Optical Lattices for Atom Based Quantum Microscopy

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We describe new techniques in the construction of optical lattices to realize a coherent atom-based microscope, comprised of two atomic species used as target and probe atoms, each in an independently controlled optical lattice. Precise and dynamic translation of the lattices allows atoms to be brought into spatial overlap to induce atomic interactions. For this purpose, we have fabricated two highly stable, hexagonal optical lattices, with widely separated wavelengths but identical lattice constants using diffractive optics. The relative translational stability of 12 nm permits controlled interactions and even entanglement operations with high fidelity. Translation of the lattices is realized through a monolithic electro-optic modulator array, capable of moving the lattice smoothly over one lattice site in 11 µs, or rapidly on the order of 100 ns.

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1. INTRODUCTION

Optical lattices have provided a basis for numerous recent experiments with ultracold atoms, ranging from basic physics of single atoms in lattice potentials [1, 2], to interacting quantum gases [3], and promises extension into quantum magnetism and exotic quantum phases [4]. Particularly stimulating applications arise from the field of quantum information, where ultracold atoms in optical lattices are proposed to be good vehicles for the storage and processing of information [5, 6, 7, 8, 9, 10, 11]. Carefully engineered lattice potentials, even with dynamic modes of control, have become more common in modern quantum gas experiments [12, 13]. General methods for introducing additional degrees of freedom to periodic optical potentials to, for example, engineer the structure of a unit cell [14], or trap and manipulate multiple atomic species [11] are necessary to make further progress in these fields. Furthermore, the ability to probe and manipulate atomic information [13, 16, 17, 18, 19, 20, 21] with a spatial resolution well below the lattice spacing is of primary importance in these types of experiments [22, 23].

We describe the construction of an apparatus to achieve these aims using a new type of cold atom based microscopy, which we refer to as atomic quantum microscopy. This technique is a marriage of microscopy and quantum control, allowing the use of one quantum object to probe and manipulate a larger, more complex quantum system. Here, we employ two species of ultracold atoms, each confined near the minima of an optical lattice potential. The lattice wavelengths and intensities are chosen to ensure that each atomic species can be fully controlled by its respective lattice [11]. Through the combined use of controlled atomic collisions and spatial overlap of their wavefunctions, information concerning internal states and external degrees of freedom can be transferred from one species to the other, as illustrated in Fig. 1. This apparatus makes possible new types of measurements, such as probing the full quantum structure of complex many-body systems of interacting gases of atoms. Since the probe can be entangled with the sample, information can be read out in a way that does not interfere with the underlying more complicated quantum system, permitting idealized projective quantum measurements on a many-body system. In addition, entanglement between spatially separated portions of the sample can either be induced or interrogated. Application of this apparatus for scalable quantum information processing was described previously [11], where a lattice potential at one wavelength confines qubit-atoms, and the probe atoms play the role of auxiliary messengers mediating entanglement among (distant) qubits. Controlled interactions between species were proposed to entangle the internal states of atoms brought into close spatial contact.

We utilize novel techniques in the construction of optical lattices to produce commensurate lattice spacings with widely separated laser wavelengths, while providing precise differential control of the lattice site alignment through manipulation of optical phases. A relative translational stability of 12 nm is demonstrated. Based on previous quantitative analysis of a practical lattice configuration [11], this yields an overlap fidelity of > 99%.

In this article, we describe novel optical and opto-electronic components, including diffractive optical elements, aberration-balanced imaging, a monolithic array of electro-optic phase modulators, and the necessary driving electronics. These methods are applicable to both ultracold atom experiments exploring many-body physics and quantum information processing, where optical lattices with complex and/or dynamically manipulable unit cells are desired. The techniques may also be exploited in the manipulation of microscale objects of biological or other interest [24].
FIG. 1: Controlled overlap of two atomic species in two optical lattices with tunable translation. The target atoms (blue circles) are confined in one lattice (blue lines), while the probe atom (red circles) is confined by another lattice (not shown). The overlap of the probe and target atoms is controlled by shifting the optical phases of the lattice beams. The figure shows an interaction between a target and probe atom at point A. After the operation is finished, the probe atom can either have its state read by measurement, or alternatively transported to another target atom for a second quantum manipulation, as shown at point B.

