

Dynamical spatial light modulation in the ultraviolet spectral range

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Spatial light modulators enable arbitrary control of the intensity of optical light fields and facilitate a variety of applications in biology, astronomy, and atomic, molecular, and optical physics. For coherent light fields, holography, implemented through arbitrary phase modulation, represents a highly power-efficient technique to shape the intensity of light patterns. Here, we introduce and benchmark a spatial light modulator based on a piston micromirror array. In particular, we utilize the reflection-based device to demonstrate arbitrary beam shaping in the ultraviolet (UV) regime at a wavelength of 322 nm. We correct aberrations of the reflected wave front and show that the modulator does not add detectable excess phase noise to the reflected light field. We utilize the intrinsically low latency of the architecture to demonstrate fast switching of arbitrary light patterns synchronized with short laser pulses at an update rate of 1 kHz. Finally, we outline how the modulator can act as an important component of a zone-based architecture for a neutral-atom quantum computer or simulator, including UV wavelengths.

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I. INTRODUCTION

Spatial and dynamical light-field control is a ubiquitous experimental capability in atomic, molecular, and optical physics. As one notable example, tweezer arrays of tightly focused laser beams have emerged as a powerful platform for quantum science experiments with neutral atoms, trapped ions, and molecules [1–18]. Various approaches have been followed for the generation of optical tweezers, including dynamical acousto-optic deflectors (AODs), static microlens arrays [19], metamaterials [20–22], digital micromirror devices (DMDs) [23], or phase-only spatial light modulators. The latter are most widely used due to

their appealing features, such as power efficiency and high optical quality and control, combined with the possibility of dynamically adjusting the optical potential during an experimental sequence [24,25]. So far, the vast majority of experiments utilize near-infrared and visible light for generating optical traps [26–28]. This limitation is inherent to liquid-crystal-on-silicon spatial light modulators (LCOS SLMs), the most widely used technology available for phase-only spatial light modulation. However, this technology is incompatible with modulation of light in the ultraviolet (UV) spectral range below approximately 350 nm due to liquid-crystal degradation under UV-light exposure [29]. An alternative approach is based on microelectromechanical system (MEMS) phase-only modulators, where the optical phase is controlled through the position of each micromirror in an array. Recently, the advanced spatial light-shaping capabilities and dynamical control of this approach have been demonstrated in the visible spectral range [30,31]. Compared with conventional approaches based on LCOS SLMs, this technology is fully compatible with operation at UV wavelengths [32].

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This opens interesting perspectives for arbitrary dynamical spatial light-control in the UV, which is highly relevant for new applications in trapping atoms at ultra-small distances [33] or for homogenizing UV beams for zone-based quantum computing and quantum simulation architectures [34].

Here, we follow this route and extend the working range of phase-only spatial light modulation into the UV spectral range using a reflection-based micromirror array (MMA) [30,31]. We characterize the performance of the MMA at a wavelength of 688 nm, demonstrating the arbitrary optical potential shaping, low phase-noise operation, and high optical power efficiency of the device. Furthermore, we implement arbitrary beam-shape control in the UV regime at 322 nm. Using spatially resolved interferometric optical-path-length measurements, we characterize the wave front of the reflected light and reach a root-mean-square (rms) flatness of $\lambda/100$ at a wavelength of 322 nm. Starting from this aberration-corrected beam, we realize several different tweezer-array configurations with a residual intensity nonuniformity smaller than 0.3% after equalizing the amplitudes of the tweezers using camera feedback [35]. We shape the incoming light into flat-top beam profiles with excellent intensity homogeneity of as little as 0.75% rms and 3.65% peak-to-peak variation over a distance of 113 μm . To demonstrate dynamical control, we synchronize the deflection of the MMA with short laser pulses and show configurable patterns at an update rate of 1 kHz, currently only limited by the electronic circuitry of the device.

II. BEAM SHAPING WITH A MICROMIRROR ARRAY

For our experiments, we use a prototype of a micromirror-array system (64k customer evaluation kit piston MMA α -module) with 256×256 square uncoated aluminum mirrors with a pitch of 16 μm . Each mirror is individually controlled electrostatically to configure its piston stroke with a resolution of 8 bits and a maximal stroke of 350 nm. Starting with a flat phase profile of the incoming beam, a programmable phase pattern is imprinted onto the reflected beam by tailoring the stroke of the mirror array. The MMA is illuminated at an incident angle of approximately 7° and reflects the beam [see Fig. 1(a)]. In this configuration, the imprinted phase profile corresponds to twice the path-length difference given by the mirror stroke, such that a full phase-modulation contrast of $\phi(x,y) \in [0, 2\pi]$ is feasible for wavelengths up to 700 nm. We continuously flush the MMA surface with a weak flow of nitrogen to prevent damage to the micromechanical components of the chip from ozone, which forms from ambient air under intense UV irradiation.

