Ultra-fast Dynamic Hologram Generation for Local Addressing in an Atom Array

A thesis presented
by

Theodor Lukin Yelin

to

The Department of Physics and
The Department of Computer Science

in partial fulfillment of the requirements
for the degree of
Bachelor of Arts with Honors
in the subjects of
Physics and Computer Science

Harvard University
Cambridge, Massachusetts
March 2022
Ultra-fast Dynamic Hologram Generation for Local Addressing in an Atom Array

Abstract

One of the most useful tools for manipulating particles, such as individual atoms, is fast and precise control over patterns of laser light. Current tools lack either the speed or the versatility to be easily used across a wide variety of applications, due to the reliance on slowly-updating holograms generated by spatial light modulators (SLMs), or the limitation to one-dimensional structures for acousto-optic devices. In this thesis we present a system which uses an acousto-optical modulator array to address an SLM from different angles. This allows us to generate multiple spatially shifted copies of an image generated by the SLM, producing arbitrary patterns within a region of interest. We further show that through precise phase control of the resulting images, we can overlap the basis images to create complex interference patterns, including continuously moving pulses of light. We show that the system can operate on a switching-timescale of 50 ns, with low levels of crosstalk between channels, extremely high contrast ratios, and low phase-drift.
# Contents

Abstract ................................................................. iii
Acknowledgments ......................................................... v

1 Introduction .......................................................... 1
1.1 Motivation .......................................................... 1
1.2 Previous Approaches .............................................. 1
1.3 Our Work .......................................................... 3
1.4 Applications ....................................................... 3

2 Theory of Operation ................................................ 5

3 Method of Operation ................................................. 7
3.1 Overview .......................................................... 7
3.2 AOM Design ....................................................... 8
3.3 SLM Design ....................................................... 9
3.4 Layout Specifics ................................................... 11

4 Software Design ...................................................... 12
4.1 Hologram Generation ............................................. 12
  4.1.1 Performance Characterization ............................ 15
4.2 AOM Waveform Management ................................. 17

5 Measurements and Capabilities .................................. 18
5.1 Performance Characteristics ................................... 18
5.2 Phase-Controlled Interference ................................ 19
5.3 Continuously Moving Holograms ............................... 21

6 Conclusion ........................................................... 23

References ............................................................... 24

Appendix A Holograms Used for Algorithmic Characterization 26
Acknowledgments

First and foremost, I would like to thank my advisor, Professor Markus Greiner, as well as my graduate advisor, Sepehr Ebadi, for their incredible insight and support throughout the entirety of this project. I would also like to thank Dolev Bluvstein for his help in editing this work, and providing creative solutions for problems throughout, as well as the rest of the graduate students working on the Atom Array project. Personal thanks go out to Alistair and Elizabeth for long nights of support, and of course my family, without whom none of this would have been possible.
1 Introduction

1.1 Motivation

In modern experimental atomic and optical physics, one of the biggest challenges to practical realization of complex systems is control over spatial modes of light. In many experimental setups involving small numbers of atoms or molecules, such as quantum computation with trapped ions [8], or single-molecule chemical reactions [9], coherent laser light is the primary tool used to interact with and manipulate these particles. On the other hand, the light itself can be the object of interest, such as in quantum communication protocols, where information is encoded in the precise intensity and phase of light sent through an optical fiber [12]. In all of these use cases, and many others, a method of control is required which can both rapidly and accurately manipulate laser light.

1.2 Previous Approaches

There are a number of existing approaches to this problem, however all are lacking in either speed, accuracy, complexity of patterns, or versatility due to limited number of channels they can achieve. The most common tools currently used for creation of arbitrary optical spatial patterns are spatial light modulators (SLMs), such as digital micro-mirror devices (DMDs) and liquid crystal devices (LCoS SLMs). These approaches utilize modifying the intensity or the wavefront of an incoming illumination to generate patterns either holographically or by direct illumination. These devices on their own, however, have a number of limitations; DMDs operate at up to 20kHz, but their wavefront modulation is binary, meaning image generation is extremely inefficient, while the typical LCoS SLM operates at ~100 Hz [16]. Due to the fact that coherence times of single-particle systems (such as ground-rydberg
encoded atoms, and 2D quasi-particles) are often on the order of single microseconds [3], these systems lack the ability to update over the length of a single experimental run, which drastically limits their usefulness in complex setups. In quantum communication as well, patterns must be updated between every photon sent, so the slow update rate corresponds directly to an efficiency bottleneck of the system [12].