2. COMMENSURATE, MULTI-CHROMATIC OPTICAL LATTICES

Optical lattices are formed by overlapping two or more laser beams with wavenumbers \( k = 2\pi/\lambda \) on the atomic sample. When two beams intersect with an angle \( \Delta \theta \), they create a sinusoidal interference pattern with spatial frequencies \( k' = k/(2 \sin \Delta \theta) \), and phases determined by the relative optical phases of the beams. Here our goal is to construct bi- or multi-chromatic optical lattices with extreme relative phase stability and commensurate lattice constants for quantum microscopy. We achieve these goals by forming two lattices holographically, employing only common-mode optics.

The optics for a hexagonal lattice are schematically shown in Fig. 2; this is the simplest two-dimensional geometry which is topologically stable against drifts in relative optical phases [25]. Two co-propagating beams with separated wavelengths \( \lambda_1 \) and \( \lambda_2 \) are incident on the diffractive optical element (DOE) shown in Fig. 3, which imprints a patterned phase shift across the profile of the incident beam to create a two-dimensional diffraction pattern. The manufacture of intricate diffractive optical elements is a well-established technique, typically accomplished with photographic emulsions, patterned metallic coatings, or photolithographed [29, 30] transmissive glass. We fabricated a reflective variant of a photolithographed DOE by first patterning a fused-silica substrate with reactive ion etching and subsequently coating the etched surface with a reflective gold layer.

In order to efficiently diffract a single beam into three with the proper geometry, the element shown in Fig. 3 was designed. This grating can be modeled as three identical sawtooth-blazed line gratings, superposed with an angular separation of \( \Delta \theta = 2\pi/3 \). This is equivalent to a two-dimensional array of alternatingly raised and recessed equilateral triangles, as shown in Fig. 3. The

FIG. 2: Method for generation of a bichromatic optical lattice. Two overlapped beams of wavelength \( \lambda_1 \) and \( \lambda_2 \) are incident on the diffractive optical element. The three primary diffracted orders at each wavelength are collimated by the the back lens, phase-modulated with the electro-optic modulator array, and focused onto the atoms by a pair of lenses. The angles of recombination are naturally matched to produce commensurate lattices.

that the resultant lattice geometries are identical in the absence of lens aberration (discussed in Sec. 2B). A separate one-dimensional lattice potential (not shown in the figure), applied along the optical axis and common to both atomic species, is used to complete the three-dimensional lattice potential.

A. Diffractive Optics

The central element in producing the bichromatic lattice above is the two-dimensional diffractive optical element (DOE) shown in Fig. 3 which imprints a patterned phase shift across the profile of the incident beam to create a two-dimensional diffraction pattern. The manufacture of intricate diffractive optical elements is a well-established technique, typically accomplished with photographic emulsions, patterned metallic coatings, or photolithographed [29, 30] transmissive glass. We fabricated a reflective variant of a photolithographed DOE by first patterning a fused-silica substrate with reactive ion etching and subsequently coating the etched surface with a reflective gold layer.
height separating raised and recessed plateaus reflects the line gratings’ blaze angles, determining the amplitude of each diffraction order. We etch to a depth corresponding to a half-wave phase shift, resulting in optimal extinction of the zeroth order. The size of the triangles determines the diffraction angle; for this experiment the side length is chosen to be 26 μm, resulting in 1.7° and 2.7° for λ1,2 chosen as 681 nm and 1064 nm, respectively.

The grating pattern is transferred from a photoplotted chrome mask to a photoresist-coated fused silica surface and subsequently processed with reactive ion etching. Etching is performed with CF4 and O2 plasmas, repeated for the same pattern with multiple etch depths. Diffraction efficiency was optimized near the depth of 218 nm, one-quarter wave at the average of 681 nm and 1064 nm.

