochastic nature of the single-atom loading process is reflected by the random distribution of stored atoms within the 3D lattice, as pictured in Figs. 2(a) (left) and 2(b) (left) for the tweezer arrays of planes T_0 and $T_{-1/2}$. We observe a maximum probability of 0.6 to load an atom for central sites. This necessitates the incorporation of techniques for individual atom transport [17–21] and deterministic target pattern assembly [9,21–25], as a broad range of applications prerequisites defect-free atom arrays and the ability to mend atom loss during operation. For this purpose, we use a superposed movable optical tweezer. This technique lends itself to 3D layered configurations of tweezer arrays [55] and is applicable to any Talbot plane in a straightforward fashion as demonstrated in this Letter. In our setup, the transport tweezer is aligned with the imaging system and therefore automatically focused to the selected plane. The principle of operation is detailed in [39,56], where it has been applied to the rearrangement of atoms in the plane T_0 so far. Starting from the initial atom distribution, which serves as a reservoir, a sequence of transport operations is performed in order to reach complete filling of a predefined target structure. We define a 9×9 atom cluster as target structure and operate on a reservoir grid of 19×19 sites. On average, we initially prepare 191(17) atoms. Figures 2(a) and 2(b) show fluorescence images of the atom pattern before and after successful assembly in the planes T_0 and $T_{-1/2}$. After rearrangement, we observe an average filling fraction on the order of 0.9 and a typical success rate for a defect-free cluster of 12%. This demonstrates that defect-free atom assembly is possible in all principle planes of the Talbot tweezer lattice.

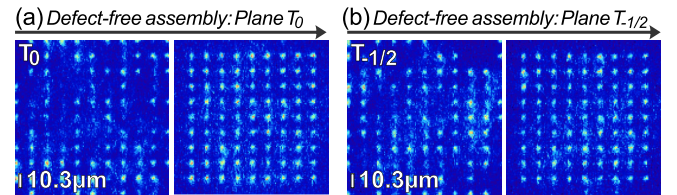


FIG. 2. In-plane assembly of defect-free target structures of individual atoms using an auxiliary transport tweezer. The reimaged focal plane T_0 (a) and the Talbot plane $T_{-1/2}$ (b) are shown (atom arrays are centered in the images due to cropping). Parameters: $\lambda = 797.3$ nm, $a = 10.3(3)$ μm , $z_T/2 = 133(8)$ μm , $w_0 = 1.45(1)$ μm , transport tweezer size (waist) $2.0(1)$ μm . The *in situ* atomic fluorescence of individual atoms at resolved trapping positions reveals the initial atom distribution [left in (a),(b)] and the successful creation of a 9×9 cluster via atom-by-atom assembly in both Talbot planes [right in (a),(b)]. The assembly process involves multiple cycles of atom rearrangement and position detection.

As a consequence, the Talbot tweezer lattice exhibits superior scalability by extending the assembled atom configurations from 2D to 3D. The 3D scaling properties as a function of laser power P , i.e., the number of trapping sites per principal plane multiplied by the number of planes with sufficient trap depth are governed by the following argument: within the 2D focal plane, the number of traps is identical to the number of illuminated lenslets, which is proportional to the square of the trap beam radius at the position of the MLA. The Talbot effect gives rise to an additional linear increase in the number of suitable principal Talbot planes and thus in the total number of traps as a function of the trap beam radius. In total, this leads to a cubic scaling of the integral trap number N_{int} in all principal planes of the 3D tweezer lattice. On the other hand, the required laser power increases linearly with the number of illuminated lenslets and quadratically with the trap beam radius at the MLA. No extra laser power is required for trapping of atoms in the additional Talbot planes. Extending to the third dimension comes for free! Furthermore, N_{int} is proportional to the ratio w_0/a of trap size and trap pitch. An increased spot size reduces the divergence of the propagating laser beams and accordingly reduces walk-off effects in the Talbot planes. A similar effect results from a reduction of the trap pitch, as this contracts the Talbot lattice. As usual for optical traps, the required power scales quadratically with the inverse trap size: $P \propto w_0^{-2}$. Hence, we obtain the overall scaling $N_{\text{int}} \propto P^{3/2}/(aw_0)$.