On the other end of the spectrum, devices such as acousto- or electro-optical modulators (AOMs and EOMs) can be used to illuminate a number of static phase plates. Each of these phase plates generates a different image, and with the help of beamsplitters these individual images can be projected into the same location [14]. The main advantage of this approach is in the high speed of the modulators, with the fastest devices working in the gigahertz range, but that main disadvantage is in difficulty of achieving complexity. Since a separate phase plate is required for each desired pattern, a severe limit is placed on such a systems usefulness in applications where a large number of different configurations is desired, such as in an experiment where small adjustments are constantly being made to how particles are distributed.

Finally, an approach by Braverman et al. from 2020 [2] sought to combine these ideas, but using a single AOM deflecting at different angles to illuminate a number of different dynamic holograms. This system combines a high speed, with a switching rate of ~500 kHz, with reconfigurability due to the dynamic holograms. Nevertheless, on the technical side, there is a high level of crosstalk (~4% on average between pairs of channels) due to the fact that the different holograms are displayed on the same plane, and accuracy is fairly low, with a reconstruction fidelity of the desired modes of 63.6%. More important, however, is the fact that this system is only capable of generating 10 individual patterns, with a single one being active at a time, due to the size of the SLM being used and the fact that the AOM can only direct light at one hologram at a time. Again, this can be quite limiting, especially as atomic systems continue to scale, and more operations can be performed within a single experimental run. Radwell et al. in 2014 [11] also demonstrated a similar system, however this one achieved an update rate of only 10 kHz. The aim of this work, then, is to present a
system which is both fast and accurate, and has the capability to generate a large number of easily reconfigurable modes.

1.3 Our Work

The basis of this system is a 16-channel AOM. Each channel of the AOM works by using a piezoelectric transducer to generate sound waves in a crystal of tellurium dioxide (TeO$_2$) in order to deflect a beam of light passing through it. In this way, it acts as a switch for the light which can be turned on and off very rapidly (on the order of \(~20\) MHz). Additionally, due to the fact that the light is effectively scattering off of a moving plane, by varying the frequency and phase of the sound wave, the frequency and phase of the outgoing light will vary accordingly. These individual beams, switched by the AOM array, illuminate the SLM from different angles, projecting a different part of the generated image, and hence a different light pattern, into a region of interest. Due to the fact that an array of individually-controlled AOMs is used, rather than a single AOM with different deflection angles, the individual addressed images can be combined and interfered to produce more complex patterns. With the $N = 16$ channels used in this system, this opens the possibility for up to $2^N = 2^{16}$ different patterns. Additionally, due to the reconfigurability of the SLM hologram, these patterns can be easily changed between individual experimental runs, making this a promising tool for complex experimental use.

1.4 Applications

Although a system for light modulation has many applications, certain design choices for our work have been driven by the specific atom array experiment this work has been built for. As such, we briefly describe the system, what it is meant to achieve, and why this is such a useful tool. In this experiment individual atoms (up to 289) of Rubidium-87 are trapped by a 2D array of optical tweezers [6], with entanglement mediated by Rydberg interactions (for more information on these interactions, see [13] section I.A). Using this
platform, a number of interesting experiments can be performed given sufficient control over the light patterns used to trap the atoms.

One of the most common uses of such a system is for quantum simulation, where exotic quantum states are encoded in the ground/Rydberg states of the atoms, and the evolution of the system is observed. In a recent work by Ebadi et al., the system was used to encode a graph in the layout of the array, such that the evolved state of the system represented a solution to the maximum independent set (MIS) problem (see [5]). Here, the dynamics of the system occur at sub-microsecond timescales, so any light patterns used for control must be applied correspondingly quickly. In this regime, the system we present could be used, for instance, to manipulate quasi-particles in a spin-liquid, a 2-dimensional phase of matter in which quasi-particles known as anyons have properties unlike those of fundamental particles, such as being asymmetric under exchange operations (see [1]).

