Design and construction of a quantum matter synthesizer

Jonathan Trisnadi, Mingjiamei Zhang, Lauren Weiss, and Cheng Chin
James Franck Institute, Enrico Fermi Institute, and Department of Physics,
The University of Chicago, Chicago, IL 60637, USA
(*Electronic mail: cchin@uchicago.edu)
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The quantum matter synthesizer (QMS) is a new quantum simulation platform in which individual particles in a lattice can be resolved and re-arranged into arbitrary patterns. The ability to spatially manipulate ultracold atoms and control their tunneling and interactions at the single-particle level allows full control of a many-body quantum system. We present the design and characterization of the QMS, which integrates into a single ultra-stable apparatus a two-dimensional optical lattice, a moving optical tweezer array formed by a digital micromirror device, and site-resolved atomic imaging. We demonstrate excellent mechanical stability between the lattice and tweezer array with relative fluctuations below 10 nm, high-speed real-time control of the tweezer array at a 2.52 kHz refresh rate, and diffraction-limited imaging at a resolution of 655 nm. The QMS also features new technologies and schemes such as nanotextured anti-reflective windows and all-optical long-distance transport of atoms.

I. INTRODUCTION

Over the last two decades, quantum simulation using ultracold atoms has proven to be a fruitful endeavor toward the exploration of many quantum phenomena. Progress in this field has accelerated tremendously thanks to the growing experimental toolkit that enables precise control of the many-body system and access to a rich variety of research topics.

Two mainstays of cold atom quantum simulation platforms are optical lattices and moving optical tweezer arrays. Experiments with atoms trapped in optical lattices have demonstrated phenomena such as quantum phase transitions, quantum transport, and artificial gauge fields. A powerful feature of optical lattice systems is the tunability of the tunneling and interaction energy, which allows tailoring of the Hamiltonian of atoms. Novel lattice geometries can be realized with appropriate configuration of the laser beam interference. The integration of high-resolution imaging further enables the detection of atom occupancy in the lattice at single-site level. Moving tweezer arrays formed by deflecting and focusing multiple laser beams have proven useful for initiating atom distributions with reliable filling, realizing quantum information processing, and assembling molecules from single atoms.

Here we report on the construction of a quantum matter synthesizer (QMS), a quantum simulation apparatus that combines atoms in an optical lattice with the dynamic rearrangement capability of tweezer arrays. The marriage of these two technologies allows arbitrary initial state preparation using tweezers while maintaining the uniform and closely-spaced optical lattice site potentials for Hubbard model studies. In this paper, we present the design, construction, and characterization of the QMS, with a focus on the mechanical stability of the optical potentials, the cooling and site-resolved imaging of atoms, and the generation of moving tweezers based on a digital micromirror device (DMD).

In the following sections, we describe the key components of the QMS, starting with the mechanical design in Sec. II. The precise control of an atom in a lattice site requires exquisite stability between the lattice and tweezer potentials. We gain the required stability by implementing a rigid mechanical structure and sharing the same optical path for both potentials, see Sec. III. Next, the triangular lattice and optical tweezer potentials are prepared to confine and pattern the atoms in a nanotextured glass cell, described in Sec. IV. The lattice beams are described in Sec. V and the DMD potential in Sec. VI. Finally, we will discuss atom transport and in situ imaging of atoms in the lattices in Sec. VII and Sec. VIII respectively.

II. WORKING PRINCIPLE OF THE QUANTUM MATTER SYNTHESIZER

The QMS operates by assembling and patterning the sample via stereotactic manipulation of individual atoms. This is realized through highly coordinated and stable control of optical tweezers in combination with high resolution imaging of single atoms in an optical lattice. This capability will greatly increase the flexibility and fidelity of quantum simulation and allow for fast and efficient removal of entropy to prepare atoms in the quantum degenerate regime. Moreover, in contrast to traditional cold atom experiments which typically study ground state or thermal equilibrium distributions of atoms, the QMS can tailor far-from-equilibrium, designer quantum states.