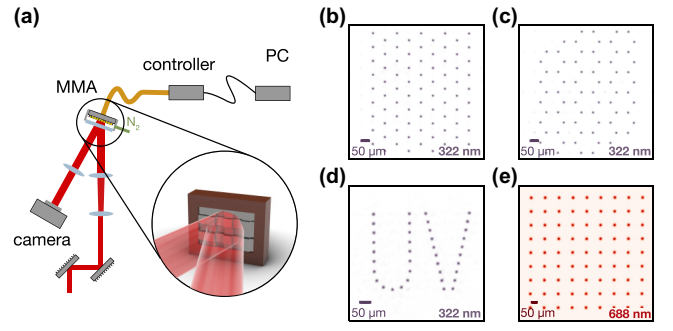


FIG. 1. Beam shaping with a piston micromirror array. (a) The optical setup to generate configurable beam shapes with a phase-only spatial light modulator based on a micromirror array (MMA). The individual mirrors are axially displaced by up to 350 nm, thereby realizing an adjustable phase delay that is imprinted onto a laser beam reflected from the device. We characterize the generated patterns on a camera. (b)–(d) We benchmark the device at a wavelength of 322 nm and demonstrate various tweezer arrays—(b) triangular, (c) honeycomb, and (d) a UV-letter shape—and reach state-of-the-art normalized homogeneity across the tweezer arrays of 0.3% peak-to-peak variation of the intensity. (e) A tweezer array at a wavelength of 688 nm, with 9×9 sites also reaching normalized peak-to-peak homogeneity of the intensity of 0.3%.

A. Phase-shifting interferometry

The generation of diffraction-limited potentials requires the compensation of optical aberrations in the system. We employ phase-shifting interferometry to obtain a spatially resolved stationary phase-correction pattern, which reflects the optical aberrations in the entire optical setup and can be used to correct the system [36,37]. To obtain the phase-correction map, we display a blazed grating on two circular patches of the MMA, one acting as reference, and the other one as probe superpixel, each with a radius of 10 pixels. Both superpixels diffract the light of the incoming beam along different paths through the optical system, which results in an interference fringe on the camera [see Fig. 2(a)]. The relative phase picked up by the beamlets emanating from the two superpixels translates to the phase of an interference fringe on the camera, which can be extracted directly. Keeping the position and phase of the reference pixel located in the center of the MMA fixed and varying the phase and position of the second superpixel, we map out the entire spatially dependent phase profile due to aberrations in the system. We subtract the gradient across the phase map to remove any tilt of the beam with respect to the imaging plane. In our setup, the initial wavefront error is dominated by astigmatism [see Fig. 2(c)]. Subsequently, we correct the phase front by adding the corresponding correction pattern and characterize the phase front with another round of phase-shifting interferometry. After one round of phase correction, we reach a state-of-the-art rms flatness of $\lambda/100$ at our wavelength of 322