Another promising application for such a system is in the regime of quantum computing, where the large number of atoms enables error corrected systems, where a single logical qubit is encoded nonlocally in multiple physical atoms for protection against errors (see, for example, [15]). In this mode of operation, our ability to generate complex modes of light would allow for addressing the entire ensemble of atoms representing a logical qubit with only a single control channel. Alternatively, each channel can be linked to a corresponding physical qubit in each logical ensemble, to perform large-scale error detection/correction operations. This addressing can be used to perform both local lightshifts (corresponding to a $\sigma_z$ operation) and local driving through the Raman transition (corresponding to a $\sigma_x$) enabling a full error-correction protocol.

Finally, as alluded to in the last paragraph, a modification of this system to be optimized for 420 nm light, rather than 830 nm, would allow for local Rydberg driving to be performed. Compared to the current system, in which Rydberg driving must always be done globally, this would allow for increased complexity and optimization of procedures in both regimes of operation by allowing selective operations without the need for atom repositioning, a fairly slow process.
2 Theory of Operation

Before describing the system in technical detail, we first provide a high-level overview of the operation in order to guide further description.

![Mode 1: Beam Switching](image1)
![Mode 2: Image Selection](image2)
![Mode 3: Basis Set Multiplexing](image3)

Figure 2.1: Visualization of the three modes of operation, in order of increasing complexity. Mode 1 demonstrates switching of the beams, with the SLM used only to create the beam array. Mode 2 shows the use of the second SLM pass to turn each beam into an image. Mode 3 shows that these images can be interfered both constructively and destructively.

The first panel of figure 2.1 shows the most basic mode of operation, in which the system simply acts as an on/off controller for a linear beam array. In this mode, the system uses the SLM only to generate an array of equally spaced beams, which pass through the multi-channel AOM to be turned on and off. Such an operation is useful in applications such as 1-dimensional arrays of trapped ions (see [4]), where the addressing locations are held fixed, as well as characterization of rise time and on/off contrast, where the generated patterns are irrelevant.

Mode 2 now demonstrates the incorporation of a second SLM, where each of the individual beams from mode 1 can be turned into an arbitrary pattern in the image plane.
Together with the beam switching by the AOM, this allows arbitrary images, such as shapes or patterns of multiple dots, to be switched between. This mode enables control of more complex setups, such as 2-dimensional arrays of trapped atoms, or 1-dimensional arrays with unequal spacing.

Finally, the last panel shows the complete capability of our system, and presents a mode of operation which other systems have not achieved. Due to the fact that we are using an AOM array with individual channels, rather than a single AOM with different deflections angles, to address the SLM, multiple generated patterns may be active simultaneously, as shown in the upper example in mode 3. This allows the 16 individual images to be used as a basis set, from which any of $2^{16}$ combinations may be active at once. This allows control schemes such as addressing sub-grids of a larger lattice. Additionally, in sections 3.2 and 4.1, we describe how we achieve precise control over not only the intensity but also the phase of the produced image, such that in overlapping them we can both constructively and destructively interfere the light to achieve complex patterns, as shown in the bottom figure, as well as continuously moving holograms (see section 5.3).
3 Method of Operation

Figure 3.1: Schematic of the optical layout of the system, showing the interface of the acousto-optical modulator (AOM) and two passes of the spatial light modulator (SLM), as well as the control electronics for the AOM array.

3.1 Overview

The experimental setup is shown schematically in figure 3.1. Broadly, the system is divided into three key parts: the AOM array, as well as its associated control components; the SLM, of which the active surface is divided in half and utilized two separate times in the beam path; and finally the optical system which connects the components, and allows for measurement and calibration of the setup. We address each of these components in turn.
3.2 AOM Design

The main driver behind the fast switching ability of this setup is an array of 16 TeO$_2$ acousto-optical modulators (Crystal Technology, Inc. Model 110/16), mounted such that the channels are in one vertical plane. Each channel of this array is driven independently by a 110 MHz RF signal, which is obtained by generating a 20 MHz signal on a programmable arbitrary waveform generator (AWG) card and mixing this signal with a 90 MHz output from a voltage-controlled oscillator (VCO), and finally amplified to the 30 dBm signal strength required by the AOM (This process is shown diagrammatically in figure 3.1 as well). This procedure allows us to use an two 8-channel AWGs (Spectrum Instrumentation M2p.6568) which are capable of producing only 80 MSample/sec (corresponding to a 20 MHz waveform), since faster AWGs come at a significant price increase, and support less channels per card leading to an increase in both physical and software complexity. The use of an RF mixer with high L-R isolation (Minicircuits ZX05-1-S+) allows the VCO to output a constant wave without interfering with the AOM operation, such that all of the wave control comes solely from the AWG. The efficiency of the AOM is >70%, and rise/fall times for the 50 µm beam are <50 ns.

