Integrated System Technologies for Modular Trapped Ion Quantum Information Processing

by

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Daniel J. Gauthier

Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Electrical and Computer Engineering in the Graduate School of Duke University

2016
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Abstract

Although trapped ion technology is well-suited for quantum information science, scalability of the system remains one of the main challenges. One of the challenges associated with scaling the ion trap quantum computer is the ability to individually manipulate the increasing number of qubits. Using micro-mirrors fabricated with micro-electromechanical systems (MEMS) technology, laser beams are focused on individual ions in a linear chain and steer the focal point in two dimensions. Multiple single qubit gates are demonstrated on trapped $^{171}\text{Yb}^+$ qubits and the gate performance is characterized using quantum state tomography. The system features negligible crosstalk to neighboring ions ($< 3 \times 10^{-4}$), and switching speeds comparable to typical single qubit gate times ($< 2\mu s$). In a separate experiment, photons scattered from the $^{171}\text{Yb}^+$ ion are coupled into an optical fiber with 63% efficiency using a high numerical aperture lens (0.6 NA). The coupled photons are directed to superconducting nanowire single photon detectors (SNSPD), which provide a higher detector efficiency (69%) compared to traditional photomultiplier tubes (35%). The total system photon collection efficiency is increased from 2.2% to 3.4%, which allows for fast state detection of the qubit. For a detection beam intensity of 11 mW/cm$^2$, the average detection time is 23.7 $\mu$s with 99.885(7)% detection fidelity. The technologies demonstrated in this thesis can be integrated to form a single quantum register with all of the necessary resources to perform local gates as well as high fidelity readout and provide a photonic link to other systems.
To my family
### Contents

Abstract iv  
List of Tables x  
List of Figures xi  
List of Abbreviations and Symbols xv  
Acknowledgements xix  

1 Introduction 1  
  1.1 Quantum Computing Requirements 2  
  1.2 Quantum versus Classical Computing 2  
  1.3 Choice of Physical Qubits 3  
  1.4 Scaling the Ion Trap Quantum Computer 4  
  1.5 Dissertation Overview 6  
  1.6 Summary of My Contribution 6  

2 Scalable Ion Trapping and the $^{171}$Yb$^+$ Qubit 9  
  2.1 Ion Trapping 10  
    2.1.1 Sandia Thunderbird Trap 11  
    2.1.2 Sandia High Optical Access (HOA) Trap 12  
  2.2 The $^{171}$Yb$^+$ Qubit 13  
    2.2.1 State Initialization 14  
    2.2.2 State Detection 15
5.3 MEMS Beam Steering ............................................. 57
  5.3.1 Optical System Design ..................................... 58
5.4 Individual Addressing of $^{171}$Yb$^+$ Qubits Using MEMS Beam Steering 61
  5.4.1 Intensity Crosstalk Characterization .................... 63
  5.4.2 Switching Speed Characterization ....................... 66
  5.4.3 Sequential Single Qubit Gates ............................ 68
5.5 Discussion and Outlook ....................................... 69
6 Enhanced Photon Collection Through a Fiber ....................... 72
  6.1 High Numerical Aperture Lens Model ..................... 72
  6.2 High NA Lens Optomechanics ................................. 73
  6.3 High NA Lens Alignment and Aberration Correction ...... 75
  6.4 Fiber Coupling Alignment ..................................... 79
  6.5 Single-mode Fiber Coupling Efficiency Calibration ...... 80
  6.6 Superconducting Nanowire Single Photon Detectors ...... 84
    6.6.1 Cryostat System ........................................... 86
  6.7 SNSPD Detector Efficiency Calibration .................... 87
  6.8 State Detection Through an Optical Fiber .................. 89
    6.8.1 Magnetic Field Calibration .............................. 90
    6.8.2 Scattering Rate Calibration ............................ 91
    6.8.3 State Detection Using Photon Time of Arrival ...... 92
  6.9 Discussion and Outlook ....................................... 98
7 Conclusions and Future Work ...................................... 101
  7.1 Future Potential ............................................. 102
A Derivation of Analytic State Detection Error Probabilities .. 107
Bibliography .......................................................... 110
List of Tables

5.1 Table of various combinations of sequential single qubit gates on a pair of trapped ions and their corresponding gate fidelities measured using quantum state tomography. 69

6.1 Summary of the collection efficiencies of various detection methods. 89

6.2 Comparison of the average state detection time and errors for various detection beam intensities. 100
List of Figures

1.1 Schematic of an ion trap quantum processor. ........................................... 5
2.1 Projection of a linear Paul trap to a surface trap .................................... 10
2.2 Electric field profile of the ion trapping region ...................................... 11
2.3 Pictures of the Sandia Thunderbird and Sandia HOA surface ion traps 12
2.4 Energy levels of the $^{171}\text{Yb}^+$ ion ...................................................... 13
2.5 Energy level diagram of the $^{171}\text{Yb}^+$ ion showing state preparation and state detection .......................................................... 15
3.1 CAD drawing of the UHV system and custom back flange assembly. 18
3.2 Pictures of the electrical routing needed for the 96 DC electrodes ......... 20
3.3 CAD layout of the top and bottom layers of the UHV PCB .................. 22
3.4 Picture of the assembled UHV PCB and ion trap. Picture of the fully assembled vacuum chamber ......................................................... 22
3.5 CAD cross-section of the helical resonator. ............................................. 24
3.6 Circuit diagram for one channel of the readout circuit. ............................. 27
3.7 Differential spectrum of the counts recorded by the PMT readout circuit 28
3.8 The noise spectrum of the PMT readout circuit .................................... 29
3.9 The schematic of the optical layout of the polarization spectroscopy locking. ................................................................. 31
4.1 SEM image of a tilting MEMS mirror .................................................... 33
4.2 Single axis tilting MEMS mirror schematic .......................................... 34
4.3 Cross-section diagram of the SUMMiT process ...................................... 37
4.4 Microscope image of the aluminum coating damage. 39
4.5 SEM image of a released MEMS device, and a picture of a fully packaged MEMS device. 39
4.6 Plot of the radius of curvature of the MEMS mirror as a function of deposited metal thickness. 41
4.7 Simulation of the reflectance of aluminum as a function of metal thickness. 42
4.8 White light interferogram detailing the curvature of the MEMS mirror after metal deposition. 42
4.9 Plot of the measured tilt angle as a function of applied voltage. 44
4.10 Plot of the transient response of a MEMS mirror with a resonant frequency of 260 kHz. 45
4.11 Intensity profile of the beam at the Fourier plane. 46
4.12 Schematic of the MEMS electronics. 47
4.13 Schematic of the MEMS optical shutter. 48
4.14 Extinction ratio of the MEMS-based beam shutter. 49
4.15 Plot of the transient response of the MEMS shutter for both the turn on and turn off cases. 50
5.1 The Bloch sphere visualization of a qubit. 52
5.2 Simplified energy level diagram of $^{171}\text{Yb}^+$ showing the microwave gate transition. 52
5.3 The probabilities of finding each of the two individual ions in the $|1\rangle$ state as a function of the duration of the microwave field. 54
5.4 Simplified energy level diagram of $^{171}\text{Yb}^+$ showing a Raman transition. 55
5.5 Schematic of the two frequency combs that drive the Raman transition. 56
5.6 Schematic of ion qubits individually addressed by two independently steerable lasers. 57
5.7 Schematic of the MEMS beam steering optical system. 58
5.8 Picture of the optical layout of the MEMS beam steering system. 60

xii
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9</td>
<td>Characterization of a single beam addressing range.</td>
<td>61</td>
</tr>
<tr>
<td>5.10</td>
<td>Schematic of the optical setup of the imaging and MEMS beam paths.</td>
<td>62</td>
</tr>
<tr>
<td>5.11</td>
<td>Crosstalk characterization of the MEMS beam steering system.</td>
<td>64</td>
</tr>
<tr>
<td>5.12</td>
<td>Characterization of the beam waist at the ion location.</td>
<td>65</td>
</tr>
<tr>
<td>5.13</td>
<td>Characterization of the timing response of the MEMS beam steering system.</td>
<td>67</td>
</tr>
<tr>
<td>5.14</td>
<td>State tomography of individual qubits.</td>
<td>70</td>
</tr>
<tr>
<td>6.1</td>
<td>Ray tracing diagram of the high NA lens and a picture of the assembled lens system.</td>
<td>73</td>
</tr>
<tr>
<td>6.2</td>
<td>CAD drawings of the fiber coupling optomechanics.</td>
<td>74</td>
</tr>
<tr>
<td>6.3</td>
<td>Schematic of the experimental system to couple light scattered by an ion into a fiber.</td>
<td>76</td>
</tr>
<tr>
<td>6.4</td>
<td>Through focus images of the ion through the high NA lens.</td>
<td>77</td>
</tr>
<tr>
<td>6.5</td>
<td>Through focus simulation of an aberrated ion in Zemax.</td>
<td>77</td>
</tr>
<tr>
<td>6.6</td>
<td>Image correction of a single trapped ion.</td>
<td>78</td>
</tr>
<tr>
<td>6.7</td>
<td>Count rates as a function of $x$ and $y$ displacement of the coupling fiber.</td>
<td>81</td>
</tr>
<tr>
<td>6.8</td>
<td>The effective scattering rate of the $^{174}$Yb$^+$ ion through a single-mode fiber as a function of detection beam power.</td>
<td>83</td>
</tr>
<tr>
<td>6.9</td>
<td>Schematic of the operation of a superconducting nanowire single photon detector.</td>
<td>85</td>
</tr>
<tr>
<td>6.10</td>
<td>Picture of the cryostat system and the three cooling stages.</td>
<td>86</td>
</tr>
<tr>
<td>6.11</td>
<td>The effective scattering rate of the $^{174}$Yb$^+$ ion as a function of detection beam power with various detection methods.</td>
<td>88</td>
</tr>
<tr>
<td>6.12</td>
<td>Histograms of the dark and bright state of the ion.</td>
<td>90</td>
</tr>
<tr>
<td>6.13</td>
<td>Bright pumping, dark pumping, and effective scattering rates as a function of detection intensity.</td>
<td>93</td>
</tr>
<tr>
<td>6.14</td>
<td>The detection error probability of the ion prepared in the dark and bright state as a function of detection time.</td>
<td>95</td>
</tr>
</tbody>
</table>
6.15 Detection error probability as a function of detect time, adjusted for state preparation errors. .................................................. 97
6.16 Detection error probability as a function of average detection time . . 99
7.1 Schematic the scalable trapped ion quantum computer. .................. 104
7.2 Energy level diagrams detailing the generation of a frequency qubit. . 105
List of Abbreviations and Symbols