Figure 3 depicts these Talbot-specific scaling properties alongside an experimental implementation of a single-atom Talbot tweezer lattice optimized for a large number of traps. In Fig. 3(a), the integral number of traps N_{int} of all principal planes is given as a function of the trap laser power on the MLA. To calculate this number, the Talbot tweezer lattice is simulated by propagating an array of Gaussian beams [41]. Traps shallower than one-fifth of the normalized trap depth are neglected, which is in agreement with the experimental observations. For comparison, the green curve visualizes the linear scaling of the number of traps in one Talbot plane as a function of laser power. Obviously the scaling of the integral number of traps surpasses the scaling of the number of traps in one plane: the traps in the additional Talbot planes come for free. The image of Fig. 3(b) shows averaged fluorescence of the $T_{-1/2}$ plane of our largest implemented Talbot tweezer lattice. In this realization, the trapping laser was set to a wavelength of 796.3 nm and a radius (waist) of 17.5 lens pitches. A total power of $P = 0.803$ W was illuminating the lens array. The ratio of trap size and trap pitch was $w_0/a = 0.14$. These parameters result in 17 relevant principal planes originating from an array of 777 tweezers of sufficient depth in the plane T_0 . The variation along the principal planes is shown in Fig. 3(c). For the central tweezer intensity, a comparison of the ideal model (dashed blue line) to the results obtained when accounting for uncertainties of the MLA parameters

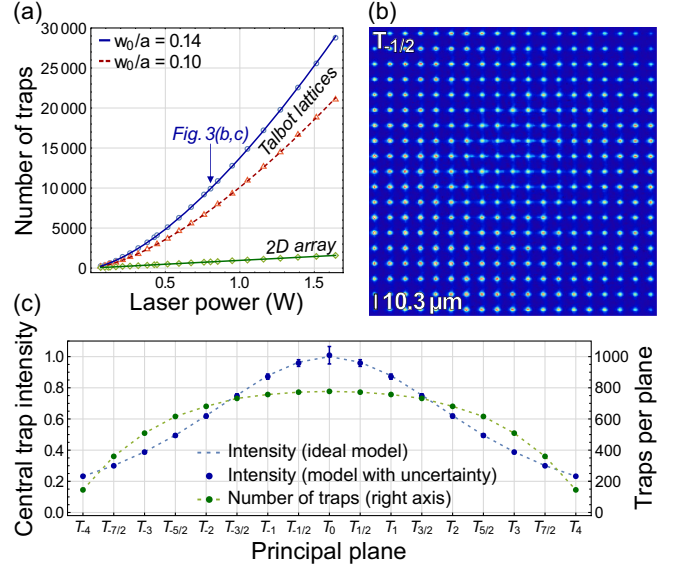


FIG. 3. Scaling properties of the Talbot tweezer lattice and large-scale implementation. (a) The integral number of traps of all principal planes in the 3D lattice shows a scaling of $N_{\text{int}} \propto P^{3/2}$ as function of the trap laser power. The scaling is plotted for the two experimental values of $w_0/a = 0.10$ [red dashed, corresponding to Figs. 1(c) and 4] and $w_0/a = 0.14$ [blue, corresponding to Figs. 2 and 3(b)]. In one plane (2D array), the number of traps is directly proportional to the laser power (green, linear scaling). (b) Experimental implementation of a 3D tweezer lattice with 10^4 traps [see indication in (a) and text for details]. The image shows a 19×19 detail of single atoms stored in the plane $T_{-1/2}$ (averaged fluorescence). (c) Intensity and trap number variation along the Talbot tweezer lattice of Fig. 3(b). The intensity of the central trap normalized to T_0 is given for the ideal model (dashed blue line) and the model including uncertainties (blue dots). Green dots depict the in-plane number of traps (right axis).