The operation of our QMS consists of three steps:

Step 1: Sample preparation. The QMS starts by collecting precooled Cs atoms in a magneto-optical trap (MOT), cooling them with degenerate Raman sideband cooling (dRSC), and then transferring them into a glass science cell using a moving 1D optical lattice. In the glass cell, the atoms are loaded into a 2D optical lattice, where each site has random occupancy.

Step 2: Ground state cooling and imaging. We first determine the atomic distribution in a deep 2D lattice based on site-resolving in situ imaging. During the imaging, the dRSC is employed to suppress tunneling and heating of the atoms. The photons emitted during cooling cycles are collected to image the site occupancies in the lattice (see Section VII). With an imaging resolution of 655 nm, small compared to the lat-
FIG. 1. Working principle of the quantum matter synthesizer and general experimental design. (a) Within a single experiment cycle, the QMS images the initial atomic distribution in a 2D-lattice and generates a set of moves for a controllable tweezer array which re-arranges the atoms into a pre-specified final configuration. (b) The general optics scheme for the system is shown, featuring two high-numerical-aperture microscope objectives and three CCD cameras. The 2D lattice beams and the tweezer light are sent through the top objective, which also collects fluorescence from the atoms to image them on the upper CCD. The lower objective sends the trapping light to a diagnostic CCD, which images the optical potentials in order to diagnose aberrations and positional drift. The emitted photons from atoms are also collected on the lower CCD which serves as a secondary imaging camera.

**Step 3: Rearranging atoms.** Based on the measured distribution in the lattices, we rearrange atoms into a desired pattern. To move the atoms to new locations, we use an array of optical tweezers at 532 nm prepared by a DMD. We first tune up the tweezer potential slowly to securely localize the atoms in the tweezer potential. We then drag atoms to new lattice sites adiabatically by video streaming a series of light patterns from the DMD. Throughout the relocation process, atoms are tightly confined in the tweezers to prevent tunneling. At the end of the process, atoms are released back to the lattice sites and cooled back to the ground state to remove excess entropy gained during the motion (see Fig. 1a).

III. MECHANICAL STRUCTURE AND STABILITY

In order to image, trap, and manipulate atoms at the site-resolved level, the relative mechanical stability between the optical lattice at 935 nm, the tweezer array at 532 nm, and the atom fluorescence at 852 nm must be kept within the spatial extent of the on-site wavefunction in our system (approx. 30 nm). To this end, we prepare the imaging, lattice, and tweezer beam paths such that all pass through the microscope optics in order to reduce their relative mechanical instability (see Fig. 1b).

The optical system is comprised of two identical microscopes placed symmetrically above and below the atom sample. The objectives (Special Optics, Inc.) are custom-designed to offer diffraction-limited performance at all the relevant wavelengths of 532 nm, 852 nm, and 935 nm. The objectives have a numerical aperture of $NA = 0.8$ and a working distance of 1.05 cm. This dual microscope configuration allows us to image the tweezer and lattice light using the diagnostic CCD in order to analyze the quality of the optical potentials on the atoms.

An ultra-stable stainless steel cage around the glass cell holds the two microscope objectives and other supporting components (Fig. 2a). By connecting the two objectives via a cage, the relative vibrational noise between these two sensitive optics is greatly reduced. In addition to the objectives, the stainless steel cage also supports auxiliary mirror mounts. A nearby water-cooled Bitter electromagnet is mounted on a separate structure to avoid acoustic noise caused by the water flow or large magnetic field quenches.

We test the relative mechanical stability of the 935 nm optical lattice and the 532 nm tweezers by imaging them on the lower diagnostic CCD at a fast frame rate of 650 Hz. By fitting the recorded images of the lattice sites and the tweezers, we track the variations of their positions $x_L$ and $x_D$ over time with high precision (see Fig. 2b). Details about the optical setup of the imaging, the lattice, and the tweezers can be found in Sections V and VI.