Symbols

\[ q \quad \text{Trap Stability Parameter} \]
\[ Q \quad \text{Loaded Quality Factor} \]
\[ P_{RF} \quad \text{RF Power} \]
\[ V_{RF} \quad \text{RF Voltage} \]
\[ I \quad \text{Moment of Inertia} \]
\[ D \quad \text{Damping Coefficient} \]
\[ K \quad \text{Torsional Stiffness of a Spring} \]
\[ \omega_r \quad \text{Resonant Angular Frequency} \]
\[ \zeta \quad \text{Damping Ratio} \]
\[ t_f \quad \text{Film Thickness} \]
\[ t_s \quad \text{Substrate Thickness} \]
\[ \sigma \quad \text{Film Stress} \]
\[ E_{si} \quad \text{Young’s Modulus of Silicon} \]
\[ \lambda \quad \text{Wavelength} \]
\[ \varepsilon_{sys} \quad \text{System Efficiency} \]
\[ \varepsilon_{PG} \quad \text{Collection Optics Efficiency} \]
\[ \varepsilon_{FC} \quad \text{Fiber Coupling Efficiency} \]
\[ \varepsilon_{fiber} \quad \text{Fiber Transmission Efficiency} \]
\[ \varepsilon_{det} \quad \text{Detector Efficiency} \]
Γ Linewidth

Δ Detuning

Ω Rabi Frequency

$\Delta_{HFP}$ Hyperfine Splitting of the $^2P_{1/2}$ Energy Level

$\Delta_{HFS}$ Hyperfine Splitting of the $^2S_{1/2}$ Energy Level

$R_o$ Scattering Rate

$\varepsilon$ Efficiency

$R_b$ Bright Pumping Rate

$R_d$ Dark Pumping Rate

$R_{dc}$ Dark Count Rate

$f_{qubit}$ Frequency of the Qubit Hyperfine Transition

$f_{rep}$ Repetition Rate

Abbreviations

ADC Analog to Digital Converter

AFM Atomic Force Microscopy

AOM Acousto-Optic Modulator

CAD Computer Aided Design

CPGA Ceramic Pin Grid Array

CW Continuous Wave

DAC Digital to Analog Converter

DDS Direct Digital Synthesizer

ELU Elementary Logic Unit

EMCCD Electron Multiplying Charge Coupled Device

EOM Electro-Optic Modulator

FPGA Field-Programmable Gate Array
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCL</td>
<td>Hollow Cathode Lamp</td>
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<td>HOA</td>
<td>High Optical Access</td>
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<td>HWP</td>
<td>Half-Wave Plate</td>
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<tr>
<td>ID</td>
<td>Inner Diameter</td>
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<tr>
<td>MEMS</td>
<td>Micro-Electromechanical Systems</td>
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<tr>
<td>NA</td>
<td>Optical Numerical Aperture</td>
</tr>
<tr>
<td>NEG</td>
<td>Non-Evaporable Getter</td>
</tr>
<tr>
<td>NMR</td>
<td>Nuclear Magnetic Resonance</td>
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<tr>
<td>OD</td>
<td>Outer Diameter</td>
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<tr>
<td>PBS</td>
<td>Polarizing Beam Splitter</td>
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<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
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<tr>
<td>PD</td>
<td>Photodiode</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional-Integral-Derivative</td>
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<tr>
<td>PMT</td>
<td>Photo-Multiplier Tube</td>
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<tr>
<td>PSD</td>
<td>Position Sensitive Device</td>
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<tr>
<td>QE</td>
<td>Quantum Efficiency</td>
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<td>QIP</td>
<td>Quantum Information Processing</td>
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<tr>
<td>qubit</td>
<td>Quantum Bit</td>
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<tr>
<td>QWP</td>
<td>Quarter-Wave Plate</td>
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<tr>
<td>RMS</td>
<td>Root Mean Squared</td>
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<tr>
<td>SNSPD</td>
<td>Superconducting Nanowire Single Photon Detectors</td>
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<tr>
<td>SPAM</td>
<td>State Preparation and Measurement</td>
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<tr>
<td>SPI</td>
<td>Serial Peripheral Interface</td>
</tr>
<tr>
<td>SSB</td>
<td>Single Sideband Mixer</td>
</tr>
<tr>
<td>SUMMiT</td>
<td>Sandia Ultra-Planar Multi-Level MEMS Technology</td>
</tr>
<tr>
<td>TSP</td>
<td>Titanium Sublimation Pump</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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<tr>
<td>TTL</td>
<td>Transistor-Transistor Logic</td>
</tr>
<tr>
<td>UHV</td>
<td>Ultra-High Vacuum</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>Yb</td>
<td>Ytterbium</td>
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</tbody>
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Acknowledgements

None of the work presented in this thesis would have been possible without the support of my family, friends, and colleagues. I’ve learned that success isn’t based solely on talent or hard work, it is also dependent on how willing you are to learn from others and accept their support. Throughout my time at Duke, there have been many people to help me along my journey, and I would like to thank some of them here.

First of all, I would like to thank my wife, Megan, for believing in me and supporting me throughout my graduate student career at Duke. She believed enough in me to move halfway across the country to start a new life. When times were tough in the lab, she proved to be a great outlet for me to clear my head and gain perspective on the situation. Megan and our dogs (Tobey and Jess) have been a constant source of happiness as I worked towards my degree, and I can’t imagine doing any of this without them.

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to do my best.

My advisor, Dr. Jungsang Kim, was the main reason why I chose to pursue my doctoral degree at Duke. From our first meeting, he inspired me to believe in the viability of an ion trap quantum computer. At the time, I did not have any experience with quantum mechanics or optics, and he patiently taught me valuable skills as both an advisor and a professor. Having the opportunity to work in a lab dedicated to optics and quantum mechanics has been an experience that will stay with me forever. His perspective on the direction the field is progressing and on research in general is something that I hope to learn someday.

While working in the MIST lab, I have been fortunate to work with some amazing people. My first project was to work with a senior graduate student, Dr. Caleb Knoernschild, on tilting MEMS mirrors. He was kind enough to teach me the basics of graduate research and his work ethic stuck with me throughout my time at Duke. I also worked extensively with Dr. Emily Mount, who taught me the basics of ion trapping and how to enjoy life in the lab. Emily’s ingenuity and creativity helped me think outside the box and gave me a different perspective on our experiments. Dr. Rachel Noek, Dr. Hui Son, Dr. Kyle McKay, Ryan Clark, Andre van Rynbach, and Daniel Gaultney have all provided support and help throughout my time in the MIST group as well as making coming to work a fun and enjoyable endeavor. Newer students Clinton Cahall, Dan Renaud, Tripp Spivey, Chao Fang, and Yuhi Aikyo have had a refreshing effect on the lab environment and reminded me why I chose to start this process in the first place. Postdocs Dr. So Young Baek, Dr. Geert Vrijsen, and Dr. Kai Hudek were also instrumental in my development as a scientist. I’d also like to thank Dr. Peter Maunz as both a research scientist with our group and as a collaborator at Sandia National Labs for all of his patient help and time committed to making our work go as smoothly as possible.

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research advisor at the University of Arkansas, Dr. Magda El-Shenawee. She taught me what it takes to do scientific research and gave me the chance to succeed and confidently present my work to others. She encouraged me to pursue my ambitions and to go on to a graduate degree.

Finally I’d like to thank the Office of the Director of National Intelligence (ODNI), and Intelligence Advanced Research Projects Activity (IARPA), through the Army Research Office ARO. I am thankful for the opportunity to work on the MUSIQC program with all of the other great people associated with this program. I’d also like to thank the National Science Foundation and their financial support through the beginning of my graduate student career.
Even with the ever increasing computational power of integrated circuit technology, there are classes of problems that cannot be solved with classical computers and classical computational methods. By the early 1980’s Richard Feynman considered a shift in computing by basing a computational model on quantum mechanics (Feynman, 1984). He argued that any arbitrary system could be simulated by a universal quantum computer. Schemes have been developed to take advantage of particular properties of quantum mechanics in order to solve these problems, most notably the Shor algorithm for factoring (Shor, 1997) and the Grover search algorithm (Grover, 1996). However, the physical realization of a quantum computer suffers from the ability to effectively scale the system to the number of qubits required by these algorithms. There is theoretical work to be done to design algorithms that would require fewer qubits; however, in this thesis I will outline one proposed solution to the scalability problem from the hardware engineering perspective.

Quantum communication (Bennet and Brassard, 1984)
1.1 Quantum Computing Requirements

In 2005, David DiVincenzo proposed five critical requirements for the implementation of quantum computers (Divincenzo, 2000). The first requirement is a scalable physical system with well-characterized quantum bits (qubit). A qubit is a quantum two-level system that is the analog of the digital bit (0 and 1). The second requirement outlined by DiVincenzo is the ability to initialize the state of the qubits to a simple known initial state such as $|000...\rangle$. The need for long decoherence times is the third critical requirement for the physical implementation of quantum computers. The decoherence time of the qubit needs to be longer than the gate operations or the risk of losing information during the computation is high. The fourth and fifth requirements for a physical quantum computer are the need for a universal set of quantum gates and a qubit specific measurement capability. A universal set of gates allows for any quantum algorithm, typically a series of unitary transformations, to be performed by those sets of gates. In order for a quantum computer to be useful, the results of the computation must be read.

1.2 Quantum versus Classical Computing

The classical bit in a computer can only possess one of two values, either 0 or 1, typically stored as a magnetic state on a hard disk drive or the state of NAND gates in flash memory. One of the appealing advantages of quantum computing comes from its inherent quantum properties to store and process information in a superposition of states. For example, if the basis states of the quantum computer are $|0\rangle$ and $|1\rangle$, then the state of the system can be expressed as a superposition of the two basis states,

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle$$  \hspace{1cm} (1.1)
where $|\alpha|^2 + |\beta|^2 = 1$ and $\alpha$ and $\beta$ are complex numbers. As the number of bits increases, the quantum computer can process all possible bit combinations simultaneously. For example, a two qubit system can be expressed as

$$|\psi\rangle_{12} = \alpha_1 \alpha_2 |00\rangle + \beta_1 \alpha_2 |10\rangle + \alpha_1 \beta_2 |01\rangle + \beta_1 \beta_2 |11\rangle$$  \hspace{1cm} (1.2)

where the subscript denotes the qubit with which the probability amplitude designates. A quantum computer with $n$ qubits can then in principle be in an arbitrary superposition of up to $2^n$ states simultaneously. The phenomena of quantum entanglement can be used for facilitating multi-qubit gates as well as instantaneous long-range communication between qubits. An example of an entangled state is $|\psi\rangle = \alpha_1 \alpha_2 |00\rangle + \beta_1 \beta_2 |11\rangle$. Unlike the state in Equation 1.2, this state cannot be factored into two separate wavefunctions.

$$|\psi\rangle_{12} = |\psi\rangle_1 \otimes |\psi\rangle_2$$  \hspace{1cm} (1.3)

1.3 Choice of Physical Qubits

There are several candidates for the physical implementation of a quantum computer. These include nuclear magnetic resonance (NMR), trapped neutral atoms, solid state devices, superconducting devices, and trapped ions. NMR, neutral atoms, and trapped ions all rely on various pairs of energy levels as their qubits. Solid state devices have several options for qubits, which include the spin states of quantum dots, the spin states of donor impurities, and the orbital or charge states of the quantum dots. The qubit for the superconducting quantum computer can be represented by either the charge (Cooper pair) or by the flux.

There are well-defined protocols for trapping ions that lead directly to its use for quantum computation. For use in quantum computation, the physical qubits for local operations are the trapped ions, with the two states of the qubit defined as two
of the internal energy levels of the ion (Cirac and Zoller, 1995). Cold trapped ions as a physical implementation of a quantum computer are appealing because they allow for the implementation of n-bit quantum gates between any set of ions in the system (Cirac and Zoller, 1995; Haffner et al., 2008). Also, a universal set of logic gates has been demonstrated with trapped ions (Blatt and Wineland, 2008; Benhelm et al., 2008; Monz et al., 2009). The ions exhibit a long decoherence time, and the final readout of the computation can be done with close to 100% efficiency (Noek et al., 2013).