This control scheme for the AOM array has several key properties which make it particularly suited to our method of operation. First, it gives us full control of turning on/off the beam using just the AWG, as all other components operate at a “steady state”. Additionally, the power of the signal from the AWG is transformed linearly throughout the mixing/amplifying process, meaning that we can also control the power going to the AOM directly from the AWG. This is useful as different channels of the AOM have their peak deflection efficiencies at slightly varying powers due to manufacturing inconsistencies, so the compensation for this can be done in software rather than hardware. Finally, the mixer also linearly transforms the phase/frequency of the incoming wave, meaning we can vary the phase/frequency of the RF signal going to the AOM. This, in turn, allows us to vary the phase and frequency of the light beam being switched. This is particularly useful when we
consider interfering multiple images, as described in the third mode of operation in section 2. In order to vary the relative phases of different images being overlapped, we can do this by directly varying the phase of the beam before the second SLM pass, rather than updating the generated image at the SLM, which would be comparatively very slow.

Figure 3.2: Diagramatic depiction of how different channels are used to multiplex the filmstrip image from the SLM. a) A demonstration of how different AOM channels address the SLM at different angles to move a different image into the region of interest. b) A depiction of the "filmstrip" layout used to split a series of images into a version addressable by the AOM, as well as a real image from the system showing this layout. c) A time depiction of how the different channels of the AOM would be used to "move" the light pulse through space.

3.3 SLM Design

The other major component of the system is the spatial light modulator (SLM, Thorlabs Exulus HD-2), which allows the generation of arbitrary patterns. A key feature of this system, which reduces both its physical footprint as well as its cost, is the fact that the single
The active surface of the SLM (Thorlabs Exulus HD-2) is divided horizontally in half and used as two entirely separate SLMs, each serving their own function in the optical system. The first half is kept static, and is used to generate the 16 separate beams which pass through the 16 channels of the AOM. Due to the one-dimensional nature of the pattern, the hologram for the first bounce is both extremely efficient as well as easy to generate, so real-time tuning is easy.

The other half of the active surface, then, is used to generate the 16 arbitrary images, with each image being addressed by one of the beams leaving the AOM. One of the key aspects of this system is how precisely this addressing is done. Due to the limited resolution of the SLM (1920x1200), it is infeasible to subdivide the surface into 16 different “sub-SLMs”, each of which has a separate beam shining on it. Instead, we make use of the fact that the light arriving from the AOM will be entering at different angles, due to the vertical separation of the channels. As shown in figure 3.2 a), this means that the resulting image, after the second bounce, will be vertically displaced depending on which channel the light originates from. To take advantage of this, the SLM is programmed such that the resulting image is the 16 basis images stacked vertically, demonstrated in figure 3.2 b). This is aligned precisely such that one of the 16 images occupies the region-of-interest (ROI) at the output image plane. By then displacing the overall image vertically using the AOM, we are able to move a different one of the 16 basis images into the ROI, effectively “displaying” a single image at a time. Although this approach leads to a loss of efficiency as only $\frac{1}{16}$ of the light in the image is used at a time, this is remedied by the fact that we can display multiple channels at once, and through our high-efficiency hologram generation described in 4.1.1.

Figure 3.2 b) demonstrates how this principal can be used to turn, for example, a pattern of beams meant to move an optical tweezer around a circle into the corresponding “filmstrip” layout generated by the SLM. By activating the corresponding AOM channels at the given time, as shown in figure 3.2 c) we are then able to “move” the pulse of light in discrete steps around the given shape.
3.4 Layout Specifics

Finally, we describe the optical system which connects these components. Light from a 830nm TiSaph laser passes through a polarizing beamsplitter, ensuring that the incident light to the SLM is linearly polarized, and then passes through a 2x magnification telescope composed of lenses L1 and L2 (f1 = 75mm, f2 = 150mm), such that when it reaches the active surface of the SLM, the beam waist is 4mm. After reflecting off of the SLM the first time, the beam passes through a 4f system consisting of L3, L4, and L5 (f3 = 300mm, f4 = -75mm, f5 = 200mm). The two 2” mirrors then allow us to align the 16 beams which are separated by ~1mm, with a beam waist of 74µm. The same system is then repeated in reverse, with two mirrors aligning the beam into L6, L7 and L8. The beam then reflects off the second hologram, before passing through L9 (f9 = 300mm) and finally reaching the imaging point.