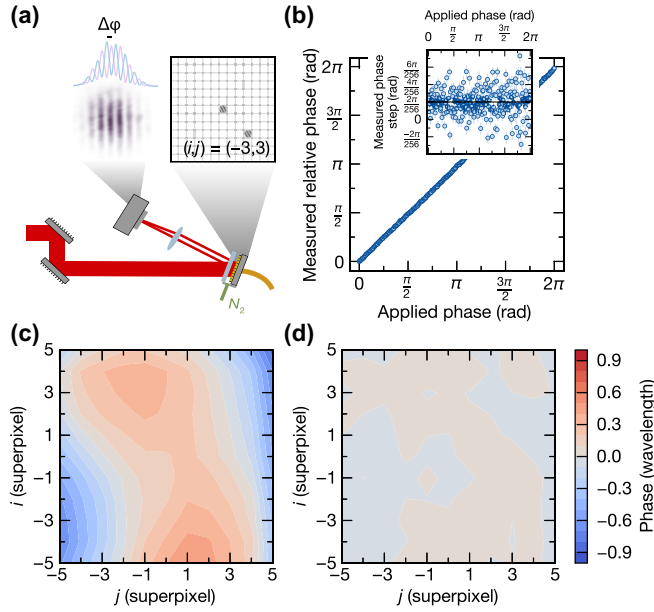


FIG. 2. Phase-shifting interferometry. (a) To correct optical aberrations in the setup, we carry out phase-shifting interferometry by sequentially activating various superpixels on the MMA display. By varying the phase of one superpixel with respect to a common (and fixed) reference superpixel in the center of the MMA, we map out the phase mask required for aberration correction. We measure the interference fringe on the camera and fit the collapsed one-dimensional fringe to extract the phase. (b) We choose one reference superpixel $(-3, 3)$ and step the phase of the grating from $[0, 2\pi)$ in steps of $2\pi/256$. We observe a linear relationship of the measured phase with respect to the applied phase, confirming the average phase step of $2\pi/256$ (inset). (c) The unwrapped and interpolated phase is shown as a function of the superpixel index after subtracting a global tilt of the wave front with respect to the imaging plane. (d) After the first round of wave-front measurement, we apply the measured phase as correction and repeat the wave-front-error measurement using the same technique. The result is a flat phase profile, verifying that the correction is effective.

nm across a circular aperture with the residual curvature shown in Fig. 2(d). To create arbitrary beam shapes such as the structures shown in Figs. 1(b)–1(e), we compute a hologram for the desired intensity pattern and measure the resulting intensity homogeneity on the camera [38]. Finally, we perform another round of optimizations of the hologram to equalize the tweezer intensity by weighing the amplitudes of the individual tweezers based on the measured image. The intensity patterns created in this way reach an inhomogeneity (standard deviation over mean) of 0.3% both in the visible and UV spectral range [see Figs. 1(b)–1(e)]. To characterize the phase resolution of the MMA, we step the phase of one superpixel in steps of $2\pi/256$ from $[0, 2\pi)$. The interferometrically measured phase confirms the average step size of $2\pi/256$

[see Fig. 2(b)]. The fluctuations of the measured phases indicate that the resolution of the optically realized hologram is reduced compared to the electronic resolution. From the deviation to a linear fit, we calculate the integral nonlinearity as the largest absolute value of the residuals as $2.2 \times 2\pi/256$ [39] and obtain a standard deviation of $0.91 \times 2\pi/256$.

III. MMA PHASE NOISE AND TIMING

A. Phase noise of the MMA

Applications of arbitrary light patterns for trapping and manipulating individual atoms are particularly sensitive to noise in optical potentials [40]. As each mirror of the MMA is mounted on a springlike structure and is controlled electrostatically to set the piston stroke, the noise characteristics need to be carefully analyzed to assess the range of possible applications of MMAs. To benchmark the stability of the displayed phase pattern, we measure the phase-noise power spectral density with a Mach-Zehnder interferometer [see Fig. 3(a)]. A collimated input beam at a wavelength of 688 nm is split into two paths using a beam splitter. One arm of the interferometer impinges on the MMA, which displays a flat phase profile with a stroke of π . A second beam splitter is used to recombine the light with the reference path to superimpose both light fields on a photodetector. To avoid masking the signal in low-frequency noise, we frequency offset the reference path by 80 MHz using an acousto-optic modulator (AOM) and derive the relevant signal from the resulting ac signal on the photodetector. The phase noise of the MMA modulates the phase of the beat signal, which we characterize using an electrical phase-noise analyzer. We configure a deflection duration of 500 ms and trigger the sweep of the phase-noise analyzer during activated MMA deflection. As a reference, we repeat the measurement with the MMA in the OFF state. Comparing the two measurements directly, we observe no noticeable excess noise when the MMA deflection is active [see Fig. 3(b)]. Our measurement thus yields an upper bound to the phase noise of the MMA, which is negligible compared to the phase noise induced by mechanical instabilities of the optomechanical setup up to frequencies of a few kilohertz. At higher frequencies in the (10–100)-kHz regime, our measurement is limited by phase noise on the radio-frequency signal used for driving the AOM, but we do not expect significant noise contributions from the MMA in this frequency range. We conclude that the phase noise of the MMA is compatible with typical optical setups used for holographic tweezer generation and, thus, will not limit the achievable performance of the device. In particular, the characteristic switching noise of LCOS SLMs is not present in this architecture, which might have beneficial consequences for extremely sensitive applications.