We observe that the two optical potentials experience highly correlated motion, indicating the common-mode behavior of the optical paths (see Fig. 2c). While $x_L$ and $x_D$ display a root-mean-square instability of 26 nm, their relative instability is only 9 nm (Fig. 2d), smaller than the expected on-site wavefunction extent. Thus, the small relative instabil-
FIG. 2. Mechanical design and stability of microscope optical system. (a) A thick stainless steel cage (blue) holds the two microscope objectives (green) around the glass cell (yellow). Nearby optics and components are also shown, including 45° steering mirrors (orange), Bitter electromagnets and mounts (red), fixed mirror mounts and magnetic shim coil (cyan), the vacuum chamber (dark grey), and the 3-layer breadboard structure (light grey). (b) We analyze the mechanical stability between the tweezer light and the lattice light by imaging both simultaneously on the diagnostic CCD and observing their positions over time. We fit the lattice position (red dashed line) and the tweezer position (green dashed line) using the CCD image (inset). (c) The deviations of the tweezer position $x_D$ and lattice position $x_L$ are highly correlated as a result of their shared beam paths. Data are shown for a measurement that is 1 second in duration. (d) The difference in lattice and tweezer positions $x_D - x_L$ (orange) shows a much tighter distribution than the mean position of the lattice and DMD (blue). The RMS noise of $x_D - x_L$ is 9 nm, which is much smaller than their average fluctuation of 26 nm. Data is taken over a 20 second long measurement.

**IV. NANOTEXTURED GLASS CELL**

In order to maximize the optical transmission at wide acceptance angles for imaging, projection, and lattice formation at different wavelengths, we adopt a glass science cell (Precision Glassblowing Inc.) constructed with special nanotextured windows, rather than a traditional polymer-coated solution. The windows (TelAztec LLC) provide excellent broadband anti-reflection (AR) in the 532 nm to 1064 nm range for angles of incidence up to 45°.

The glass cell window is textured with roughly 100 nm protuberances that have a large degree of randomness in the size and spacing, which contribute to their broadband, wide-angle AR performance (Fig. 3a). The nanotexturing provides a smooth transition in the index of refraction from air to glass, thus avoiding the large mismatch that causes strong reflections. These nanostructures are similar to the so-called “moth-eye” metamaterials that typically consist of a 2D array of pillars which are uniform in size and work well for narrowband applications.

We measure the window reflectivities (combined front- and back-reflections) at various wavelengths and verify that their reflectivity is 1% or less at angles of incidence up to 45° (Fig. 3b). Lastly, we also note that due to the absence of polymer coating on the windows, the glass cell can be baked to higher temperatures in excess of 200° C than the windows with dielectric coating, which promises better vacuum.

**V. 2D TRIANGULAR LATTICE**

Horizontal trapping of atoms in the glass cell is provided by a 2D triangular lattice formed by interfering three laser beams at wavelength $\lambda = 935$ nm. Here 935 nm is a so-called “magic wavelength” for the Cs D$_2$ transition at which atoms in the ground state and 6P$_{3/2}$ excited state experience the same lattice potential landscape. A 1064 nm light sheet with the tight axis in the vertical direction compresses and holds the sample vertically.

In the lattice setup, we split one laser beam (SolsTiS, M Squared Lasers) into three beams each with 0.25 W of power, and send them off-axis downwards through the upper objective (Fig. 4a). They are aligned to be symmetric around the optical axis of the objective. After the glass cell window, the three beams propagate inwards with an angle of $\theta = 45^\circ$ and intersect each other at a projected angle of 120° in the horizontal plane. The interference of the three beams creates a triangular optical lattice with an expected lattice constant of...
FIG. 3. Optical properties of nanotextured windows. (a) Photo of the glass science cell (left) and a scanning electron microscope (SEM) image of the nanotextured surface (right). SEM photo courtesy of TelAztec LLC. (b) The nanotextured surface gives rise to low broadband reflectance over a large range of angles of incidence. Shown are the percent reflected from both surfaces of a window for 700 nm (blue), 852 (black), and 935 nm (red).