(blue dots) is given. As evident, the two models show only minor deviations. Furthermore, the self-imaging process results in a healing of perturbations for Talbot planes apart from T_0 . A detailed analysis of the properties of the MLAs used in this work and of the resulting Talbot tweezer lattices, as well as the impact of light field imperfections and production tolerances of MLAs are given in the Supplemental Material [41]. The in-plane trap count is depicted in green (dots, right axis). In total, we calculate a number of 10^4 traps of sufficient depth for this Talbot tweezer lattice, as presented in Fig. 3(a). Within the readily accessible limits of titanium-sapphire laser technology, the power illuminating the MLA can be scaled by at least a factor of 5 beyond the given power. This increases the integral number of traps N_{int} in the 3D lattice by a factor of 11, pushing the number of attainable single atom qubit sites beyond 10^5 based on the parameters of Fig. 3(b). No specific measures for reducing the spectral width beyond the typical parameters of commercial titanium-sapphire lasers are required due to the small variation of the lengths of the beam paths contributing to each Talbot spot [57].

In order to further explore the potential of Talbot tweezer lattices for quantum computation and simulation, we combine the scalability of our platform with the ability to parallelize quantum operations using interleaved Talbot lattices. This technique enables the dynamic modification of configurations in interleaved 2D subarrays and furthermore the realization of 3D layered geometries with layer separations not limited to the Talbot length. Thereby the class of accessible geometries is significantly expanded to elaborate arrangements that incorporate parallelized transport [11,18,21], enable multispecies trapping [9,15,29,58], can be configured to implement atom subgroups and ancilla atoms [25,58–60], and give access for applying inhomogeneous interaction potentials [61]. Versatile interleaved and layered Talbot tweezer lattices can be implemented by employing multiple MLAs [18,62] as well as by the illumination of a single MLA with multiple laser beams. The latter approach, as presented here, results in axially superposed lattice planes if the interleaved tweezer lattices are of near-identical wavelength. Lateral displacement of the lattice sites is achieved through a modification of the incident angle on the MLA. While the displacement is a linear function of the MLA's focal length for the plane T_0 , for all other Talbot planes one has to consider the effective focal length, which is enlarged by the absolute value of their axial separation from the focal plane before reimaging. Hence, working in a Talbot plane significantly reduces the required angular displacement for achieving a sufficient lateral displacement. This allows one to dynamically compose tweezer arrays of versatile geometries with flexible site separation from superposed movable subarrays that can be controlled independently.

Figure 4 shows configurations of two tweezer subarrays in the Talbot plane $T_{1/2}$, which are created from two interleaved lattices. These are implemented by extending the setup of Fig. 1 by a second trapping laser beam illuminating the same MLA under a variable angle. The two beams of equal size are set to a frequency difference of 30.0 MHz to avoid interference effects. An enclosed angle of 12.3 mrad introduces an offset of $a/2$ between the respective subarrays. Figure 4(a) (left) shows a uniform arrangement that reduces the trap separation by a factor of $\sqrt{2}$, with each site of one respective subarray (red) being equidistant to four sites of the other one (blue). Furthermore, the trap positions can be tuned to create atom chains and to favor pairs of atoms as presented in Fig. 4(a) (middle and right). In the current implementation, traps stay independent for a minimum separation of 3 μm , which is consistent with the trap waist. Considering applications of interacting atoms (e.g., via Rydberg interactions) the latter two asymmetric configurations allow for the implementation of selectable interaction geometries with interactions taking place, e.g., only along the columns as in Fig. 4(a) (middle) or only between multiple realizations of atom pairs as in Fig. 4(a) (right).