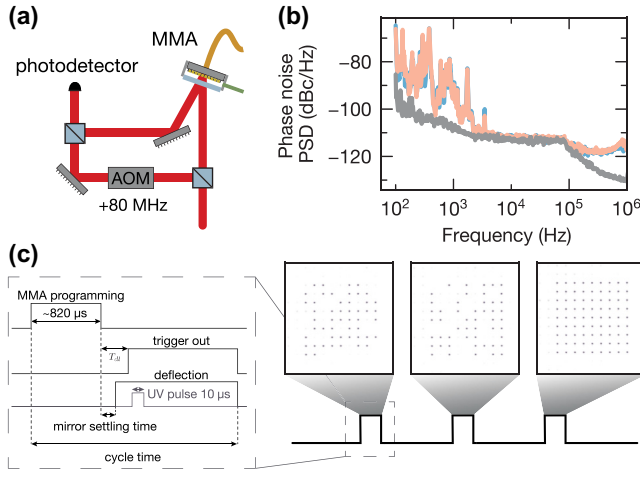


FIG. 3. Phase-noise characterization and MMA timing. (a) To measure the phase noise imprinted by the MMA, we set up an interferometer and frequency shift the reference arm by 80 MHz using an acousto-optic modulator (AOM). We interfere the frequency-shifted light with the light reflected from the MMA and detect the beat signal on a photodetector. (b) For the phase-noise measurement, we program a constant displacement on the MMA. The phase noise is recorded with an electrical spectrum analyzer (Keysight N9020B), which is synchronized with the MMA. We observe no noticeable difference of the phase noise with activated MMA deflection (blue) compared to deactivated deflection (orange). The phase noise of the radio-frequency signal used to drive the AOM is shown in gray. (c) The typical timing cycle of the MMA is shown starting with the programming duration of 820 μ s. After the mirror settling time of approximately 30 μ s, a user-configurable output trigger indicates that the desired deflection pattern is reached.

B. Timing and duty cycle of the MMA

Synchronization of the MMA deflection is possible via the transistor-transistor logic (TTL) inputs and outputs of the MMA controller. The MMA deflection cycle starts with an 820- μ s-long programming duration, in which the stroke of each mirror is configured. After programming, the device indicates the *ready* status with a corresponding TTL output and the deflection becomes active after a mirror settling time of approximately 30 μ s. Synchronization with additional devices is possible via a user-configurable TTL output signal indicating the completed deflection. Currently, the MMA allows for a maximal deflection duration of a few seconds and our interferometric phase-noise measurements indicate a degradation of the phase profile after approximately 1–2 s, which we attribute to variations in the control voltages that set the piston stroke. To demonstrate rapid switching of phase patterns, we perform a proof-of-concept experiment in which we synchronize short laser pulses with the deflection of the MMA. At an update rate of 1 kHz, we apply light pulses of 10- μ s duration controlled via an acousto-optic deflector. For these settings, corresponding to a duty cycle of 1%, we observe

no degradation of the MMA for peak powers up to 100 mW at 322 nm and a beam waist of 1 mm. Our sequence, which mimics, e.g., a gate sequence in a neutral-atom quantum simulator or computer, establishes piston micromirror arrays as a promising platform for a gate controller [41] of atom arrays in the UV spectral range.

IV. APPLICATIONS FOR NEUTRAL-ATOM BASED QUANTUM TECHNOLOGIES

In a final set of measurements, we demonstrate the perspectives of using the MMA for quantum simulation or quantum computing. In particular, we focus on zone-based architectures recently brought forward [13] and successfully employed for quantum computing [34,42,43] and digital quantum simulation [44]. In this approach, atoms are dynamically shuttled between different zones optimized for storage, manipulation, and readout [see Fig. 4(b)]. The manipulation zones host multiple atoms to allow for parallel execution of the gate operation, which benefits strongly from a homogeneous illumination of the entire zone. This is ideally realized with one or several flat-top beams to minimize the alignment sensitivity of the system and maximize the number of gates executable in parallel. Creating such flat-top beams poses a challenge for transitions in the UV, as found for Rydberg *p* states in alkali atoms [45,46] and Rydberg *s* states in strontium [47–49] or ytterbium [14,43,50], starting from the metastable states. We leverage the phase control of the MMA to create flat-top beams in the UV and visible spectral ranges, exploiting the programmability of the MMA compared to passive and static beam-shaper assemblies, which are tailored to a specific input beam shape and wavelength. To compute the phase mask for a flat-top beam, we take the measured amplitude on the MMA during the phase-correction measurement as the input field and assume a flat phase profile. We then apply a round aperture on the MMA, directing light outside of the aperture in the zeroth diffraction order of the MMA. We then create an amplitude target in the image plane with super-Gaussian decay of order $N = 3$ in the flanks and a flat amplitude profile at the center. With UV laser light, we create a one-dimensional flat-top beam, suitable for executing fast entangling gates across an array of atoms. In the visible wavelength range, we also create a two-dimensional flat-top beam with a flat center along both the *x* and *y* directions with rounded corners, which is especially robust against beam-pointing fluctuations. We optimize the phase profile in a first stage by running a gradient-optimization routine minimizing the rms difference between the propagated far field and the target in a specified region of interest around the flat-top beam. Initially, this procedure results in a flat-top beam with significant intensity variations. We therefore image the beam and optimize both the input amplitude for the gradient-descent algorithm as well as the phase correction