While the grating could function either in transmission or reflection, reflection is preferable as it eliminates etalon effects from second surface reflections, is better suited to withstand high laser powers, and eliminates dispersive effects in the substrate. After the grating is etched to the correct depth, the surface is coated with a 120 nm thick layer of gold using electron beam deposition (to aid in the adhesion of the gold film, a 5 nm thick layer of chromium is applied prior to the gold coating).

The performance and surface topography of the completed grating are assessed by optical measurements of diffraction efficiency and atomic force microscopy (AFM). This permits assessment of geometric distortions to the phase pattern, due to limited lithographic resolution and uniformity in etching and coating. The gratings direct approximately 10% of the incident light into each of the three first orders at the optimal wavelength.

With a 1/e2 beam diameter of 350 μm, the diffraction efficiency remains unaffected until the incident laser power exceeds two watts. The damage threshold is found to be 4 kW/cm2, at which point we record a 5% permanent drop in the first order efficiency.

B. Abberation Cancelation

To construct optical lattices with significant atom tunneling, it is necessary to produce lattices with small site spacing and large beam intersection angles, requiring large numerical aperture optics. While sufficient control over aberrations at high numerical aperture is possible using aspheric imaging optics, simultaneous control over chromatic effects at large wavelength separations becomes technically challenging. This can be remedied in a straightforward way by canceling spherical aberrations with chromatic.

To form both lattices at the same distance along the optical axis, two front lenses (illustrated in Fig. 2) are necessary to correct for spherical and chromatic aberrations - we note that with a single spherical plano-convex lens, the separation between the two foci Δf would be larger than a millimeter. This distance is the aggregate effect of longitudinal spherical aberration (LSA) and longitudinal chromatic aberration (LCA). The LSA is the distance between the axial intersection of a beam and the paraxial focus. The LCA, representing the axial distance between foci for the two wavelengths, has an opposite sign compared with LSA for normally dispersive lens media, presenting an opportunity to cancel their effects.

Our solution to this problem, without resorting to an arbitrary aspheric optical surface, is to use a standard aspheric lens (Asphericon GmbH, 50-40HPX-B) with focal length f1 = 40 mm (50 mm diameter) and a weaker spherical lens with f2 = 175 mm, as shown in Fig. 4. Without the weak lens, the system has little spherical aberration, and Δf = −0.6 mm is negative because of the dominating chromatic aberration. The weak lens introduces enough spherical aberration to cancel the chromatic.
FIG. 5: Figure (a) and (b) are images of the bichromatic hexagonal lattice potential with $\lambda_1 = 681$ nm and $\lambda_2 = 1064$ nm, respectively, taken with a CCD camera and microscope objective with 100-fold magnification. Figure (c) is a plot of a cut for the 1064 nm (filled circles) and 681 nm (open circles) lattices and a sinusoidal fit (solid lines) of the potentials. The lattice constants are 1.48 $\mu$m and 1.51 $\mu$m for 1064 nm and 681 nm, respectively.

FIG. 6: Absolute and relative stability of the two-color lattice potential. Both lattices were imaged onto a CCD with a microscope objective. Pictures of each lattice were taken simultaneously every second. The plot shows the position of a lattice site of each color and the relative motion between the two colors. The relative motion is substantially suppressed due to the use of common-mode optics.

An essential element in atomic quantum microscopy is the ability to precisely address individual atoms by dynamically translating and overlapping lattice sites. For this, it is necessary to impart controlled phase shifts to the lattice beams. While there are several methods available for this, we have chosen electro-optic techniques to take advantage of high modulation bandwidths, and precise displacement without hysteresis. To preserve the stability provided by use of common-mode optics, the phase-shifting elements have been introduced in the form of a monolithic spatial light modulator formed by a single crystal of lithium niobate.