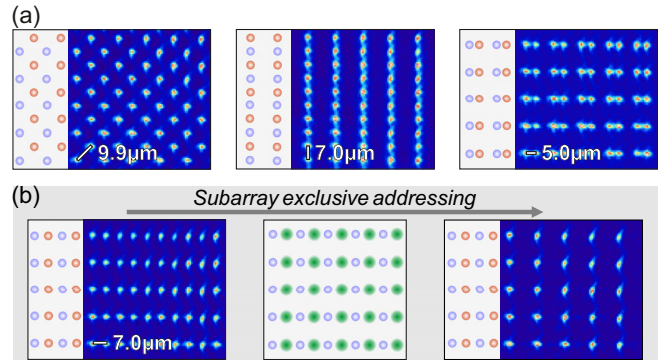


FIG. 4. Interleaved configurations of two Talbot tweezer lattices. All images show averaged fluorescence of the $T_{1/2}$ plane and the geometries are visualized by red and blue dots depicting the sites of the two lattices. (a) Single atom arrays with tunable atom separation. The separation of neighboring traps is (from left to right): 9.9(3) μm , 7.0(2) μm , and 5.0(2) μm . (b) Sublattice-exclusive addressing (green, middle) is used to convert a spin-polarized array ($F = 2$, left) to a configuration of columnwise antiferromagnetic ordering via preparation of alternating spin states ($F = 2$ and $F = 3$, right). State-selective detection records fluorescence for atoms in $F = 2$.

Laser-induced state manipulation and atom-atom coupling also profit from our approach: the sites of each sublattice remain independently laser-addressable in a parallelized fashion through the MLA, which focuses the addressing light onto the stored atoms and thereby amplifies state manipulation and atom-light coupling. If the addressing beam is set to spatial overlap with the trapping light before illuminating the MLA, it is auto-aligned with the traps while the spacing of interleaved tweezer arrays in a selected Talbot plane can be arbitrarily set within the limits given by trap pitch and trap waist.

In the experiments of Fig. 4(b) we demonstrate parallelized laser addressing in sublattices with the transfer of the spin state of single atoms stored in tweezer subarrays with a spacing of 7.0(2) μm . First, all atoms in the full set of traps are initialized to the $F = 2$ state of the ^{85}Rb ground-state hyperfine manifold and state-selectively detected afterwards by removing the population of the $F = 3$ state prior to detection (left). The results displayed on the right account for a modified experimental sequence where laser addressing transfers the atoms to the $F = 3$ state in a sublattice-exclusive fashion after initial state preparation, resulting in vanishing fluorescence at the addressed sites. This presents atom chains exhibiting antiferromagnetic ordering along the horizontal dimension in Fig. 4(b). The addressing light at 795 nm is brought to spatial overlap with the respective sublattice by superposing it with the respective trapping laser beam using a single mode optical fiber. For the center trap, the measured occupation probability after initial state preparation is 0.47(2). This value is reduced to 0.01(1) when including the subarray-exclusive state transfer before the state-selective detection. For the

unaddressed subarray, we observe a reduction on the order of 2%. We contribute this crosstalk to chromatic aberrations causing imperfect overlap of the addressing light and addressed sites as well as residual scattering in the unaddressed sublattice.

In summary, we have created Talbot tweezer lattices unfolding multisite 3D atom configurations with customizable structure sizes in the micrometer regime. With the presented work, microlens-generated tweezer arrays enter a regime that has formerly been accessible only by phase-sensitive standing wave configurations [63,64], yet they retain the simplicity and robustness of the MLA-based optical setup as well as their inherent features of coherent quantum state transport [18] and single-site addressability for qubit and spin-state manipulation [65]. The straightforward assembly of defect-free atom arrays facilitates bottom-up engineering of quantum systems in 2D and 3D geometries. In addition, atom separations can be dynamically adapted in 3D using layered interleaved configurations, while sublattice-exclusive addressability extends techniques for the initialization and readout of quantum states and allows for the parallelization of operations. The implemented Talbot tweezer lattices provide several thousand of single-addressable atomic qubits with separations well within the limits for coherent Rydberg-mediated interactions [56] with direct implications for neutral atom quantum information science. Extending the reported results within the limits of available technology, Talbot tweezer lattices in the regime of 100 000 quantum systems are accessible already to date.

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