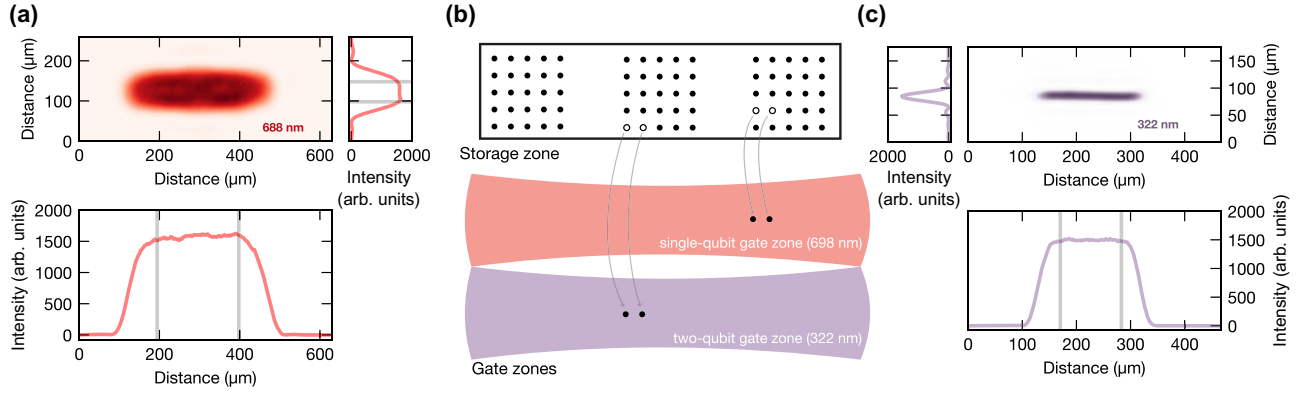


FIG. 4. Flat-top beam generation. (a) The generated flat-top beam profile at a wavelength of 688 nm. (b) An overview of the zone architecture for neutral-atom-based quantum information processors. Arrays of neutral atoms are dynamically shuttled between dedicated zones for storage and for driving single- and two-qubit gates, where homogeneous flat-top illumination is highly advantageous. Additionally, individual atoms are addressed through a high-resolution objective. Executing programmable quantum circuits requires rapid switching of the addressing pattern to realize local control by switching the light intensity on each qubit. (c) The generated flat-top beam profile at a wavelength of 322 nm.

by optimizing over the amplitude of Zernike polynomials up to eighth order. By this procedure, we generate flat-top beams at wavelengths of 322 nm and 688 nm (see Fig. 4). At a wavelength of 322 nm, we reach a residual rms inhomogeneity of 0.75% and peak-to-peak variation of 3.65% over a distance of 113 μm at a power efficiency of 28%, which is compatible with reaching state-of-the-art logical gate fidelities across a large number of qubits [51]. At 688 nm, we demonstrate a two-dimensional flat-top beam reaching an rms inhomogeneity of 1.8% (1.4%) and peak-to-peak variation of 7.4% (6.2%) in the x (y) directions at a power efficiency of 38%.

V. CONCLUSIONS AND OUTLOOK

Our measurements demonstrate that piston micromirror arrays can be used for dynamical arbitrary spatial light-field control in the visible and UV and are a promising alternative to LCOS SLMs. We reach state-of-the-art performance, both in phase-correction as well as tweezer homogeneity. Scaling up the number of mirrors would enable even higher diffraction efficiencies for large arrays of thousands of tweezers. We show that MMA technology holds promise to enable high-fidelity entangling gates across even larger qubit arrays by generating homogeneous flat-top beams. In particular, the current speed limit is not set by fundamental mechanical mirror properties but, rather, by the underlying MEMS-control electronics, which we expect can be updated in a further developed version of the MMA. Beyond the demonstrations shown in this work, the fast update rate of 1 kHz opens up possibilities for rapid switching between phase masks with multiple applications for atom-based quantum technologies, such as the recently demonstrated parallel atom

resorting [24,25,52] or power-efficient implementations of parallel-executed gates in large systems.

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DATA AVAILABILITY

The data that support the findings of this paper are openly available [53].