There a number of key optimizations made to the system for the sake of compactness, which are worth briefly addressing here. The first is the folding of the beam path in order to minimize the reflection angle on the SLM. By crossing the beam path as pictured in figure 3.1, the angles of the reflections are reduced to 5.7° and 11.4°. These angles are limited by the physical size of the L3, L8 and L9 lenses, which must be placed side by side. The second is the 4f system comprised of lenses L3, L4 and L5 (and again in reverse by L6, L7 and L8). In theory, one could use a simple 4f telescope between the SLM and the AOM to focus the beam. However, by moving the second lens of the telescope (L4 and L7) closer to the first lens (L3 and L8) by some distance ∆x, the generated image moves closer by \( \left( \frac{f_4}{f_3} \right)^2 \times \Delta x \). Since \( \left( \frac{f_4}{f_3} \right)^2 = 16 \), we can significantly reduce the length of our telescope, while still keeping the second lens close to the conjugate point, and hence degrading performance by a negligible amount.
4 Software Design

Figure 4.1: Block diagrams showing the procedure of the iterative hologram generation algorithms. (I)FT symbolizes the (inverse) Fourier transform. a) Procedure of the Gerchberg-Saxton algorithm. b) Procedure of our novel phase-controlled mixed-region amplitude freedom (MRAF) algorithm. The final phase hologram is given by the value of \( \phi(x, y) \) after a number of iterations has completed.

4.1 Hologram Generation

A core requirement for the function of this system is the ability to generate high-fidelity holograms using the SLM. In this section, we describe existing algorithms for intensity-stable computer hologram generation, as well as our contribution of a region-specific phase- and
intensity-stable algorithm, which allows for interference of images with specific phases. Concretely, the problem we are trying to solve is as follows: Given an input amplitude profile $|F(x, y)|$, we aim to find a phase $\phi(x, y)$ such that the Fourier transform of the resulting signal, $I(x, y) = FT\left(|F(x, y)| e^{i\phi(x, y)}\right)$ has some desired properties, such as a specific intensity distribution $|I(x, y)|$.

The simplest algorithm for hologram generation, also called an iterative phase retrieval algorithm, is the Gerchberg Saxton algorithm [7]. The goal of the Gerchberg Saxton algorithm is to produce an output profile with a specific amplitude across the entirety of the region, with an unspecified (random) phase. This algorithm works by starting with a random phase profile, then taking the Fourier transform (FT) of the signal, replacing the resulting amplitude with the desired amplitude $|I(x, y)|$, taking the inverse FT, replacing the amplitude again with the input amplitude $|F(x, y)|$, and repeating until a desired fidelity criterion is reached. The desired phase hologram is then given by the phase of the determined input field. This procedure is also shown diagrammatically in figure 4.1 a). Formally, the new input field $G(x, y)$ is generated from the propagated field $E_{out}(x, y)$ and the desired target intensity $I(x, y)$ as

$$G(x, y) = \sqrt{|I(x, y)| e^{i\arg[E_{out}(x, y)]}}$$

This algorithm works well for simple tasks, and is used in our system to generate the beam-array on the first SLM pass, however it lacks in some key areas. First, due to the constrained nature of the problem, forcing a specific amplitude profile across the entirety of the region limits the reconstruction fidelity, and hence the smoothness, of the resulting image. Additionally, there is no phase control, so in applications where phase control is required, such as when complex interference patterns are desired, the Gerchberg Saxton algorithm is not enough.