Two useful modes of lattice translation are possible for controlling atomic overlap. In the first, atoms are moved adiabatically over several lattice constants by slowly ramping the relative phase of beams with the EOM. The characteristic timescale for acceleration should then be matched to the vibration frequency for atoms on a lattice site, of order 10-100kHz. In the second, the lattice potential can be shifted rapidly enough by one lattice constant such that no atomic motion occurs. The combination of these modes allows essentially unlimited range of translation without vibrational excitation of the atoms. These two modes can be enabled through the use of a wide-range linear amplifier to drive the EOM, in combination
with a fast switching technique to suddenly reset its output by a controlled amount.

A. Dynamic lattice translation

The EOM consists of six independent longitudinal modulators shown in Fig. 7(a), formed in a single crystal lithium-niobate wafer with multiple reflective silver electrodes on one side, and transparent, conductive indium-tin-oxide (ITO) pads on the other. The lithium niobate wafer is 75 mm in diameter, 3 mm thick, and has a z-cut configuration (the optical axis is perpendicular to the wafer face). One of the pads is shown schematically in Fig. 7(b). The silver electrodes were evaporated to a thickness of 120 nm, serving not only as a transparent electrode, but simultaneously as a quarter-wave matching (antireflective) coating near the mean wavelength between the indices of lithium-niobate and glass; a BK-7 window is then matched to the crystal with electrically nonconductive index fluid. The total front surface reflection is thereby reduced from the natural Fresnel reflection by over 14% per surface to a reasonable 4% total loss. Stray reflections are subsequently blocked by apertures aligned to the main beams.

![Image](image-url)

**FIG. 7:** (a) The electro-optic spatial light modulator consists of multiple longitudinal phase-modulator elements patterned onto a single lithium niobate crystal. Visible are the evaporated silver pads, which serve simultaneously as mirror coatings and electrical contacts; transparent indium-tin-oxide (ITO) coatings lie on the opposite face of the crystal, forming both the opposite electrodes, and an anti-reflection coating. The crystal is 75 mm in diameter. (b) Schematic drawing of one EOM pad. The incident laser beam propagates through the lithium niobate crystal and is reflected by the silver pad. A voltage $V$ can be applied between the silver and ITO pads. The phase of the beam $\phi$ is shifted by $\pi \times V / V_0$, where $V_0$ is the half-wave voltage. The polarization of the beam is parallel to the crystal surface and perpendicular to the optical axis (z-axis) of the crystal.

The half-wave voltage in a single-pass longitudinal modulator is given by $V_0 = \lambda / (n_0^3 r_{13})$, with the incident wavelength $\lambda$, the index of refraction for the ordinary ray $n_0$ and the electro-optic coefficient $r_{13}=8.6 \text{ pm/V}$ [27].

Since the electric field is parallel to the optical axis, and the polarization of the beams chosen to be perpendicular to the optical axis, only the $r_{13}$ coefficient need be considered. The half wave voltage, taking the double-pass and the incidence angle into account is $V_0=3.4 \text{ kV}$. To shift over one lattice site, one needs to apply twice the half wave voltage on one pad. In Fig. 8(a), we demonstrate a slow translation of the 681 nm lattice over 1.5 lattice sites with a differential swing of 10.4 kV across one pair of modulator pads. In Fig. 8(b), we demonstrate a fast jump of the lattice.

**FIG. 8:** Two dynamic modes of translation of the optical lattice. The lattice position was determined by recording and fitting images as shown in Fig. 7(a) (a) We demonstrate a slow shift of the 681 nm lattice over 1.5 lattice sites by applying +5.2 kV to one EOM pad and -5.2 kV on the other two pads. (b) A fast jump can suddenly displace the potential.