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- [1] M. Saffman, Quantum computing with atomic qubits and Rydberg interactions: Progress and challenges, *J. Phys. B: At. Mol. Opt. Phys.* **49**, 202001 (2016).
 - [2] A. Browaeys and T. Lahaye, Many-body physics with individually controlled Rydberg atoms, *Nat. Phys.* **16**, 132 (2020).
 - [3] A. M. Kaufman and K.-K. Ni, Quantum science with optical tweezer arrays of ultracold atoms and molecules, *Nat. Phys.* **17**, 1324 (2021).
 - [4] M. Morgado and S. Whitlock, Quantum simulation and computing with Rydberg-interacting qubits, *AVS Quantum Sci.* **3**, 023501 (2021).
 - [5] N. Schlosser, G. Reymond, I. Protsenko, and P. Grangier, Sub-Poissonian loading of single atoms in a microscopic dipole trap, *Nature* **411**, 1024 (2001).
 - [6] D. Barredo, S. de Léséleuc, V. Lienhard, T. Lahaye, and A. Browaeys, An atom-by-atom assembler of defect-free arbitrary two-dimensional atomic arrays, *Science* **354**, 1021 (2016).
 - [7] M. Endres, H. Bernien, A. Keesling, H. Levine, E. R. Anschuetz, A. Krajenbrink, C. Senko, V. Vuletić, M. Greiner, and M. D. Lukin, Atom-by-atom assembly of defect-free one-dimensional cold atom arrays, *Science* **354**, 1024 (2016).
 - [8] A. Cooper, J. P. Covey, I. S. Madjarov, S. G. Porsev, M. S. Safronova, and M. Endres, Alkaline-earth atoms in optical tweezers, *Phys. Rev. X* **8**, 041055 (2018).
 - [9] M. A. Norcia, A. W. Young, and A. M. Kaufman, Microscopic control and detection of ultracold strontium in optical-tweezer arrays, *Phys. Rev. X* **8**, 041054 (2018).
 - [10] S. Saskin, J. T. Wilson, B. Grinkemeyer, and J. D. Thompson, Narrow-line cooling and imaging of ytterbium atoms in an optical tweezer array, *Phys. Rev. Lett.* **122**, 143002 (2019).
 - [11] A. W. Young, W. J. Eckner, W. R. Milner, D. Kedar, M. A. Norcia, E. Oelker, N. Schine, J. Ye, and A. M. Kaufman, Half-minute-scale atomic coherence and high relative stability in a tweezer clock, *Nature* **588**, 857 (2020).
 - [12] S. Ebadi, T. T. Wang, H. Levine, A. Keesling, G. Semeghini, A. Omran, D. Bluvstein, R. Samajdar, H. Pichler, W. W. Ho, S. Choi, S. Sachdev, M. Greiner, V. Vuletić, and M. D. Lukin, Quantum phases of matter on a 256-atom programmable quantum simulator, *Nature* **595**, 227 (2021).
 - [13] D. Bluvstein, H. Levine, G. Semeghini, T. T. Wang, S. Ebadi, M. Kalinowski, A. Keesling, N. Maskara, H. Pichler, M. Greiner, V. Vuletić, and M. D. Lukin, A quantum processor based on coherent transport of entangled atom arrays, *Nature* **604**, 451 (2022).
 - [14] S. Ma, G. Liu, P. Peng, B. Zhang, S. Jandura, J. Claes, A. P. Burgers, G. Pupillo, S. Puri, and J. D. Thompson, High-fidelity gates and mid-circuit erasure conversion in an atomic qubit, *Nature* **622**, 279 (2023).
 - [15] S. J. Evered, D. Bluvstein, M. Kalinowski, S. Ebadi, T. Manovitz, H. Zhou, S. H. Li, A. A. Geim, T. T. Wang, N. Maskara, H. Levine, G. Semeghini, M. Greiner, V. Vuletić, and M. D. Lukin, High-fidelity parallel entangling gates on a neutral-atom quantum computer, *Nature* **622**, 268 (2023).