1.4 Scaling the Ion Trap Quantum Computer

One of the largest challenges with choosing trapped ions as a physical qubit is the ability to scale the system to the large number of qubits required to beat its classical counterpart. The proposed solution that we have chosen to pursue is to build a modular system that can be scaled to an arbitrary number of qubits (Kim and Monroe, 2013). The core of the modular system is based on ion trap quantum registers where local qubit operations are performed using Coulomb-based gates by applying an external field to the ions (laser beams). A superposition of the qubit state can be translated to a superposition of the position of the qubit, so when this is performed on a chain of ions, gates can be executed between any arbitrary ions in the chain, not just nearest-neighbors. The qubits used for these interactions are termed the "computational" qubits.

Long range interaction between qubits, or interaction between two qubits in separate traps, can be achieved through the use of photons scattered by a single ion (Maunz et al., 2007; Hucul et al., 2015). This “communication” qubit emits a photon who has two distinguishable states (either frequency or polarization) which is entangled with the ion qubit. When two photons from two separate trapped ion quantum registers are interfered on a beamsplitter, the entanglement between the
Surface Ion Trap (171Yb+ Ions) 
Trapped Ion Quantum Register 
Optical Fiber 
High NA Lens 
Addressing Beams

**Figure 1.1**: Schematic of an ion trap based quantum register. The trapped ions can be split into a computational region and a communication region. Lasers can address individual ions in the computational region. Local qubit interactions are performed by exciting the modes of motion of the ions in a chain. Photons scattered by the communication ion are coupled into an optical fiber via a high numerical aperture (NA) lens.

Two ion qubits is heralded by the coincidence detection of photons on the output detectors. Due to the resonant scattering of the communication qubit, computational and communication qubits can be spatially separated as needed. Figure 1.1 shows a schematic of a single trapped ion quantum register.

This thesis will focus on the technologies needed to realize a single trapped ion quantum register with the goal of ease of scalability. This will include the hardware necessary for the trapping chains of ions, a scalable system for addressing of single computational qubits in a chain, and hardware and scheme for coupling the photons emitted by a communication qubit into an optical fiber. The results of this thesis should help provide a clear path towards a scalable and modular solution for trapped
1.5 Dissertation Overview

The thesis begins with a brief introduction of quantum computing in Chapter 1. Chapter 2 discusses the $^{171}\text{Yb}^+$ qubit and the fundamentals of ion trapping. Chapter 3 outlines the hardware that has been developed in order to realize a scalable quantum computer. This includes the vacuum system and electronics with which we trap the qubits, a readout circuit and strategy for detecting individual qubits in a chain, and the supporting laser hardware and locking schemes. Chapter 4 discusses the technology with which we address individual qubits. The microelectromechanical systems (MEMS) mirror design and fabrication are detailed as well as the development of a laser beam shutter system based on the MEMS mirrors. Chapter 5 focuses on the experiments verifying the individual addressing capabilities of the MEMS mirror beam steering system. We investigate the intensity crosstalk on neighboring sites, the switching speed, and performing sequential single qubit gates. Chapter 6 highlights the efforts to fiber couple scattered photons from the trapped ion into a fiber, as well as state detection using superconducting nanowire single photon detectors (SNSPD). Chapter 7, reviews all of the results and discusses the future experiments and the future of scalable quantum computing.

1.6 Summary of My Contribution

For a project of this scale, there are multiple people that have worked on various aspects of the project. This section is meant to highlight my specific contributions to the results and content of this document.

Chapter 2 is mainly a summary of theory and experimental approaches that have been developed over the past few decades. While the structure of the code to simulate
the electric field potential for the surface ion trap was developed mainly by Dr. Peter Maunz, I modified the code to suit the needs of this particular experiment.

Chapter 3 shows the vacuum chamber design, on which I collaborated with others in the group (Multifunctional Integrated Systems Technology (MIST)). I made the final computer aided design (CAD) model of the chamber and performed the assembly and baking of the chamber. The ultra-high vacuum (UHV) printed circuit board (PCB) design was initially started by Seongphill Moon, but the final revisions and major design changes were performed by myself with inputs from others. The helical resonator design was the result of previous models by current and former graduate students. However, the newest design was the result of the work performed by myself and Dr. Kai Hudek. I also implemented the resonator into the ion trapping system. The digital to analog converter system was designed and fabricated by Daniel Gaultney, but I integrated the system into my particular experiment, which included the testing and construction of the housing. The segmented photo-multiplier tube (PMT) readout circuit was started by Dr. Peter Maunz and visiting undergraduate Wang Ye with a circuit testing only a single channel. I expanded on their ideas to design and construct the 32-channel circuit board as well as the water cooling system and housing and the digital interface. The characterization of the final circuit was also my responsibility. The laser system setup was first built by former graduate students and postdocs, but I performed maintenance throughout my time in the group. In particular, the laser locking setup was designed and built by Dr. Geert Vrijsen, Dr. Kai Hudek, and Lou Isabella.

The MEMS theory and design work in Chapter 4 was the result of the efforts by Dr. Caleb Knoernschild, a former graduate student in the group. Sandia National Laboratories fabricated the MEMS devices and I performed all of the post-processing work, such as the metallization and packaging. I also performed the testing and characterization of the MEMS mirrors used in these experiments. The MEMS shutter
design and testing was performed in collaboration with Dr. Emily Mount.

The work on the individual addressing experiments in Chapter 5 was mostly performed by myself. However, Dr. Emily Mount constructed this particular vacuum chamber and trapping setup, and Dr. So Young Baek performed the initial alignment of the pulsed laser and frequency doubling stage. The intensity crosstalk characterization, the MEMS speed tests, and the sequential qubit gates were all my own work.

The initial design and simulation of the high numerical aperture (NA) lens in Chapter 6 was performed by Daniel Gaultney. The optomechanical design and implementation was my work. The alignment of the high NA lens to the ion and the fiber coupling was also my own work. The cryostat system was designed and built by Clinton Cahall, and the SNSPDs were provided by the Jet Propulsion Laboratory (JPL). The state detection theory was the result of work done by Dr. Rachel Noek and Dr. Geert Vrijsen; however, I performed the state detection experiments and collaborated with Dr. Vrijsen and Clinton Cahall on the state detection error probability analysis.
The first decision to be made in implementing a scalable quantum computer is the choice of a physical qubit. There are many different realizations of a qubit including superconducting circuits, quantum dots, trapped neutral atoms, and nitrogen vacancies. However, cold trapped ions as a physical implementation of a qubit are particularly appealing because they allow for the implementation of n-bit quantum gates between any set of ions in the system (Cirac and Zoller, 1995; Haffner et al., 2008; Wineland, 2009), they exhibit a long decoherence time (Langer et al., 2005), and the final readout of the computation can be done with nearly 100% efficiency (Noek et al., 2013). The states of the ion qubit can be defined as two of the internal energy states of the ion. The physical hardware and experimental protocols needed to trap atomic ions need to be carefully designed in order to have a scalable path for implementing many qubits.
2.1 Ion Trapping

An ionized atom or atoms can be trapped with a combination of radio frequency (RF) and direct current (DC) fields, which forms a linear Paul trap. Electrodes close to the ion trapping location provide the RF and DC fields. An example of the electrode geometry can be seen in Figure 2.1(a); this is referred to as a three dimensional 4-rod trap. RF fields are applied to the diagonal rods for radial confinement ($x - z$ plane) while DC fields are applied to the end rods for confinement in the axial ($y$) direction. Although the 4-rod trap has been proven to have excellent trapping characteristics, scalability remains a limitation for realizing a useful quantum computer. Each of these traps needs to be hand built and exact reproducibility is hard to achieve. In order to solve these issues, the linear Paul trap can be projected onto a surface, creating a two dimensional trap structure as shown in Figure 2.1 (Seidelin et al., 2006). Like the three dimensional trap, the RF electrodes confine the ions in the radial direction on the surface trap. Segmented DC electrodes along the RF rails confine the ions in the axial direction. The null of the static electric field from the DC electrodes overlaps the minimum of the RF pseudopotential to create a stable trapping region. The pondermotive pseudopotential is defined as:

$$\psi_p = \frac{v_{rf}^2 q^2}{4 m_{ion} \omega_{rf}^2} E^2, \quad (2.1)$$
Figure 2.2: Electric field profile along the radial direction for the combined RF and DC electric fields. The trap axis is rotated to allow efficient Doppler cooling in all directions.

where $v_{rf}$ is the max voltage on the RF electrodes, $q_e$ is the charge of an electron, $m_{ion}$ is the mass of the ion, $\omega_t$ is the driving frequency of the RF field, and $E$ is the electric field with 1 V placed on the RF electrodes. Any misalignment of the DC and RF nulls results in ion micromotion. An example of the combined RF and DC electric field in the radial direction of the trap is shown in Figure 2.2.

2.1.1 Sandia Thunderbird Trap

The first surface trap used for these experiments was fabricated by Sandia National Laboratories using standard photolithographic silicon processes (Figure 2.3(a)) (Allcock et al., 2011; Mount et al., 2013). This trap features two central DC control electrodes, two RF electrodes, and 40 outer DC control electrodes. A 100 $\mu$m slot is etched in the middle of the chip between the two central electrodes, which allows for loading from the back of the trap and for extra optical access from the top or bottom of the chip. The insulating oxide layer between the two metal layers is controllably
etched back to reduce the amount of insulating material visible to the trapping region. The Yb ion is trapped \( \sim 80 \mu m \) above the surface of the trap. Capacitors are mounted to the ceramic pin grid array (CPGA) to serve as a low pass filter for the DC control electrodes. The entire trap is coated in a 500 Å layer of gold to help reduce ion heating from contaminants on the surface of the trap. The trap used for these experiments featured radial trap frequencies of \( \sim 1.5 MHz \) and \( \sim 2.1 MHz \) (Mount et al., 2013).

2.1.2 Sandia High Optical Access (HOA) Trap

Based on experiences with previous traps, including the Thunderbird trap, Sandia National Labs designed and fabricated a new surface trap tailored for high optical access (HOA) and higher radial trap frequencies (Figure 2.3(b)) (Maunz, 2016). The HOA trap features a slot in the center of the trapping region for optical access from the front and the back of the chip, but it also features a 1.2 mm wide isthmus to
allow for tightly focused beams to be brought in from the sides of the trap. Beams traveling parallel to the trap surface have a maximum numerical aperture of 0.11 and beams traveling through the slot have an available 0.25 NA (Maunz, 2016). The trap features two central DC control electrodes, two RF electrodes, and 96 outer DC electrodes. The trap is mounted on an interposer chip which has trench capacitors for each of the 96 control electrodes. The trap was fabricated with four metal layers, one for the electrodes, one for a ground plane, and two for routing wires from the electrodes to the bond pads. The HOA is also coated with a final 500 Å layer of gold. Trap frequencies have been measured to be $\sim 2.2$ MHz and $\sim 3.1$ MHz with a trap depth of $\sim 300$ meV and trap stability parameter, $q = 0.18$.