In order to remedy the first issue, Pasienski and DeMarco in 2008 [10] introduced the mixed-region amplitude freedom (MRAF) algorithm. This algorithm operates very similarly to the previously-described Gerchberg Saxton algorithm, with the basis being an $FT$ - amplitude replacement - $IFT$ - amplitude replacement structure. The main difference here is
that intensity is only controlled within a bounded subset of the output plane, effectively “buying degrees of freedom”. This change means that with careful choosing of the bounding region, the resulting images are improved by one order of magnitude in accuracy, two orders of magnitude in smoothness, while losing a factor of three in efficiency, due to the fact that some light is “dumped” outside of the signal region. One key optimization made here is the introduction of the mixing parameter $m$, which dictates how “strongly” the amplitude in the signal region is replaced. Specifically, the propagated field $E_{\text{out}}(x, y)$ is combined with the desired target intensity $I(x, y)$ as follows (where NR and SR denote the noise- and signal-regions respectively):

$$G(x, y) = \left\{ \left( m \times \sqrt{|I(x, y)|} \right)_{\text{SR}} + (1 - m) \times |E_{\text{out}}(x, y)|_{\text{NR}} \right\} e^{i \arg[E_{\text{out}}(x,y)]}$$

This mixing parameter allows control over the replacement strength while keeping the power in the output plane constant, and as part of our algorithmic development we analyze empirically the dependence of the resulting output image as a function of $m$, which Pasienski and DeMarco did not do.

Finally, as described in section 2, we would like the ability to control the phase of our image, as well as the intensity. Phase control cannot be added to the original Gerchberg Saxton algorithm, as this would be over-constraining the problem. Instead, we use the freedom bought by the MRAF algorithm in order to add a phase-control component. In order to do this, when we replace the amplitude with the desired amplitude of the target image, we replace the phase inside the signal region as well, while maintaining the generated phase/amplitude outside of the target region. Similar to the above, this means our new input field is generated as:

$$G(x, y) = m \times \sqrt{|I(x, y)|} e^{i \arg[I(x,y)]} + (1 - m) \times |E_{\text{out}}(x, y)| e^{i \arg[E_{\text{out}}(x,y)]}$$

Again, this procedure is shown diagrammatically in figure 4.1 b). In this way, we are able to control not only the amplitude, but also the phase of our image, while maintaining high accuracy and efficiency with a careful choice of signal region.
4.1.1 Performance Characterization

In order to show the capabilities of this phase-controlled MRAF, we perform a number of empirical characterizations. Specifically, we characterize the effect of the mixing parameter on the efficiency and accuracy of the generated hologram, as well as using these numbers to understand the general performance of our algorithm for practical applications.

The primary measure of performance in a system such as ours, which involves multiple SLM passes, is the efficiency of the generated hologram. In order to measure this, we look at the image (obtained by performing the discrete Fourier transform of the hologram), and find the proportion of the total light in the image which is placed inside of the specified signal region. In particular, a higher efficiency corresponds to less “lost” light, and a higher possible intensity at the final output. The dependence of this efficiency on the mixing parameter $m$ is shown in the first panel of figure 4.2.

Second, we aim to characterize the accuracy of the generated image. In order to do this, we again look at the signal region of the obtained image and compare it to the desired output image $I$ used to generate the hologram. To calculate the error between the two, we first normalize both signal regions to account for variations in efficiency, and then sum the squared differences between the generated and desired images. This gives a relative measure of the accuracy of the generated image, and allows us to analyze the trend as we vary the mixing parameter. The dependence of this error on the mixing parameter $m$ is shown in the second panel of figure 4.2.

To perform our tests, we generate two holograms, representative of the type of image we would need for system operation. The “3 top hats” image consists of three rectangular Gaussian beams arranged vertically with flat phases, with the signal region encompassing a vertical rectangle around them. The “4 circle holo” image consists of four ellipses arranged vertically with phase windings of $0$, $2\pi$, $4\pi$, and $6\pi$ respectively, as used for continuous pulse generation described in section 5.3. These two images are shown in appendix A.
The results of the characterizations are shown in figure 4.2. For both holograms, we observe a clear dependence on the mixing parameter $m$, with a higher $m$ value leading to increased efficiency, but lower accuracy. Additionally, the precise values of efficiency which can be achieved seem to be very dependent on the image being generated, as well as possibly the signal region, but further characterization of these attributes must still be performed. Further, we observe that we can achieve fairly high values of efficiency for specific holograms, with efficiencies ranging from 2% to upwards of 50%, meaning that phase-stable hologram generation is possible without a large loss of optical power. For comparison, generating both of these holograms using the Gerchberg Saxton algorithm (and hence losing control over the phase) gives efficiencies of ~20%. Comparing this to the numbers for the non-phase-controlled MRAF shows that efficiency is not heavily impacted by the fact that we specify the phase of our image. Most importantly, the dependence of these values on $m$ means that the tradeoff can be easily controlled, and depending on the application, efficiency or reconstruction accuracy can be prioritized, increasing the possible range of useful applications for the system.
4.2 AOM Waveform Management