 - [16] L. Pause, L. Sturm, M. Mittenbühler, S. Amann, T. Preuschoff, D. Schäffner, M. Schlosser, and G. Birkel, Supercharged two-dimensional tweezer array with more than 1000 atomic qubits, *Optica* **11**, 222 (2024).
 - [17] H. J. Manetsch, G. Nomura, E. Bataille, K. H. Leung, X. Lv, and M. Endres, A tweezer array with 6100 highly coherent atomic qubits, *ArXiv:2403.12021*.
 - [18] A. Guttridge, T. R. Hepworth, D. K. Ruttley, A. A. Durst, M. T. Eiles, and S. L. Cornish, Individual assembly of two-species Rydberg molecules using optical tweezers, *Phys. Rev. Lett.* **134**, 133401 (2025).
 - [19] D. Schäffner, T. Schreiber, F. Lenz, M. Schlosser, and G. Birkel, Quantum sensing in tweezer arrays: Optical magnetometry on an individual-atom sensor grid, *PRX Quantum* **5**, 010311 (2024).
 - [20] T.-W. Hsu, W. Zhu, T. Thiele, M. O. Brown, S. B. Papp, A. Agrawal, and C. A. Regal, Single-atom trapping in a metasurface-lens optical tweezer, *PRX Quantum* **3**, 030316 (2022).
 - [21] A. Holman, Y. Xu, X. Sun, J. Wu, M. Wang, B. Seo, N. Yu, and S. Will, Trapping of single atoms in metasurface optical tweezer arrays, *ArXiv:2411.05321*.
 - [22] P. Huft, Y. Song, T. M. Graham, K. Jooya, S. Deshpande, C. Fang, M. Kats, and M. Saffman, Simple, passive design for large optical trap arrays for single atoms, *Phys. Rev. A* **105**, 063111 (2022).
 - [23] Y. Wang, S. Shevate, T. M. Wintermantel, M. Morgado, G. Lohead, and S. Whitlock, Preparation of hundreds of microscopic atomic ensembles in optical tweezer arrays, *npj Quantum Inf.* **6**, 54 (2020).
 - [24] R. Lin, H.-S. Zhong, Y. Li, Z.-R. Zhao, L.-T. Zheng, T.-R. Hu, H.-M. Wu, Z. Wu, W.-J. Ma, Y. Gao, Y.-K. Zhu, Z.-F. Su, W.-L. Ouyang, Y.-C. Zhang, J. Rui, M.-C. Chen, C.-Y. Lu, and J.-W. Pan, AI-enabled rapid assembly of thousands of defect-free neutral atom arrays with constant-time-overhead, *ArXiv:2412.14647*.
 - [25] I. H. A. Knottnerus, Y. C. Tseng, A. Urech, R. J. C. Spreeuw, and F. Schreck, Parallel assembly of neutral atom arrays with an SLM using linear phase interpolation, *arXiv:2501.01391*.
 - [26] D. Bloch, B. Hofer, S. R. Cohen, A. Browaeys, and I. Ferrier-Barbut, Trapping and imaging single dysprosium atoms in optical tweezer arrays, *Phys. Rev. Lett.* **131**, 203401 (2023).
 - [27] D. Grün, S. White, A. Ortu, A. Di Carli, H. Edri, M. Lepers, M. Mark, and F. Ferlaino, Optical tweezer arrays of erbium atoms, *Phys. Rev. Lett.* **133**, 223402 (2024).
 - [28] M. M. Aliyu, L. Zhao, X. Q. Quek, K. C. Yellapragada, and H. Loh, D₁ magic wavelength tweezers for scaling atom arrays, *Phys. Rev. Res.* **3**, 043059 (2021).
 - [29] C.-H. Wen, S. Gauza, and S.-T. Wu, Photostability of liquid crystals and alignment layers, *J. Soc. Inf. Disp.* **13**, 805 (2005).
 - [30] J. C. A. Rocha, T. Wright, U. G. Bütaitė, J. Carpenter, G. S. D. Gordon, and D. B. Phillips, Fast and light-efficient wavefront shaping with a MEMS phase-only light modulator, *Opt. Express* **32**, 43300 (2024).