2.2 The $^{171}$Yb$^+$ Qubit

The ytterbium ion, $^{171}$Yb$^+$, has been identified as a candidate for trapped ion quantum computing due to its convenient energy level transitions, large fine structure splitting, and spin 1/2 nucleus (Olmschenk et al., 2007). For this work, the
$^{2}\text{S}_{1/2}|F=0\rangle$ and $^{2}\text{S}_{1/2}|F=1\rangle$ hyperfine ground states of the $^{171}\text{Yb}^+$ ion are used as qubit states, labeled $|0\rangle$ and $|1\rangle$ respectively. These two states are first order magnetic field insensitive, which decreases the sensitivity of the qubit to stray electric fields and leads to long coherence times. In order to load the $^{171}\text{Yb}^+$ qubit, a neutral Yb atom is ionized by first exciting it from the $^1\text{S}_0$ to the $^1\text{P}_1$ state with 398.91 nm light. Another beam that is $\leq$ 394 nm provides enough energy to free an electron to the continuum. Once ionized, Doppler cooling the ion is possible with the use of a continuous wave (CW) laser that is red-detuned from the $^2\text{S}_{1/2}|F=1\rangle$ to $^2\text{P}_{1/2}|F=0\rangle$ transition. The atom can transition to the $^2\text{D}_{3/2}|F=1\rangle$ with a small probability, but can be returned to the cooling cycling transition by applying a laser at 935 nm. If cooling beyond the Doppler limit is needed, Raman beams can be used to provide motional cooling of the qubit (Mount et al., 2013). A 3.3 Gauss magnetic field created by coils located outside of the vacuum chamber is applied to lift the degeneracy of the $^2\text{S}_{1/2}|F=1\rangle$ state which destabilizes coherent dark states (Mahdifar et al., 2008). With cooling, ion lifetimes in our lab have been observed for as long as 10 hours while performing experiments, and for as long as 20 minutes without Doppler cooling (Mount et al., 2013).

### 2.2.1 State Initialization

To initialize the state of the qubit, 2.1 GHz sidebands are added by an electro-optic modulator (EOM) onto the 369.5 nm cooling beam (Figure 2.5(a)). By adding the sidebands, the 369.5 nm beam is now resonant with the $^2\text{S}_{1/2}|F=1\rangle$ to $^2\text{P}_{1/2}|F=1\rangle$ transition. From the $^2\text{P}_{1/2}|F=1\rangle$ manifold, the ion has a 1/3 chance of decaying to the $|0\rangle$ state due to selection rules. Once the ion is in the $|0\rangle$ state, the beam is no longer resonant with any allowed transitions so the ion remains in the $|0\rangle$ state. The state preparation to the $|0\rangle$ state can be performed with 99.915\% fidelity (Olmschenk et al., 2007; Noek et al., 2013).
Figure 2.5: (a) Energy level diagram showing the energy transitions used for state preparation of the qubit to the $|0\rangle$ state. 2.1 GHz sidebands are added to the main cooling laser. The population in the $^2S_{1/2}|F = 1\rangle$ state is resonantly excited to the $^2P_{1/2}|F = 1\rangle$ state and has a 1/3 chance of decaying to the $^2S_{1/2}|F = 0\rangle$ ($|0\rangle$) state. Any population in the $|0\rangle$ state is not resonant with any allowed transition. (b) Energy level diagram depicting state detection. Light resonant with the $^2S_{1/2}|F = 1\rangle$ and $^2P_{1/2}|F = 0\rangle$ states is directed onto the ion. If the ion is in the $|1\rangle$ state, it is resonantly excited to the $^2P_{1/2}|F = 0\rangle$ state and will spontaneously emit a photon as it decays back to the $^2S_{1/2}|F = 1\rangle$ state. However, if the ion is in the $|0\rangle$ state, it will not scatter any photons.

2.2.2 State Detection

The ability to detect the state of the qubit with high fidelity is crucial in realizing quantum computation. For this thesis work, ion florescence is used to determine the state of the qubit. The 369.5 nm light is tuned to be close to resonance to the $^2S_{1/2}|F = 1\rangle$ to $^2P_{1/2}|F = 0\rangle$ transition (Figure 2.5(b)). If the qubit is in the $|1\rangle$ state, the ion will scatter a photon and decay back to the $^2S_{1/2}|F = 1\rangle$ manifold (and stay in this cycling transition). If the qubit is prepared in the $|0\rangle$ state, there is no allowed transition and the ion will nominally not scatter any photons. The main source of error when detecting the $|1\rangle$ state can be explained by off-resonant excitation to the $^2P_{1/2}|F = 1\rangle$ state (Noek et al., 2013). The ion can then decay to the
$|0\rangle$ state and will no long scatter photons and is recovered to the cycling transition with low probability. The errors in detecting the $|0\rangle$ state are attributed to detector dark counts, background photons measured by the detector, and the probability of pumping to the $|1\rangle$ state and scattering photons.
In order to transition from a system with one or two qubits to a system capable of managing the large number of qubits necessary for even the most basic quantum computation, the supporting hardware and infrastructure need to be carefully planned.

3.1 Ultra-High Vacuum System

The ion trap is operated in an ultra-high vacuum (UHV) environment to reduce the number of collisions with background atoms. These collisions can cause heating of the ion or cause the ion to eject from the trap. For the two vacuum chambers used for the following experiments, the vacuum is maintained at pressures below $1.9 \times 10^{-11}$ Torr by three pumps: an ion pump, a titanium sublimation pump (TSP), and non-evaporable getter (NEG) (Fig. 3.1). Small strips of NEG are placed as close to the ion trapping location as possible to reduce the local pressure. An ion gauge is used to measure the pressure.
3.1 Vacuum Chamber Design

The first vacuum chamber assembled and used consisted of a 4.5” diameter spherical octagon which housed the ion trap. The front of the octagon was fitted with a re-entrant viewport (UKAEA) which allows for a larger percentage of the photons scattered from the ion to be collected. The trap itself was mounted on a custom socket for a 98-pin ceramic pin grid array (CPGA) package inside the spherical octagon in order to apply the DC and RF fields.

From experiences using the first vacuum chamber, a new configuration was designed to maximize the experimental potential and scalability. The 4.5” spherical octagon was replaced with a 6” spherical octagon to accommodate new designs for the electrical connections. A similar re-entrant viewport is used for high optical access from the front. The back flange of the chamber was designed specifically for...
optical access with a 1.33" viewport as well as ease of electrical connections with four sub-D feedthroughs and two high power feedthroughs. Six of the eight ports on the side of the spherical octagon are fitted with antireflection coated fused silica viewports for optical access to the trapping region, while the other two ports are used for pumping.

To provide the ytterbium for trapping, stainless steel tubes (OD = 0.042”, ID = 0.035”, wall = 0.004”) partially filled with neutral ytterbium are mounted beneath the PCB. Tantalum foil is welded to the crimped base of the tube and connected to a high power feedthrough on the back flange. The tubes are then resistively heated with ~1 A of current, which produces an atomic flux to exit from the tubes towards the trapping region. Two separate ovens are used to produce $^{174}\text{Yb}$ and $^{171}\text{Yb}$. The isotope that is loaded into the trap is determined by the frequency of the cooling and photoionization lasers. Isotopes that are unwanted are ejected from the shallow trap due to a lack of cooling as well as being inefficiently photoionized. The photoionization frequency is calibrated by performing spectroscopy with the 399 nm laser on a high flux of atoms. The absorption lines of all of the common isotopes can be resolved by by monitoring photon counts on an electron multiplying charge coupled device (EMCCD) camera. This spectroscopy calibrates the frequency of the 399 laser as well as revealing the orientation of the atomic flux.

3.1.2 UHV PCB Design

With the previous vacuum chamber, the custom 98-pin socket is connected to the back flange by ribbon cables insulated by polyimide, which can be delicate and difficult to assemble (Figure 3.2(a)). To improve the reliability of the electrical connections to the trap CPGA, a vacuum compatible printed circuit board (PCB) was designed to route the DC voltages from the four sub-D connectors to the CPGA. The PCB is made of Rogers 6002 laminate with immersion gold traces and ground
Figure 3.2: (a) The previous chamber required custom cables to be hand built and soldered. Two 50 pin micro-D cables delivered the 42 DC control voltages to the trap. The resulting cables were fragile and prone to failure. (b) The 96 DC voltages needed for the HOA trap are delivered through four subminiature-D feedthroughs on the custom 6” back flange. The PCB routes the voltages from the subminiature-D connectors to the ion trap, eliminating the need for hand built cables or connections.
plane (fabricated by Cirexx International, Inc), which exhibits extremely low out-gassing rates and is suitable for UHV environments (see Figure 3.2(b)). To ensure vacuum compatibility, no silkscreen was applied to the PCB. The PCB is grounded through standoffs that attach to the back flange. The ground plane of the PCB is explicitly connected to the trap and RF ground, ensuring there are no ground loops and minimizing any electrical pickup. The ion trap can now be removed and replaced by simply removing the back flange and keeping the rest of the chamber intact.

Press-fit pins and receptacles are used for connections to the sub-D connectors and CPGA, respectively. For extra mechanical stability, the pins and receptacles are soldered into place using a lead-free tin/silver/copper solder. After soldering the connections, any extra flux is cleaned by placing the PCB in an ultrasonic bath with Chemtronics ES132 solution (10:1 de-ionized water to cleaner) for approximately one hour. This is followed by ultrasonic baths of first acetone and then isopropanol. Connected pins and sockets are tested for open connections, and all neighboring pins and sockets are tested for shorts.

3.1.3 Chamber Assembly and Baking

Before assembly, any machined part is first cleaned with acetone and isopropanol in an ultra-sonic bath. All vacuum parts are then baked for approximately one day at 200°C to ensure that any residual water has evaporated, and to form a thin oxide layer on the surface of the metal parts. Assembly of the vacuum chamber is performed in a clean room. Any part that is used inside the vacuum chamber is dipped in Trichloroethylene (TCE) and blown dry with clean nitrogen. During assembly, care is taken to keep all parts free of contamination, including pre cleaning any tools necessary and switching gloves whenever a non-cleaned part is handled. Once the chamber is assembled, the chamber is placed inside a large oven and connected to a turbomolecular pump. Using this pump, the chamber is checked for leaks with
Figure 3.3: (a) Layout of the top side of the UHV PCB. The four subminiature-D connections rout the DC control voltages from the vacuum feedthrough to the ion trap. (b) Layout of the backside of the UHV PCB.

Figure 3.4: (a) Picture of the assembled UHV PCB with the Sandia HOA ion trap without the ground shield (Photo credit: Emily Mount). (b) Fully assembled vacuum chamber without the titanium sublimation pump.
helium. To begin the bake, the oven temperature is raised by 1 °C/min and held constant at 200 °C. Once the chamber pressure reaches $1 \times 10^{-7}$, the TSP filaments and ion gauge are degassed, and the NEG pump is activated by ramping up the current to the pump over the course of several hours. The ion pump is turned on, the all-metal valve connecting the pump to the chamber is closed, and when an equilibrium pressure is reached the oven is ramped back down to room temperature. Once at room temperature the TSP is activated, resulting in a final decrease in pressure to $\mathcal{O}(10^{-11})$ Torr.