The second key point of our software is the generation of signals on the AWG, used to drive the AOM array. The AWG functions by filling a buffer with samples for each of its 8 channels (with 2 cards being used to drive the 16-channel array), which are then played back at a rate of 80 MSamples/s. In order to generate the waveforms corresponding to switched signals, we simply generate 20 MHz sine waves at corresponding time intervals, with phases determined by the desired phase relations between resulting images. Additionally, in order to generate continuously moving holograms, as described in section 5.3, we want a small frequency offset between channels such that the relative phase of beams is changing continuously. In this case, we simply generate a wave with a frequency of \( f = 20 \text{ MHz} \pm d \text{ Hz} \), which creates a phase between waves which varies at \( d \text{ Hz} \). We then sample this resulting waveform at a rate of 80 MSamples/s, well over the Nyquist frequency of \( \sim 40 \text{ MHz} \).

For normal operation, these samples are generated and loaded onto the card in segments, and then a replay-pattern for these segments is specified. In more complex use cases, however, such as real-time phase error compensation described in section 5.2, the AWG also has a mode in which this data can be streamed and played back in real time.
5 Measurements and Capabilities

In this section, we describe the important characteristics of the system, as well as some of the more advanced manipulations we are able to achieve.

5.1 Performance Characteristics

As mentioned previously, one of the key performance elements of the system is its rapid switching time. Specifically, due to the small size of the beams at the AOM, the AOM has a measured rise time of 50ns, and since separate channels are controlled independently, this corresponds to a switching time between channels of 50ns, or a 20MHz update rate. Given the 80 MHz output rate of the AWG, and the response time of the mixing system, we find that this rate is achievable using the current hardware of the system.

The other major aspect we wish to characterize is the quality of the produced holograms. Given our results from section 4.1.1, we know the theoretical quality of the produced holograms is high, so we characterize our physical reproduction of these in terms of the contrast ratio of the produced hologram. This takes into account both the quality of reproduction by the SLM, as well as the quality of modulation by the AOM. By viewing the final image on a CMOS camera with the exposure increased until the background noise becomes measurable, we find that our produced holograms have a $> 10,000 : 1$ contrast ratio, meaning that the background is small enough to interact negligibly with the controlled atoms at normal operating power. Finally, due to the separate channels of the AOM array, and the spatial separation of optical modes, we find that there is less than 35 dBm of crosstalk between channels, which again is enough to be negligible for the purposes of atomic control.
5.2 Phase-Controlled Interference

One of the key features enabled by this system, through our use of multi-channel addressing combined with novel hologram-generation techniques, is the ability to interfere phase stable images to create complex patterns.

**Figure 5.1:** Demonstration of interfering two Gaussian beams with flat intensities and varying phase patterns to obtain a grating interference pattern in the resulting intensity. The predicted intensities and phases of the separate images are shown, as well as the theoretical and measured intensities of the resulting interference pattern.

**Figure 5.2:** Demonstration of interfering two Gaussian beams with flat intensities and varying phase patterns to obtain a tweezer array interference pattern in the resulting intensity. The predicted intensities and phases of the separate images are shown, as well as the theoretical and measured intensities of the resulting interference pattern.
Figures 5.1 and 5.2 show examples of the patterns we are able to achieve using our phase stable interference, such as generating gratings and lattices by interfering images with flat intensity. The bottom right figures show the measured patterns from the system, where we measure a > 100 : 1 extinction ratio between the constructively and destructively interfered regions of the image.