FIG. 4. Triangular optical lattice setup. (a) We generate a 2D triangular lattice by intersecting three beams (L1, L2, L3) sent from the upper objective (light brown shaded area). The light sheet propagating along y-axis provides a tight confinement in the vertical z-direction. (b) The three lattice beams (red arrows) are circularly-polarized (blue arrows). (c) The lattice intensity pattern directly measured on the diagnostic CCD. The lattice constant is measured to be consistent with our prediction of 881 nm.

VI. DMD TWEEZER ARRAY

We rearrange atoms on the optical lattice using an array of mobile optical tweezers. The tweezers are formed by reflecting a 532 nm laser (Sprout-Solo, Lighthouse Photonics) with a digital micromirror device (DMD), which is capable of projecting arbitrary intensity patterns on the atoms at high speed.\cite{DMD}

Our DMD (DLP4500, Texas Instruments) contains a 912 × 1140 array of 7.64 µm square mirrors that can quickly flip between an on- and an off-state. When a mirror is turned on, incident light is reflected into the upper microscope objective toward the atomic sample (Fig. 1b). Light reflected from off-mirrors is sent to a beam dump. Since 532 nm light is blue-detuned for the cesium D2 transition, our tweezer array is formed by dark spots on a bright background (Fig. 5b). Due to diffraction effects related to the periodic structure of the mirrors, 60% of the incident power is directed toward the atoms.

We place the DMD in the image plane of the upper microscope objective, so that the pattern of on-mirrors matches the intensity profile imposed on the sample. In our system, approximately 10 DMD mirrors correspond to one lattice spacing of 881 nm, providing sufficient spatial resolution for smooth tweezer motion. Smooth motion is imperative to minimize the heating of atoms associated with discrete changes in the light intensity.
VII. LONG DISTANCE OPTICAL TRANSPORT OF ATOMS

Our experiment starts with atoms pre-cooled in the MOT chamber before transferring them 28 cm to the glass cell (Fig. 6). To transport the atoms, we load them into a 1D optical lattice and move the lattice sites by shifting the frequency of one of the lattice beams (see Refs. 35 and 36).

The 1D transport lattice is formed using light at wavelength \( \lambda_0 = 1064 \text{ nm} \) with 40 W of power (Mephisto MOPA, Coherent, Inc.) and the frequency shift is realized using two acousto-optic modulators (AOMs) in a double-pass configuration, see Fig. 6. When a detuning \( \delta(t) = f_2(t) - f_1 \) is applied to the second AOM drive, the retro-reflected beam is frequency shifted by \(-2\delta(t)\), which results in the lattice sites acquiring a velocity equal to \(\delta(t)\lambda_0\). This all-optical transport scheme does not require any moving parts, is insensitive to mechanical vibrations, and can proceed quickly with atoms in a deep lattice.

In the experimental sequence, atoms in the MOT chamber are first cooled by degenerate Raman sideband cooling and loaded into the transport lattice (250 \( \mu \text{K} \) trap depth, 170 kHz trap frequency). Immediately after cooling, \(\delta(t)\) is smoothly increased to its final value of 600 kHz, reaching a max speed of one of the lattice beams (see Refs. 35 and 36).

We measure the light reflected by the DMD on a fast photodiode in order to confirm the switching speed and playback quality. By alternating the DMD mirrors between on and off states at max speed we observe the expected 2.52 kHz refresh rate (Fig. 5d). We also confirm that long sequences of binary patterns are played in the correct order without pauses, skipping, or flickering.

![Diagram](image_url)

FIG. 5. Dynamical control of a tweezer array generated by a digital micromirror device (DMD). (a) The spatial resolution of the DMD projection system can be estimated by taking an image of a DMD-generated point source. The resolution based on the Rayleigh criterion is measured to be 450(25) nm, which is near the diffraction limit. (b) The DMD can generate arbitrary optical potentials, such as the 72-tweezer pattern shown here. (c) Fast real-time pattern updating is realized by assembling every 24 binary patterns into a standard 24-bit color video-streaming signal, which results in a 2.52 kHz switching speed, see text. (d) The photodiode signal shows the DMD operating at max speed. Here the DMD is switching between all-on and all-off binary patterns.