### 3.2 Helical Resonator Design

To provide the RF power to the ion trap, a direct digital synthesizer (DDS, Analog Devices 9912) is first used to generate the RF signal. The frequency and amplitude of the signal is digitally controlled. The output of the DDS is connected to an amplifier with a gain of 40 dB, passed through a coupler and delivered to a helical resonator (Macalpine and Schildknecht, 1959). The helical resonator provides filtering and amplification of the RF signal, as well as matching the output impedance of the DDS (50 Ω) to the ion trap (~15 pF). The output of the helical resonator is connected to one of the high-voltage feedthroughs on the custom 6” back flange of the vacuum chamber (made by Accu-Glass Products, Inc.). This feedthrough is connected to the UHV PCB where the signal is routed to the appropriate pin of the ion trap CPGA. The total RF voltage delivered to the trap is approximated by the relation

$$V_{RF} = \epsilon \sqrt{P_{RF}Q} \quad (3.1)$$

where $\epsilon$ is the geometric factor and is fixed to be 30, $P_{RF}$ is the RF power, and $Q$ is the loaded quality factor of the helical resonator. For the ion traps used in this work, the maximum RF voltage that can be safely applied due to the risk of arcing is 300 V. The back reflection from the resonator is monitored using a spectrum analyzer.
Figure 3.5: CAD model of the redesigned helical resonator used for generating the RF voltage. The main body is machined out of copper. The coupling coil is wound around the cylindrical Teflon puck at the top of the resonator and is translated along the axis of the main coil by a fine-pitched threaded rod.

and the coupling is tuned by minimizing the reflected signal. The resonant frequency of the helical resonator, and therefore the RF frequency of the trap, is determined by maximizing the axial trap frequencies while maintaining an adequate trap stability parameter \((q)\).

The stability of the helical resonator is important when performing logic operations on the ion qubit. The original design of the helical resonator consisted of a copper tube with a thick copper wire coil. One end of the copper wire is soldered directly to the inner wall of the tube to provide a ground connection and the other end is connected to the vacuum feedthrough. A coil attached to the lid of the tube is roughly adjusted in and out of the main coil to provide maximum coupling. The mechanical stability of the two coils and the adjustability of the coupling coil have been the limiting factors in providing a stable RF signal to the ion trap.

Figure 3.5 shows the cross section of an improved design of the helical resonator.
Instead of a copper tube, the main body of the resonator is machined out of a rectangular copper block. This has the advantage of easier and more stable mounting and grounding options. Holes are drilled along the main shaft to provide the option of inserting cartridge heaters and thermistors for active temperature stabilization. The coupling coil is wrapped around a Teflon cylinder, which provides additional mechanical stability. A bushing is used to attach the Teflon cylinder to an adjustment screw that is threaded into the top of the body. When the adjustment screw is turned, the bushing decouples the rotation from the Teflon cylinder in such a way that the coil will travel up and down but will not rotate with the screw. Two guide posts are added to ensure linear travel in only one dimension (axially with respect to the main coil). For a design of a 45 MHz resonator for a trap capacitance of 21 nF, the coil diameter is calculated to be 1.37” with a length of 2”. The pitch of the coil is 0.354 inch⁻¹ and is made by machining a Teflon comb with the calculated pitch. The teeth of the comb keep the coil pitch constant and uniform.

3.3 DAC System

The DC voltages for the trap are supplied by a custom PCB designed by Daniel Gaultney that has 25 DAC (DAC8734) chips, each with four independently controlled channels (Mount et al., 2015b). The DAC resolution is 16 bits with a maximum output of ±10 V and a maximum update rate of 430 kHz. A Python GUI sends the voltage data to an onboard FPGA (Opal Kelly XEM6010), which can then change the DAC voltages in real time via an serial peripheral interface (SPI) bus. The voltages are then passed through a low-pass RC filter with a 3 dB cutoff frequency of 338 kHz and to the four subminiature-D cables. At the back flange of the chamber, the subminiature-D cables are connected to a commercial pi low-pass filter (API Technologies 56-705-005) with a cutoff frequency of 800 kHz. A final set of filters are included on the ion trap chip as trench capacitors, as previously mentioned.
3.4 High NA Lens

To improve light collection from the ion and the detection fidelity, a 0.6 NA lens was designed and fabricated by Photon Gear, Inc (Noek et al., 2013). The six lens system was designed to fiber couple the light emitted by the ion into a 0.07 NA single mode fiber to establish a photonic link between separate ELUs. The lens has a shallow depth of field (+5.25 µm, -4.08 µm) and a small field of view (±225 µm). More information regarding the alignment procedure and optical performance of the lens discussed in Chapter 6.

3.5 Segmented PMT Readout Circuit

For state detection of a single ion, a single photomultiplier tube (PMT) is used. For the state detection of more than one ion, distinguishing between the number of bright ions can be done by comparing the histograms of the collected photons. However, a single PMT will not be able to distinguish specific single photons from specific ions. A 32-channel segmented PMT (Hamamatsu H7260) is used to detect the state of individual ions in a chain. The H7260 has 32 separate ultra bialkali photocathodes with effective detection areas of 0.8mm x 7mm. This PMT is ideal for fast state detection with a typical rise time of 0.6 ns. This PMT array features a low dark current of 0.2 nA per channel and a quantum efficiency of 32% at 370 nm.

Photons first pass through the antireflection coated front window of the module and strike the photocathode. The photon excites electrons in the photocathode and photoelectrons are emitted into the vacuum. The photoelectrons are then accelerated and focused onto the first dynode where they are multiplied by secondary emission. This multiplication process continues through multiple dynodes until an anode collects all of the resulting electrons and outputs a current pulse. A custom readout circuit was designed to convert this current pulse to a transistor-transistor
Figure 3.6: Circuit diagram for one channel of the readout circuit. Two amplifiers, UPC3215 and AD8009, are used in conjunction with a comparator, LT1715, to produce a TTL signal from the current pulse generated by the PMT. $V_{TH}$ is set to discriminate the PMT signal from the electronic noise. High pass filters are placed between each amplifier stage and a low pass filter is added to the $V_{TH}$ input to help reduce noise.

Ideally, the readout circuit needs to amplify and convert the current pulse from the PMT without adding any significant noise to the signal, while having a response time that is faster than the length of the current pulse. The first stage of the circuit is a transimpedance amplifier, which converts the current pulse to a voltage pulse. The voltage pulse is then amplified in order to have a large enough dynamic range to set a threshold voltage for a comparator. The comparator produces a TTL signal by comparing the input voltage pulse to a set threshold voltage. The pulses from the PMT are not uniform in height, so it is imperative to set the threshold voltage as low as possible in order to accurately measure the number of incident photons. The variance of the pulse heights is due mainly to the fact that the secondary emission of the dynodes is not uniform. Other factors include non-uniformity in the multiplication factor of each dynode in the series, and electrons deviating from optimum trajectories in the PMT. By measuring the differential counts as a function of threshold voltage, we can properly set the threshold voltage above the electronic noise floor.
and capture as many of the counts as possible (Figure 3.7). Proper shielding and grounding is critical to eliminating as much noise on the circuit as possible. With the added shielding between the field-programmable gate array (FPGA) and the readout circuit, the noise measured is reduced to the inherent thermal noise of the circuit (see Figure 3.8). An aluminum housing was machined to isolate the circuits from any external noise sources. The PMT module is enclosed in an aluminum housing with water cooling in order to reduce the number of dark counts due to thermal effects.

3.6 Laser Systems and Stabilization

3.6.1 Laser Configurations

For the trapping of $^{171}$Yb$^+$ ions, we require four separate laser frequencies: detuned 369.5 nm, on-resonance 369.5 nm, 935 nm, and 399 nm. As discussed in the previous chapter, the detuned 369.5 nm light is used for Doppler cooling the ions and the on-resonance 369.5 nm light is used for state detection. The 935 nm light is required to
Figure 3.8: The noise spectrum of the PMT readout circuit was measured to ensure proper shielding was implemented. The peak ~ 100 MHz corresponds to the clock of the FPGA which reads the digital counts.

pump the ion out of the $^2D_{3/2}$ level. The ion can decay to the $^2D_{3/2}|F = 1\rangle$ level from the $^2P_{1/2}|F = 0\rangle$ level with a 0.5% probability. The ion is then optically pumped to the $^3[3/2]_{1/2}$ level by the 935 nm light, and can decay back to the $^2S_{1/2}|F = 1\rangle$ energy level to start the cooling cycle again. The 399 nm light is used in conjunction with the cooling beam to photoionize the neutral ytterbium flux while loading. Each of these lasers have different requirements for their stability and power.

The 369.5 nm light for both cooling and detection is produced by an interference based external cavity diode laser (Isabella, 2015). This design results in a compact laser housing that is stable against environmental fluctuations. The frequency tunability of the laser is dependent on the adjustment of the interference filter angle with respect to the beam. The external cavity that provides feedback to the laser diode is formed by a partially reflecting mirror. Two lenses in a cat-eye configuration images the output beam from the diode onto the partially reflecting mirror (Isabella, 2015). This design desensitizes the angular alignment of the diode with respect to the cav-
ity mirror. Large frequency tuning is done by changing the angle of the interference filter, and fine frequency tuning is accomplished by changing the length of the cavity. A piezo-electric actuator changes the position of the cavity mirror along the optical access. The transmitted beam through the mirror is then collimated and delivered to the experimental setup. The laser housing is constantly purged with pure nitrogen and a thermoelectric cooler is used for active temperature stabilization.

The other lasers are all constructed with a grating based external cavity. A diffraction grating is used as one side of the optical cavity as well as a frequency selective device. The light from the diode is directed onto the diffraction grating, where the first order beam is reflected back to the diode to form the optical cavity. The zeroth order beam is used for the experiments. The coarse frequency tuning is accomplished by manually rotating the angle of the diode with respect to the diffraction grating and fine tuning is performed by a piezo-electric actuator that changes the angle of the diffraction grating.

3.6.2 Laser Frequency Locking

Precise frequency control of the lasers is critical for efficient Doppler cooling and state detection of the ion. We implement a locking scheme based on polarization spectroscopy of ytterbium ions in a discharge using a hollow cathode lamp (HCL) (Lee et al., 2014; Streed et al., 2008). A schematic of the optical design can be seen in Figure 3.9. The linearly polarized fiber coupled laser is passed through a quarter waveplate (QWP) and a polarizing beamsplitter (PBS). The QWP allows for control over the ratio of the optical power in each of the two beam paths (the pump and the probe beam). The probe beam is directed through an acousto-optic modulator (AOM) which provides amplitude modulation for lock-in detection. The first order beam passes through another QWP and is focused through the $Yb^+$ discharge in the HCL. The pump beam is focused through the HCL from the opposite direction and
Figure 3.9: The schematic of the optical layout of the polarization spectroscopy locking. The collimated fiber input from the master laser is first passed through a quarter-wave plate (QWP1) and a polarizing beam splitter to split the beam into the pump and probe paths. The probe beam is modulated using an AOM for lock-in detection and is passed through QWP2 and through the Yb hollow cathode lamp. The pump beam is overlapped with the probe beam in the ion discharge. Because of circular dichroism, the amplitudes vertical and horizontal polarizations of the pump beam become unbalanced. This is measured by a balanced photodiode circuit which feeds the signal to the lock-in amplifier.

its beam waist is overlapped with that of the probe beam. Because the pump and probe beams are counter-propagating, we can achieve sub-Doppler resolution.