Additional, we can characterize the stability of these phase overlaps, which are important when using this as a method of e.g. generating trapping tweezers. In order to perform this measurement, we generate two dots, and interfere them at a photodiode. The measured intensity, then, directly corresponds to the phase between the channels. Figure 5.3 shows a graph of this measured intensity, where the phase was first deliberately varied through its full range, and then kept still. By comparing these two temporal regions, we see that the relative phase of the two channels is stable enough such that the intensity varies by < 5% of its total range over a timescale of 0.1 seconds. If this level of stability does not suffice, or if a longer range of stability is required, the fact that this relative phase can be easily measured opens the door for active stabilisation, with a feedback loop to vary the phase of the light at
the AOM.

5.3 Continuously Moving Holograms

Figure 5.4: Demonstration of the Fourier-series combination of images with different phase windings in order to generate a pulse of light along the contour of the image. a) The combination of images with uniform intensities, but varying phase windings, produced a single pulse of light when they are interfered. b) By varying the phase offset between the phase windings, the position of the pulse can be varied along the contour determined by the intensity profile of the image. c) A demonstration of this concept with 4 interfered images, showing the pulse of light moving around an ellipse.

The final culmination of the novel software techniques and hardware design demonstrated in this work is the ability to generate continuous movement. Figure 5.4 demonstrates the basic concept behind the generation of a moving pulse. As shown in panel a) of figure 5.4, interfering images with a flat intensity but varying phase windings allows the intensity to destructively interfere in all parts of the image besides one, leaving a single pulse of light. Conceptually, this is very similar to using a Fourier-series to approximate a comb function (with a period of $2\pi$), and the more terms we have in the series, or equivalently the more
phase-woundings we interfere, the tighter the pulse becomes.

The real usefulness of this approach, however, emerges from the fact that by varying the overall relative phase of the images, the position of the pulse along the path changes. As shown in panel b), if we offset the phase of the first image by $\delta \theta$, the phase of the second image by $2\delta \theta$, and so on, the position of the pulse moves by precisely $\delta \theta$. This is particularly useful in our case, as the overall phase of the interfering images can be varied at the AOM, much faster than any variation we could do at the SLM, and due to the finely tunable nature of the phase offset (see section 4.2), we can control the position of this pulse continuously, generating extremely smooth movement, compared to what we could achieve with 16 discrete positions.

Panel c) of figure 5.4 shows a demonstration of this concept on the constructed system, albeit with only 4 interfered images, leading to a much wider pulse, due to the narrower spectrum in Fourier-space. The movement of the pulse is clearly shown, as well as the high level of extinction we can achieve in the non-pulse areas of the image through the complex interference of the individual images. Due to the fact that the intensity profile of the image can be chosen arbitrarily, this pulse may be made to travel around any given path, and given our fine level of phase control at the AOM, the position/velocity of the light pulse is similarly easily determined. This mode of operation enables the continuous movement of particles trapped using the light pulse, used in applications involving both atoms as well as 2D quasi-particles such as anyons (see section 1.4). In particular, such a mode of operation is only possible due to the unique set of design choices made in this system, and has not been achievable using any previous similar system.
6 Conclusion

In this work, we have presented a novel system for the rapid manipulation of spatial light modes, for use in atom-array experiments. Through the use of an AOM array for fast switching and an SLM for arbitrary pattern generation, coupled with a novel hologram generation algorithm, we demonstrate accurate and efficient generation of light patterns. We further show that through careful phase control, these patterns can be interfered both statically and continuously to generate a patterns for control of complex systems, which makes this system an extremely useful tool for a wide range of experiments.

There are a number of directions for further exploration. The first is further characterization of the hologram generation, including gaining a deeper understanding of what types of patterns are efficient to display, and how parameters such as the signal region affect hologram quality. Second, in order to further improve stability of interfered patterns, an active feedback loop between phase measurement and phase control at the AOM is required, and we have already demonstrated the necessary tools in order to do this. Finally, there is still the possibility for expanding this system into an even larger number of channels and hence degrees of control, with the help of additional optical techniques and a larger array of AOMs.
7 References


[12] Yongxiong Ren, Zhe Wang, Guodong Xie, Long Li, Yinwen Cao, Cong Liu, Peicheng Liao, Yan Yan, Nisar Ahmed, Zhe Zhao, Asher Willner, Nima Ashrafi, Solyman Ashrafi,


A  Holograms Used for Algorithmic Characterization

Figure A.1: The holograms used to test performance of the hologram generation algorithms. The vertical stacking of patterns represents exactly the filmstrip layout of different images used in any sort of control scheme implemented using the system.