We characterize the resolution of the DMD projection system by imaging point-like patterns on the lower CCD at a wavelength of 532 nm. We fit the intensity pattern, which yields a near-diffraction-limited resolution of 450(25) nm based on the Rayleigh criterion (Fig. 5a).

High-fidelity control of the tweezer array requires fast updating of the DMD pattern with minimal delay time. To meet this requirement, we operate the DMD in a video-streaming mode where the computer treats the DMD as a display device (Fig. 5c). To improve the streaming bandwidth, we package every 24 binary tweezer patterns into a single 24-bit color image. The color images are then transmitted to the DMD at the maximum streaming rate of 105 Hz. For each color image, the DMD plays the constituent 24 binary patterns in sequence, thus achieving a final update rate of the tweezer patterns of \(24 \times 105 \text{ Hz} = 2.52 \text{ kHz} \). If we move the tweezers by translating their positions one micromirror at a time, then moving one atom to a neighboring site takes an estimated time of 4 ms, which is comparable to other tweezer rearrangement experiments. Lastly, we measure the total delay time to transmit images from the computer to DMD to be only 30 ms, which is short compared to the atom lifetime.

![Diagram](image_url)

FIG. 6. Long distance transport of atoms based on a 1D optical lattice. An incident beam at \(\lambda_0 = 1064 \text{ nm} \) is retro-reflected, passing a pair of AOMs twice. The first AOM is driven by a fixed frequency \(f_1 = 80 \text{ MHz} \) while the second AOM operates at a tunable frequency \(f_2(t) = 80 \text{ MHz} \mp \delta(t)\). We take the +1 order from the first AOM and the −1 order from the second AOM, which results in the retro-reflected beam acquiring a frequency shift of \(-2\delta(t)\). We vary \(\delta(t)\) along a smooth trajectory to translate the lattice sites 28 cm with speed \(\delta(t)\lambda_0\). Both the incident and retro-reflected beams have a beam waist of 300 \( \mu \text{m} \) near the center of transport, resulting in a long Rayleigh range and good trap uniformity to within 5% for the entire length. The images show the initial atom cloud in the MOT chamber and the transported cloud in glass science cell.
FIG. 7. Site-resolved fluorescence imaging. (a) Typical raw fluorescence images taken 5 ms apart on the lower CCD with markers drawn in the central region to guide the eye. Each image has an exposure time of 200 ms. Sites that were empty and became filled are marked red, and sites that were filled and became empty are marked black in the second image (right). (b) Radial profile of a point source averaged over 180° (black) and Gaussian fit (red). The width (based on the Rayleigh criterion) of 655(3) nm indicates diffraction-limited performance. Inset: Averaged image of a point source generated using a sparsely-filled atom sample. (c) Histogram of counts per site in the central region using data from 40 images shows a peak for unoccupied sites (blue, \(N=0\)) and a peak for occupied sites (red, \(N=1\)). The blue and red lines are Gaussian fits, and the vertical dashed line defines the threshold for the determination of site occupancy.

of 64 cm/s, after which it decreases back to zero so that the atom cloud gently comes to a stop at the center of the glass cell. We typically transport 20–30% of the initial atom number in 400 ms to the glass cell and end with \(6 \times 10^5\) atoms.

VIII. COOLING AND SITE-RESOLVED IMAGING

Once atoms are transported into the glass cell, they are cooled into the 2D triangular lattice using dRSC. Photons emitted during the cooling process are collected by the microscope objectives to produce site-resolved images of atoms on the CCDs.

After atom transport we perform an initial dRSC stage to cool the sample into the 2D triangular lattice. The dRSC scheme closely follows Ref. [37]. In our system, the lattice beams as described in Section V provide both the trapping potential and the Raman coupling necessary to reduce the vibrational energy. Circularly polarized \(\sigma^+\) optical pumping (6\(S_{1/2}, F = 3 \rightarrow 6P_{3/2}, F' = 2\)) and repumping (6\(S_{1/2}, F = 4 \rightarrow 6P_{3/2}, F' = 4\)) beams are applied in the same direction as the magnetic field to complete the cooling cycle. The magnetic field is in the horizontal plane bisecting the \(x\)- and \(y\)-axes as shown in Fig. 4b. After cooling the sample for 20 ms, we reach a temperature of 5 \(\mu\)K in the lattice.