The locking signal is produced by circular dichroism due to the interaction of the pump beam with the ion discharge (Pearman et al., 2002). After exiting the HCL, the probe beam is passed through half wave plate (HWP) to rotate its polarization by 45°. A polarizing beamsplitter is used to separate the vertical and horizontal polarizations. The two separate paths are then directed onto a balanced photodiode circuit, where the difference in the two photodiodes contains the information about the locking signal. The circular dichroism induces an amplitude imbalance between the vertically and horizontally polarized components of the probe beam. In order to distinguish the signal from the noise, the signal from the balanced photodiode
circuit is passed to a lock-in amplifier. By tuning the frequency of the laser beam, the signal from each type of ytterbium isotope can be found. For our experiments, the frequency is locked to the $^{172}\text{Yb}^+$ error signal. The error signal from the lock-in amplifier is sent to an analog to digital converter (ADC) and FPGA where a digital proportional-integral-derivative (PID) lock is implemented (Mount et al., 2015b).

The laser that is frequency locked to the transitions of the Yb$^+$ discharge serves as the master laser, and slave lasers can be locked to the master laser with a set frequency offset (Mount et al., 2015b). The master laser and slave laser are overlapped and focused onto a photodiode. The photodiode measures the difference frequency of the two lasers. The difference frequency is sent to a frequency divider and a phase detector, which compares the frequency to a reference frequency provided by a DDS. The output of the phase detector is a signal from 0 to 5V and can be locked to 2.5V when the two input frequencies are identical. The output is sent to an ADC and FPGA where another digital PID lock is performed. The absolute frequency stability of the cooling and detection laser is now dependent on both the stability of the polarization spectroscopy lock and the frequency offset lock. The frequency stability is measured to be $<$1MHz.
Optical MEMS for Quantum Information Science

MEMS technology has assisted light steering applications in the fields of imaging, optical communication systems, displays, optical data storage, and many others. For use in quantum information systems, MEMS are particularly promising due to their scalability and versatility. MEMS devices can be designed to accommodate multiple wavelengths, and the switching speed they provide is critical to the requirements of implementing a physical quantum computer.

Figure 4.1: SEM image of a titling MEMS mirror with 125 μm radius
4.1 MEMS Mirror Design

In order for MEMS to be a viable solution for the individual addressing of trapped ions, certain optical and mechanical requirements must be met. Because the relevant transitions of the $^{171}$Yb$^+$ qubit are in the UV range, specifically the 350-400 nm range, the MEMS mirrors need to be engineered for high performance in the UV range. Also, since the ions will be grouped relatively close together in a chain, the optical quality of the incoming beam needs to be preserved in order to minimize the amount of intensity crosstalk on neighboring ions. For a large-scale quantum computer, thousands of gate operations need to be performed before the qubit memory decoheres, so the transient response of the mirror needs to be as fast as possible.

The mirror is designed to be a circular reflective plate with a radius $R$ and a thickness $T$ which tilts in one dimension. The springs that allow this tilt have widths $W$, lengths $L$, and thicknesses $T$. The mirror is situated above an actuation electrode, separated by an air gap $G$. The schematic of an example mirror is shown in Fig. 4.2.

The mirror can be modeled as an electrostatically damped harmonic oscillator with the following equation (Kim et al., 2007):

$$I\ddot{\theta}(t) + D\dot{\theta}(t) + 2K\theta(t) = \frac{1}{2} \frac{\partial C(\theta)}{\partial \theta} V^2(t)$$  \hspace{1cm} (4.1)

where $I$ is the moment of inertia with respect to the rotational axis, $K$ is the torsional
stiffness of the spring, $D$ is the damping coefficient, $C$ is capacitance as a function of tilt angle corresponding to the actuation electrode, and $V$ is the applied voltage to the electrode. The resonant angular frequency is defined as $\omega_r = \sqrt{2K/I}$ and the damping ratio is defined as $\zeta = D/(2\sqrt{2KI})$. The geometry of the mirror plates and springs determine the variables $I$ and $K$. The damping coefficient is dependent on the geometry, but also depends on the working environment. By controlling the physical dimensions of the mirror plate and the springs, one can in principal design a MEMS mirror to meet the specifications required for individual addressing of ions.

To understand the response of the mirror to the actuation voltages, equation (4.1) can be expressed in terms of a dimensionless time variable $\tau = \omega_r t$ (Kim et al., 2007):

$$\ddot{\theta}(\tau) + 2\zeta \dot{\theta}(\tau) + 2K\theta(\tau) = \frac{1}{2I\omega_r^2} \frac{\partial C(\theta)}{\partial \theta} V^2(\tau)$$

(4.2)

The mirror response can then be modeled by two different cases: the tilt case and the release case. When the voltage applied is switched to zero (the release case), it can be determined that the settling time of the mirror is on the order of $1/\omega_r$ (Kim et al., 2007). In order to achieve a fast settling time, $\omega_r$ needs to be minimized. To do this, the torsional stiffness of the spring can be reduced or the moment of inertia can be increased. The torsional stiffness can be increased by decreasing the length of the spring or by increasing the width or thickness. The moment of inertia can be reduced by decreasing the radius of the mirror.

One other factor that determines the switching response of the MEMS mirror is the damping ratio, $\zeta$. The main component of the damping ratio with the MEMS system is viscous squeeze film damping (Knoernschild, 2011). Under low switching speeds, the air in the gap between the mirror plate and the electrodes is effectively squeezed out from beneath the mirror surface. This type of damping creates a torque on the mirror plate. However, when the switching speeds become faster,
the air does not have an opportunity to be squeezed out and is instead compressed beneath the mirror plate. This creates a restoring force on the mirror plate which can be represented as an air spring. The damping is controlled by the radius of the mirror plate and the gap between the plate and the electrodes. The speeds required for individual addressing dictate that the mirrors need to operate in the non-compressing regime.

Ideally a mirror could be designed with the proper resonant frequency and damping coefficients for optimum settling times. However, the fabrication process limits some of the mirror dimensions, therefore limiting the spring constant. The MEMS fabrication dictates the material used for the mirror plates and the springs so only the dimensions can be optimized. The dimensions are restricted due to the limited thicknesses achievable by the fabrication process. For our design of the springs, only the width can be optimized. Springs that are comparable to the diameter of the mirror induce a warping of the mirror plate when an actuation voltage is applied. Compromises have to be made in order to satisfy all of the design rules of the fabrication process while still fulfilling the requirements for individual addressing.

4.2 Sandia SUMMiT-V Fabrication Process

Sandia’s SUMMiT-V (Sandia Ultra-planar Multi-level MEMS Technology) contains four mechanical polysilicon layers deposited on a polysilicon substrate (Smith et al., 1998). Tetraethoxysilane (TEOS) oxide is used as the sacrificial oxide that is deposited between each of the four polysilicon layers. The layer structure of the SUMMiT process can be seen in Fig. 4.3. One of the advantages of the SUMMiT process is that poly3 and poly4 are deposited on a chemical mechanical polished layer of sacrificial oxide. Because of the polishing, any features from previous poly layers will not propagate through the subsequent layers. This allows for a smooth final surface, which is ideal for the reflective mirror surfaces. The different polysilicon layers are
patterned using standard photolithography processes to achieve the desired structure of the device. The SUMMiT devices feature an ultra-low-stress polysilicon allowing for larger surfaces of structural material without the concern of deformation due to internal stress (Michalicek et al., 1997).

For the current MEMS design the first three poly layers are used for electrodes and the wiring to the bonding pads (Knoernschild, 2011). The many layers of the SUMMiT process allow the electrodes to shield the insulating nitride layer from the mirror plate of the device. Charging of the nitride layer causes the electrodes to effectively enlarge, causing the tilt angle of the mirror to drift (Knoernschild, 2011). The final two poly layers are used for the mirror plates and the springs. The stacked plate mirror has a single mirror plate formed by depositing poly4 directly onto poly3. The split plate mirror design uses poly3 as an actuation plate and poly4 as the reflector plate with only two anchor points connecting the two layers. This design prevents warping of the reflective surface when the mirror is tilted. The downside of using the SUMMiT process is that the gap between the electrodes and the mirror cannot be accurately controlled. This gap is varied between different
mirror designs because the gap is dependent on how much the polishing process of the third sacrificial oxide layer removes, and this can make it difficult to accurately model the characteristics of the mirror. However, because of the extra insulating layers, the chemical mechanical polishing, and a more controlled alignment process, the current MEMS devices were fabricated using the SUMMiT process.

4.3 MEMS Release Process

Because the performance of the individual addressing experiments relies heavily on the optical quality of the incoming beam, the MEMS devices need to be hand polished to reduce any scattering due to surface roughness. A 0.05 $\mu$m alumina slurry is combined with deionized water on a METLAB black Chemotec polishing cloth. The MEMS chip is then flipped upside down on the pad and rubbed across the slurry in a figure-8 motion. This pattern is repeated approximately 50 times on the pad. The MEMS chip is then moved to another polishing pad without the slurry and the process is repeated. The roughness is then checked using an optical microscope and an atomic force microscope (AFM). For the chips used in this experiment the initial RMS roughness on a mirror plate was approximately 15 nm. After polishing, the RMS roughness was reduced to approximately 2 nm.

Next, the sacrificial oxide between the mirror plates and the electrodes is etched away in order for the mirrors to actuate. First, any visible debris is cleaned off the surface using standard solvent cleaning methods. The devices are then soaked in hydrofluoric (HF) acid for approximately two hours. This soak length is governed by the amount of etch holes on the mirrors, the gap between the electrode layer and the mirror plate layer, and the radius of the mirrors. The MEMS chips are then soaked in two consecutive deionized water baths, the first for approximately 30 seconds and the second overnight. This allows any extra HF to diffuse from underneath the mirror plates. Figure 4.4 shows a case where residual HF deteriorated the reflective coating.
Figure 4.4: Microscope image of the aluminum coating damage due to excess residual HF.

of the MEMS. A critical point dryer is then used to dry the device. If the device is left to air dry, the tension created by evaporation can cause the structure to collapse. Finally, an oxygen plasma clean is performed on the device to remove any organic particles left on the surface.

After the release, the metals for the bonding pads and the mirror surfaces need to

Figure 4.5: (a) SEM image of released MEMS device with wirebonds routing the DC voltages from the edge of the chip carrier to the electrodes of the MEMS device. (b) Packaged MEMS device. The MEMS chip is attached to a 68 pin ceramic leadless chip carrier and sealed in a Nitrogen environment. A custom lid with an anti-reflection coated sapphire window allows for optical access to the device.
be deposited. A custom, non-contact shadow mask for the bonding pads is aligned with the MEMS device using a photolithography mask aligner. Chrome followed by gold is evaporated onto the device using an electron beam evaporator, resulting in \( \sim 200 \, \text{Å} \) of chrome and \( \sim 2000 \, \text{Å} \) of gold deposited. The same alignment procedure is then performed for the mirror plates and their corresponding mask. Because the devices will be used with ultraviolet (UV) wavelengths, aluminum is chosen for the mirror surface due to its high reflectivity at the UV wavelengths. To reduce as much of the stress on the mirror plates as possible, the aluminum is deposited at the highest pressure allowed by the evaporator. After the evaporation is performed, the MEMS chips are then secured to a 68 pin ceramic leadless chip carrier using a conductive silver paste. The device is then wirebonded to the pads on the chip carrier with 0.2 mil gold wire. The final step is to seal the device in a nitrogen environment. This protects the MEMS chip from physical damage and prevents the aluminum coating from oxidizing. While inside a nitrogen purged glove box, a custom lid is seam-sealed to the chip carrier. The resulting packaged device can be seen in Figure 4.5.