- [31] J. C. do Amaral Rocha, T. Wright, U. G. Būtaītē, J. Carpenter, G. S. D. Gordon, and D. B. Phillips, in *Adaptive Optics and Wavefront Control for Biological Systems XI*, edited by L. Tian, T. G. Bifano, and N. Ji (SPIE, San Francisco, California, United States, 2025), p. 9, <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/PC13328/PC1332807/Self-configuring-high-speed-multiplane-light-conversion/10.1117/12.3043882.full>.
- [32] M. Hacker, G. Stobrawa, R. Sauerbrey, T. Buckup, M. Motzkus, M. Wildenhain, and A. Gehner, Micromirror SLM for femtosecond pulse shaping in the ultraviolet, *Appl. Phys. B* **76**, 711 (2003).
- [33] T. Topcu and A. Derevianko, Possibility of triple magic trapping of clock and Rydberg states of divalent atoms in optical lattices, *J. Phys. B* **49**, 144004 (2016).
- [34] D. Bluvstein *et al.*, Logical quantum processor based on reconfigurable atom arrays, *Nature* **626**, 58 (2023).
- [35] D. Kim, A. Keesling, A. Omran, H. Levine, H. Bernien, M. Greiner, M. D. Lukin, and D. R. Englund, Large-scale uniform optical focus array generation with a phase spatial light modulator, *Opt. Lett.* **44**, 3178 (2019).
- [36] P. Zupancic, P. M. Preiss, R. Ma, A. Lukin, M. Eric Tai, M. Rispoli, R. Islam, and M. Greiner, Ultra-precise holographic beam shaping for microscopic quantum control, *Opt. Express* **24**, 13881 (2016).
- [37] D. Tsevas, Master's thesis, Fakultät für Physik, Ludwig-Maximilians-Universität München (2021).
- [38] Y. T. Chew, M. Poittrinal, T. Tomita, S. Kitade, J. Mauricio, K. Ohmori, and S. de Léséleuc, Ultraprecise holographic optical tweezer array, *Phys. Rev. A* **110**, 053518 (2024).
- [39] W. Sansen, *Analog Design Essentials*, International Series in Engineering and Computer Science (Springer, New York, 2006).
- [40] T. A. Savard, K. M. O'Hara, and J. E. Thomas, Laser-noise-induced heating in far-off resonance optical traps, *Phys. Rev. A* **56**, R1095 (1997).
- [41] B. Zhang, P. Peng, A. Paul, and J. D. Thompson, Scaled local gate controller for optically addressed qubits, *Optica* **11**, 227 (2024).
- [42] A. G. Radnaev, W. C. Chung, D. C. Cole, D. Mason, T. G. Ballance, M. J. Bedalov, D. A. Belknap, M. R. Berman, M. Blakely, I. L. Bloomfield *et al.*, A universal neutral-atom quantum computer with individual optical addressing and non-destructive readout, [ArXiv:2408.08288](https://arxiv.org/abs/2408.08288).
- [43] B. W. Reichardt, A. Paetznick, D. Aasen, I. Basov, J. M. Bello-Rivas, P. Bonderson, R. Chao, W. van Dam, M. B. Hastings, R. V. Mishmash, and *et al.*, Logical computation demonstrated with a neutral atom quantum processor, [ArXiv:2411.11822](https://arxiv.org/abs/2411.11822).
- [44] S. J. Evered, M. Kalinowski, A. A. Geim, T. Manovitz, D. Bluvstein, S. H. Li, N. Maskara, H. Zhou, S. Ebadi, M. Xu, J. Campo, M. Cain, S. Ostermann, S. F. Yelin, S. Sachdev, M. Greiner, V. Vuletić, and M. D. Lukin, Probing topological matter and fermion dynamics on a neutral-atom quantum computer, [ArXiv:2501.18554](https://arxiv.org/abs/2501.18554).
- [45] Y.-Y. Jau, A. M. Hankin, T. Keating, I. H. Deutsch, and G. W. Biedermann, Entangling atomic spins with a Rydberg-dressed spin-flip blockade, *Nat. Phys.* **12**, 71 (2016).
- [46] J. Zeiher, R. van Bijnen, P. Schauß, S. Hild, J.-y. Choi, T. Pohl, I. Bloch, and C. Gross, Many-body interferometry of a Rydberg-dressed spin lattice, *Nat. Phys.* **12**, 1095 (2016).
- [47] C. Gaul, B. J. DeSalvo, J. A. Aman, F. B. Dunning, T. C. Killian, and T. Pohl, Resonant Rydberg dressing of alkaline-earth atoms via electromagnetically induced transparency, *Phys. Rev. Lett.* **116**, 243001 (2016).
- [48] I. S. Madjarov, J. P. Covey, A. L. Shaw, J. Choi, A. Kale, A. Cooper, H. Pichler, V. Schkolnik, J. R. Williams, and M. Endres, High-fidelity entanglement and detection of alkaline-earth Rydberg atoms, *Nat. Phys.* **16**, 857 (2020).
- [49] N. Schine, A. W. Young, W. J. Eckner, M. J. Martin, and A. M. Kaufman, Long-lived Bell states in an array of optical clock qubits, *Nat. Phys.* **18**, 1067 (2022).
- [50] S. Ma, A. P. Burgers, G. Liu, J. Wilson, B. Zhang, and J. D. Thompson, Universal gate operations on nuclear spin qubits in an optical tweezer array of ^{171}Yb atoms, *Phys. Rev. X* **12**, 021028 (2022).
- [51] S. Jandura, J. D. Thompson, and G. Pupillo, Optimizing Rydberg gates for logical-qubit performance, *PRX Quantum* **4**, 020336 (2023).
- [52] H. Kim, W. Lee, H.-g. Lee, H. Jo, Y. Song, and J. Ahn, *In situ* single-atom array synthesis using dynamic holographic optical tweezers, *Nat. Commun.* **7**, 13317 (2016).
- [53] <https://doi.org/10.17617/3.DCZ7TM>.