Following the initial cooling stage, the light sheet power is ramped up in 2 ms to compress the sample vertically into a thin layer. The lattice potential is then ramped down to release excess atoms outside of the light sheet. We then ramp the lattice power back up and perform a second dRSC stage. During cooling, pairs of atoms are ejected via light-assisted collisions, resulting in each lattice site having only zero or one atoms. Within 50 ms, the atoms are cooled near the 3D vibrational ground state after which we expose the CCDs to collect the photons.

A typical imaging exposure time is 200 ms, wherein an estimated 10% of the total emitted photons are collected on each of the upper and lower CCDs (iKon-M 934, Andor Technology Ltd) after accounting for the finite solid angle of the objectives and transmission losses. We can take 8 or more images per experimental cycle in order to study the loss and tunneling behavior over time. Fig. 7 shows an example of two consecutive exposures with a 5 ms hold time in between.

We analyze a central 25 \(\times\) 25 \(\mu\)m region that contains ap-
proximately 200 lattice sites. Using a sparsely-filled sample, we can overlap the signal from single atoms to obtain the point spread function, which yields an imaging resolution of 655(3) nm based on the Rayleigh criterion. Our result is in agreement with the diffraction limit given by $\frac{0.61\lambda_{D2}/\text{NA}}{650}$ nm, where $\lambda_{D2} = 852$ nm is the wavelength of the emitted photons (Fig. 7d).

We extract the positions of the lattice sites by taking the Fourier transform of the atom images. The sites are indicated with circular markers in Fig. 7a. We determine the lattice constants to be 845 nm, 860 nm, and 874 nm, all within 5% of our expectations. We attribute the discrepancies to imperfect lattice beam alignment.

We determine the atom occupancies by extracting the photon counts from each lattice site. In order to obtain higher fidelity, we perform image deconvolution using a kernel method. With this method, a typical histogram of the photon counts is shown in Fig. 7d, and shows good separation between the distributions for sites with and without atoms. By fitting both distributions to Gaussians, we can set a threshold value to evaluate the site occupancies. The small Gaussian fits overlap suggests a high fidelity of 99% or an error rate of 1% from image reconstruction alone.

Our imaging allows us to study the particle dynamics over time by taking many images of the same atomic sample. By comparing adjacent images, we can identify changes in the site occupations, see Fig. 7a for an example. Disappearance of atoms in the later images is attributed to loss and hopping, while appearance of atoms in previously-unoccupied sites is likely due to hopping. The fidelity of atomic occupancies in two consecutive images is 91.4%, limited by atom loss and tunneling.

IX. CONCLUSION

In summary, we have presented the design and characterization of the quantum matter synthesizer, a novel cold atom quantum simulation platform that combines the clean trapping potential of a 2D optical lattice with the site-resolved control of atoms using an optical tweezer array.

Numerous innovative design elements were incorporated, including the nanotextured anti-reflective glass cell, the formation of a triangular lattice through the microscope objective, the long-distance atom transport with a 1D moving lattice, and the dual-objective microscope system. By combining the lattice and tweezer beams into the objective, we reach an exquisite mechanical instability below 10 nm, a small fraction of the on-site wavefunction extent. We also present a new type of dynamical tweezer array formed by a DMD that exhibits fast streaming speeds and low latency. Lastly, we demonstrate high-fidelity site-resolved imaging of Cs atoms in a 2D triangular lattice with relatively small exposure times of 200 ms. Through these technical developments, the QMS is well-positioned to simulate many-body physics with precise state preparation and measurement fidelity.

AUTHOR DECLARATIONS

The authors have no conflicts to disclose.

AUTHOR CONTRIBUTIONS

J.T. designed and constructed the experiment, collected and analyzed data, and prepared the manuscript. M.Z. contributed to the construction of the experiment, collected and analyzed data, and prepared the manuscript. L.W. helped prepare the manuscript. C.C. supervised the project.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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