4.3.1 Mirror Curvature

The deposition of the aluminum on the mirror plate can cause enough stress to introduce a radius of curvature depending on the thickness deposited. This radius of curvature can have a significant effect on the beam waist and propagation. The deposition causes a stress at the interface between the mirror plate and the aluminum. Other stresses include an intrinsic stress gradient in the material as well as stress due to the mismatch between the two coefficients of thermal expansion. The radius of curvature can be related to the film thickness by the Stoney equation:

\[
- \frac{1}{R} = 6 t_f \frac{\sigma}{E_{si}} t_s^2
\]  

(4.3)
Figure 4.6: Different MEMS devices were fabricated with varying metal thicknesses deposited on the polysilicon mirror plate. A white light interferometer was used to measure the stressed induced radius of curvature. Each point represents one sample with a known metal film thickness. The fit curve is used to determine the optimum film thickness to produce the largest radius of curvature.

where $R$ is the radius of curvature, $t_f$ is the film thickness, $t_s$ is the plate thickness, $\sigma$ is the film stress, and $E_{si}$ is Young’s Modulus of silicon. By varying the metal thickness and measuring the corresponding radius of curvature, we can use a fit line to calculate the optimum film thickness in order to produce the largest radius of curvature for the mirror (Figure 4.6). Figure 4.8 shows the measured curvature for two different aluminum thicknesses using a white light interferometer (Zygo). The reflectance of 370 nm light by aluminum depends on the thickness of the film, as seen in Fig. 4.7. Due to the steep decline of reflectance below 30 nm of film thickness, a device was processed with a target thickness of 30 nm. The resulting radius of curvature for this thickness is $\sim$21 cm.
Figure 4.7: Simulation of the reflectance of aluminum as a function of metal thickness.

Figure 4.8: White light interferogram of the curvature of a MEMS mirror with ~70 nm of aluminum deposited and with ~30 nm of aluminum deposited. The thinner metal film decreases the stress at the polysilicon/metal boundary causing less deformation of the mirror.

4.4 DC Characterization

With each newly released and wirebonded device, measurements are taken to determine the relationship between the tilt angle of the mirror and the DC voltage applied. The onset of instability occurs when the restoring force of the spring is no longer larger than the electrostatic force induced by the capacitor. The energy stored
in a capacitor is determined by the capacitance and the applied voltage:

\[ E = \frac{1}{2} CV^2 = \frac{\epsilon_0 AV^2}{2g} \tag{4.4} \]

where \( \epsilon_0 \) is the permittivity of free space, \( A \) is the area of the capacitor plate, \( V \) is the applied voltage, and \( g \) is the gap between the two plates. The electrostatic force on the capacitor plates is given by:

\[ F_{ES} = -\frac{\partial E}{\partial g} = \frac{\epsilon_0 AV^2}{2g} \tag{4.5} \]

The net force on the mirror plate is given by the total between the electrostatic force and the mechanical restoring force:

\[ F_{NET} = F_{ES} + F_M = \frac{\epsilon_0 AV^2}{2g} - kx \tag{4.6} \]

The equilibrium position is achieved when \( F_{NET} = 0 \) and the equilibrium gap is given by \( g = g_0 - x = g_0 - \frac{\epsilon_0 AV^2}{2kg^2} \). At the onset of instability, \( \frac{\partial F_{NET}}{\partial x} = 0 \). A solution is obtained when:

\[ \frac{x}{g} = \frac{1}{2} \Rightarrow x = \frac{1}{3} g_0 \tag{4.7} \]

which corresponds to a snapdown voltage of:

\[ V_{SD} = \sqrt{\frac{8kg_0^3}{27\epsilon_0 A}} \tag{4.8} \]

This snap-down voltage for both tilt directions of each mirror is measured by increasing the applied voltage to the electrode and monitoring the tilt angle with the Zygo. Fig. 4.9 shows the resulting measurements for the tilt angle as a function of voltage for a particular MEMS device. The stacked mirror plates have a lower snap-down voltage compared to the split mirror plates. This is due in part to the fact that the split plate mirrors have smaller electrodes and much higher spring constants.
Figure 4.9: Plot of the measured tilt angle with respect to the voltage applied to one electrode for both a stacked (red circles) and split (blue triangles) plate mirror.

4.5 Transient Response

To measure the transient response of the mirrors, a position sensitive detector (PSD) is used to measure the position of a reflected beam. The mirror is driven by a square wave from 0 to a voltage significantly smaller than the snap-down voltage. The output of the PSD is recorded using an oscilloscope. The mirror used in the individual addressing experiment has a resonant frequency of 260 kHz and a damping ratio of 0.7. The resulting transient response can be seen in Fig. 4.10. The settling time is approximately 5 $\mu$s with a close to critically damped response.

4.6 Intensity Profile of Output Beam

The MEMS system not only needs to preserve the Gaussian profile of the beam, it also needs to limit the amount of scatter that might affect neighboring ions. The
Figure 4.10: Transient response of a mirror with resonant frequency 260 kHz. Both the tilt (left) and release (right) cases are plotted. The red curve shows the applied voltage to the electrode, the blue curve is the measured data from the PSD, and the modeled fit is plotted as the green curve.

The main sources of scattering are from surface roughness, etch holes (Zou et al., 1999), and the diffraction pattern from aperturing the beam with the finite radius of the mirror. To measure the intensity profile of the beam at the output of the system, a variable attenuator is used with a beam profiler. The beam profile is measured at varying attenuations and then stitched together with a MATLAB script. Fig. 4.11 shows the intensity profile at the Fourier plane. The background level is down to $10^{-3}$ to $10^{-4}$ with a well-matched Gaussian profile. The regular pattern seen around the main beam can be attributed to the etch holes and diffraction pattern of a circular aperture.
4.7 MEMS Electronics

Fast control of the voltages applied to the electrodes is necessary in order to utilize the fast tilting speeds of the MEMS mirrors. Voltage sets are preloaded to memory on an FPGA. The main experimental control program sends a two bit address to access the four available memory slots. The FPGA then serially sends the data to the appropriate DACs. A trigger signal is sent by the main experimental program to latch the DACs and produce the analog voltage. The voltage is then amplified 12x using a high-speed high-voltage amplifier (PA84S, slew rate of 200V/s). Each mirror is controlled by two electrodes, so for a single beam system, four separate voltages are needed. However, a new circuit design by one of the group’s undergraduate students,
Figure 4.12: Schematic of the MEMS electronics. The main control program sends a two bit address value to the FPGA. When the trigger signal is sent from the main control program, the FPGA generates serial data that is sent to the DAC based on the value of the address bits. When the voltages are ready to be sent to the MEMS mirrors, the main control program sends a trigger signal to the FPGA, which passes a latch signal to the DACs in order to produce the analog voltage specified by the serial input. A high voltage amplifier (PA84S) is then used to amplify the voltage signal by 12x. A single pole double throw (SPDT) electronic switch can used to switch the voltage between the two electrodes of a single mirror.

Dennis Lynch, utilizes a high voltage single pole double throw switch. Since each mirror will only use one electrode at a time (can only tilt in one direction at a time), this allows a single beam system to only need two DAC voltages. As the system scales to more beams, this solution will reduce the cost and complexity of the electronics needed to drive the MEMS mirrors. (Fig. 4.12).

4.8 MEMS Optical Shutter

For qubit addressing that requires resonant laser pulses, one challenge associated with scalability is the need for effective laser beam shuttering for high-fidelity power extinction. A proposed solution is to combine fast electro-optic amplitude switching and high-fidelity electronic beam shuttering using a MEMS deflector coupled into a single-mode optical fiber (Scherer et al., 2012). In order to achieve fast switching speeds with thermal stability and no frequency shift, a microelectromechanical mirror is used to steer UV light out of a single mode fiber resulting in an electromechanical...
Mechanical beam shutter. The switch system is comprised of two fibers collimated by two microlenses, a focusing lens, and the MEMS mirror (Figure 4.13). A beam is delivered to the switch system through the input fiber and is collimated by a microlens placed a focal length \( f_m \) away from the tip of the fiber. The collimated beam is then focused onto the MEMS mirror using the focusing lens placed a focal length \( f_0 \) away. The MEMS mirror reflects the beam back through the lens and the second microlens, and the light is coupled back into the output fiber. When the MEMS mirror is tilted, the beam is steered off of the output fiber, effectively opening the shutter.

Laser light at 370 nm is delivered to the shutter system by an input fiber in a 1x4 UV fiber array with 250 \( \mu \)m pitch. A microlens array with the same 250 \( \mu \)m pitch is used to collimate the beam, with a radius of curvature of 297 \( \mu \)m and a corresponding focal length of \( f_m \sim 630 \mu \)m at this wavelength. The thickness of the microlens array (SussMicrooptics) results in the back focal length inside the microlens substrate, so
the microlens was polished to reduce the thickness. This was done with a polishing and lapping tool using a series of polishing pads and slurries.

The collimated light after the microlens is then focused onto the aluminum coated MEMS mirror using a focusing lens with $f_0 = 30$ mm, creating a beam waist of $75 \mu m$ on the $250 \mu m$ diameter MEMS mirror. This arrangement minimizes the diffraction of the beam arising from the finite mirror aperture.

Figure 4.14(a) shows the intensity profile of the input light incident on the MEMS mirror. The non-idealities of the microlens cause a small fraction of the intensity to be diffracted as a background outside the main Gaussian lobe. When reflected by the MEMS mirror with finite aperture, the intensity outside the main lobe will form a diffraction pattern as it exits the output fiber. The resulting output power as a function of the MEMS mirror tilt angle is shown in Figure 4.14(b). The throughput of the optical shutter is 53% at the mirror tilt angle of 0 degrees, and the output power is reduced quickly as the mirror is tilted. The extinction ratio peaks at $-52$ dB with a local maximum of approximately $-40$ dB due to the diffracted side lobes.

Figure 4.15 shows the transient response measured by applying a square wave voltage pulse (blue traces) to the actuation electrode of the MEMS mirror and mon-
Figure 4.15: Transient responses of both the switch off (a) and switch on (b) case. The slight ringing during the switch on case is due to the slightly underdamped response of the MEMS mirror for the release case (Scherer et al., 2012).

Monitoring the light output on a photodiode (green traces). The shutter settles to a final on-value within 7 µs after slight mirror ringing (Figure 4.15(a), and has a switch off transient response of approximately 2 µs (Figure 4.15(b)). The ringing behavior can be eliminated by optimizing the damping characteristics of the mirror.