B. Modulator Electronics

We use a pair of high voltage MOSFET ladder amplifiers to drive the two sides of each modulator pad (see Fig. 9). The design of the amplifier is similar to that described in Ref. [28], modified to accommodate higher breakdown voltage MOSFETs (Ixys Corp., 1XTY01N100), and to incorporate a triggered spark-gap as a switch. The upper limit in translational velocity of the lattice is determined by the slew rate of the amplifier, in turn determined by the total load and output capacitance, and available output current. Each EOM pad has a capacitance of 16 pF, a result of the necessary optical aperture, and high dielectric permittivity of the lithium niobate crystal. The amplifier is designed for modest power dissipation at a ladder voltage of 4.5 kV, resulting in a maximum output current of approximately 10 mA. This results in a modest slew-rate of 0.55 rad/µs. While this is sufficient to provide adiabatic motion of atoms confined to the lattice, it is not sufficient to suddenly reset the amplifier diabatically for atomic motion. While higher amplifier currents might be provided by vacuum-tube based designs [31], faster switching times are achievable augmenting the FET-based amplifier with semi-passive elements.
FIG. 9: Drive electronics for the electrooptic modulator. Each modulator pad is driven differentially by a pair of high-voltage amplifiers formed by a ladder of high-breakdown voltage medium-power FETs. The amplifiers are driven with an offset differential input $V_0 \pm V(t)$. Each amplifier consists of a $\sim 10$ mA static current source, formed by the depletion-mode mosfets Q1D (IXTY01N100D) and source resistor Rb. The remaining FETs in the ladder Q2-Q12 (IXTY01N100) form a series of followers to divide the supply voltage to a level below FET breakdown. This current is balanced against that flowing in the lower ladder QL1-QL12 (IXTY01N100), ultimately determined by feedback through sensing of the output voltage with the network formed by CZx and RGx, then integrated by op-amp IC1 (Analog Devices, Inc., AD712). The ladder amplifiers are powered from a 4.5 kV, 100 mA power supply, allowing for a total differential swing of nearly 9 kV; the supply, and thereby output voltage is limited by dielectric breakdown in the circuit board wiring. The amplifier pair is capable of a small signal bandwidth of 1 MHz, and a voltage slew of 600 V/µs, limited by bias current and power dissipation of the ladder FETs. Rapid discharge of the electrooptic bias into a charge on Cf is accomplished by triggering the spark gaps G (Littlefuse CG series) with the inductively coupled trigger waveform generated by discharge of one of capacitances Ct through the avalanche transistors Qt (Diodes, Inc., ZTX415). Cf is maintained at a bias opposite the modulator through the bleed resistors Rf, allowing for a larger swing on discharge. The discharge time, on order of 10 ns, is determined by the conduction-swing of Qt.

This can be accomplished using a triggered spark-gap to suddenly discharge the electro-optic capacitance as shown in Fig. 9 into the capacitor Cf. Since even a small capacitance spark gap is capable of conducting very large instantaneous currents, providing large standoff voltages, and reaching its conducting state quickly, it is ideally suited as a switch. In this case, the discharge of the electro-optic proceeds as an RC-waveform with time constant determined by the combined capacitance of electro-optic crystal, amplifier, and spark gap, and the total resistance, dominated by the surface resistivity of the electro-optic pad coatings. The most resistive element is the ITO coating; to minimize this resistance, a silver overcoat is evaporated on top of the ITO wires, resulting in a resistance smaller than 5 Ω. This, in principle, would result in a peak discharge current on order of 2 kA, with an exponential time constant on order 0.1 ns. In practice, however, we found this is limited to 10 ns timescales by the spark ignition process, which here is initiated by transformer coupling to an avalanche transistor trigger circuit. The switching amplitude can be controlled by the value of Cf.

4. CONCLUSION

In summary, we have described the functional form of a quantum microscope for ultracold atoms based on atomic collisions and precisely controlled optical lattice potentials. We have presented all of the technical elements necessary to provide the controlled bichromatic lattice to manipulate ultracold atoms in the microscope, and demonstrated the necessary precision and dynamic control to implement a basic demonstration apparatus.
Further improvements might be made by incorporating high-resolution optical microscopy of the potential in situ, and using active feedback to further stabilize lattice overlap. Significant simplification of the apparatus might be possible by integration of the diffractive element with the optical phase modulator.

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