We show that a fiber shutter utilizing a MEMS mirror provides fast switching speed (~ 2 µs off-time), high extinction ratio (< -50 dB), and adequate throughput (53%). This initial design and characterization of a MEMS-based fiber coupler shows promise for a low loss, high extinction, and fast electromechanical beam shutter system.
Individual Addressing of Trapped Ions

Trapped ions are one of the leading candidates to be used as qubits for quantum information processing (QIP) due in part to their high fidelity logic operations (Wineland et al., 1998; Blatt and Wineland, 2008). The state of the qubit and subsequent gate is best visualized using the Bloch sphere (Figure 5.1). A point on the surface of the Bloch sphere represents a pure state of a single qubit. The qubit state is defined as:

$$\psi_n = \cos\frac{\theta}{2} |0\rangle + e^{i\phi} \sin\frac{\theta}{2} |1\rangle$$  (5.1)

The values of $|0\rangle$ and $|1\rangle$ are represented as $z = -1$ and $z = 1$ respectively, and a point on the equator represents an equal superposition of the states $|0\rangle$ and $|1\rangle$. The qubit state processes about the $z$ axis at the rate corresponding to the energy difference between the $|0\rangle$ and $|1\rangle$ energy levels (12.6 GHz). For the following experiments, the duration of the resonant field at the ion location determines the amount of rotation on the Bloch sphere while the relative phase of each subsequent pulse to the first determines the angle of rotation.
Figure 5.1: The Bloch sphere visualization of a qubit, where a qubit in a pure state is represented by a point on the sphere. The coordinates of the state can be expressed as a function of $\theta$ and $\phi$.

Figure 5.2: Simplified energy level diagram of $^{171}$Yb$^+$ showing the microwave gate transition. A microwave horn is used to deliver the microwave field to the trapping region. A microwave field resonant with the hyperfine splitting of the $^2S_{1/2}$ energy level coherently drives the qubit between the $|0\rangle$ and $|1\rangle$ states.
5.1 Microwave Qubit Rotations

Single and multi-qubit operations have been performed on trapped ions using microwave fields (Ospelkaus et al., 2011; Allcock et al., 2013). The qubit can be rotated from $|0\rangle$ to $|1\rangle$ by applying an electromagnetic field that is resonant with the $^2S_{1/2}$ hyperfine frequency of 12.6 GHz. To apply a microwave field in our experiment, a microwave horn is placed outside of the UHV chamber and directed towards the ion location. A microwave source detuned from the hyperfine transition by $\sim70$ MHz is distributed to all of the individual experiments in the lab. The detuned microwave source and a 70 MHz signal from a DDS are mixed using a single-sideband (SSB) mixer in order to produce a sideband resonant with the qubit frequency. The SSB suppresses the other sideband by -34 dBc and provides only -32 dBm leakage of the input microwave signal, so any off-resonant fields are adequately suppressed.

In order to find the resonant frequency of the microwave, the ion is first initialized to the $|0\rangle$ state by optical pumping, as described in Section 2.2.1. The microwave source is then turned on for a set amount of time (typically $\sim200 \mu$s) and the frequency of the DDS is scanned. When the microwave is tuned to the resonant frequency between the $^2S_{1/2}|F = 0\rangle$ and $^2S_{1/2}|F = 1, m_f = 0\rangle$ transition, the qubit state will begin to transition from the $|0\rangle$ state to the $|1\rangle$ state. The amount of time for the field to rotate the qubit from the $|0\rangle$ state to the $|1\rangle$ state is referred to as the $\pi$-time, since the state rotates an angle $\theta = \pi$ on the Bloch sphere. The polarization of the applied field is optimized by changing the microwave horn orientation and finding the minimum amount of time required to drive the qubit fully to the $|1\rangle$ state while keeping the frequency constant. The minimum $\pi$-time in our experiments is limited by the amount of power in the microwave field.

One of the main challenges with using microwave frequencies to perform single qubit gates is the ability to individually address single ions in a chain. The wave-
Figure 5.3: The probabilities of finding each of the two individual ions in the $|1\rangle$ state as a function of the duration of the microwave field. The two ions are first prepared in the $|0\rangle$ state and then the microwave field is turned on for a varying amount of time. State-dependent resonance using a multi-channel PMT is then used to read the individual states of the two qubits. Each point represents the average of 200 experiments.

The length of the applied field is much larger than the spacing between the qubits, so any applied radiation will affect each qubit. Figure 5.3 shows the results of applying the microwave field in the presence of two qubits. The two qubits are first optically pumped to the $|0\rangle$ state, and then the microwave field is applied for a varying amount of time. State-dependent fluorescence is used to detect the resulting states of the ions. The photons scattered from each ion is collected by an imaging lens and imaged onto separate segments of the 32-channel PMT. Because the wavelength of the microwave is much bigger than the spatial separation of the two qubits, both qubits undergo the same amount of rotation.
Figure 5.4: Simplified energy level diagram of $^{171}$Yb$^+$ showing a Raman transition. Two co-propagating Raman beams (blue and red lines) coherently rotate the qubit between the $|0\rangle$ and $|1\rangle$ states.

5.2 Raman Transition Qubit Rotations

Single qubit rotations between the $|0\rangle$ and $|1\rangle$ state can be driven by a stimulated Raman transition using two laser beams with a frequency difference resonant with the hyperfine splitting, $\Delta_{hf} = 12.6$ GHz (Figure 5.4) (Mount et al., 2013). For our experiments, two frequency combs from phase-locked ultra-fast lasers are used to drive Raman transitions (Hayes et al., 2010; Mount et al., 2013). A picosecond titanium-sapphire laser (MIRA, Coherent) is used with a center frequency close to 752 nm and a 76 MHz repetition rate. The laser frequency is doubled using a bismuth borate (BiBO) crystal to produce a center wavelength of 376 nm, which is red-detuned from the ion’s $^2S_{1/2}|F = 1\rangle \rightarrow ^2P_{1/2}|F = 0\rangle$ resonance by approximately $\delta = 14$ THz. An acousto-optic modulator (AOM) is used to shift the two frequency combs relative to each other. In order to drive the Raman transition, the frequency difference between any two comb teeth is equal to the hyperfine splitting of the $^2S_{1/2}$ energy level such that

$$f_{qubit} = n \times f_{rep} \pm (f_1 - f_2)$$  \hspace{1cm} (5.2)
where $f_{\text{qubit}}$, $f_{\text{rep}}$, $f_1$, and $f_2$ are the frequency of the qubit hyperfine transition, the repetition rate of the pulsed laser, and the two AOM frequencies, respectively (see Figure 5.5). A direct digital synthesizer (DDS) sets the modulation frequencies, allowing for digital control of the frequency, amplitude, and of each comb. The frequency shift is digitally stabilized such that Equation 5.2 is satisfied (Mount et al., 2015b). The repetition rate of the laser as well as the absolute frequency do not need to be stabilized since the qubit transition is driven only by the frequency difference of two comb teeth. A DDS channel is locked to the drifting $f_{\text{rep}}$ using a digital phase-locked loop and the frequency $f_2$ is computed digitally to satisfy 5.2 with a known $f_1$ (Mount et al., 2015b). Co-propagating Raman beams are implemented by driving a single AOM with two modulation frequencies and are circularly polarized with respect to the quantization axis defined by the magnetic field. The single beam with the two different modulation frequencies is then coupled to a fiber and delivered to the beam steering system.

**Figure 5.5:** Schematic of the two frequency combs that drive the Raman transition by satisfying Equation 5.2. The spacing between comb teeth is the repetition rate of the pulsed laser, and all pairs of comb teeth that span the qubit frequency contribute to the Raman transition.
5.3 MEMS Beam Steering

Extending these single qubit operations over multiple qubits with individual qubit addressing has been accomplished by using acousto/electro-optic modulators to steer laser beams (Schmidt-Kaler et al., 2003; Yavuz et al., 2006), or engineering magnetic field gradients at the ion location (Johanning et al., 2009). However, AOMs and EOMs have severe limitations. AOMs can produce small frequency shifts, do not provide a constant deflection across the entire device, require a relatively high (∼1 W) RF drive power, and are not fast enough for large scale quantum computing. EOMs do respond quicker than AOMs (approximately 15 µs response time, compared to ∼1-2 ms), but they can also induce small frequency shifts and have a limited angular addressing range. MEMS devices have been proposed to overcome the drawbacks of conventional beam steering devices and offer a viable solution for individual addressing of trapped ions. Also, as the number of qubits in a QIP system increases, one needs a scalable approach to manipulate each individual qubit (Seidelin et al., 2006; Kim et al., 2005; Nagerl et al., 1998).
5.3.1 Optical System Design

The optical system consists of four main components: a focusing lens to image the beam waist onto the MEMS mirror, a folded 2f imaging system, tilt to shift conversion by a lens, called the Fourier lens, placed a focal length away \((f_f)\), and projection optics to demagnify the beam waist to the appropriate size for addressing ions in a chain (Fig. 5.7). The fiber coupled beam is first collimated and focused onto the first MEMS mirror. The beam waist at the MEMS mirror is chosen to be no larger than two-thirds the size of the mirror in order to reduce the amount of clipping.

*Folded 2-f Imaging System*

For individual addressing of trapped ions in a chain, the beam needs to be steered in two dimensions to accommodate a trapping axis in any direction. Two-dimensional tilting MEMS mirrors have been used in other applications (Su et al., 2001); however, the switching speeds are too slow for quantum information applications. In order to overcome the limit of switching speed, the two dimensional tilt is decomposed into two separate mirrors with orthogonal tilt axes. The reflection off of the first MEMS mirror can then be imaged onto the second MEMS mirror by a 2f-2f imaging system.
In order to use a single chip for the two orthogonally tilting MEMS mirrors, the 2f-2f imaging system is implemented with a spherical mirror with a focal length of $f_s$.

In general, the incident angle of the beam onto the first MEMS mirror is expressed by

$$\theta_i = \frac{d(2n - 1)}{4f_s}$$  \hspace{1cm} (5.3)\\

, where $d$ is the distance between the two MEMS mirrors and $n$ is the number of times the beam reflects off each mirror. By doubling the number of reflections on the each MEMS mirror, the angular range is doubled. This allows a smaller mirror to be used for the same angular range of a larger mirror, but with a much faster response. However, reflecting off each MEMS mirror twice does add extra optical loss to the beam steering system. For the following experiments, a single-bounce system is used due to the limited number of qubits that need addressing ($< 5$ and small spacing of the qubits ($\sim 5$-7 $\mu$m).

**Fourier Lens**

The Fourier lens converts the angular tilt of the beam induced by the MEMS mirror into a lateral or horizontal shift at the image plane. For a tilt of $\Delta \theta$ a lens of focal length $f_f$ translates the tilt to a shift of $l = \Delta \theta f_f$, where $\Delta \theta = 2n\alpha$ and $\alpha$ is the angular tilt of the MEMS mirror. In order to address $N$ sites with a spacing of $2\omega_0$ between the sites $l = (N - 1)\omega_0$, a focal length of $f_f = \frac{(N-1)\omega_0}{2n\alpha}$ is needed. The beam waist at the image plane is determined by $\omega'_0 = \frac{\lambda f_f}{\pi \omega_0}$, so a relation between the beam waist at the mirror and the addressing range can be found by solving for the focal length and combining the previous two equations:

$$\omega_0\alpha = \frac{(N - 1)\lambda}{2n\pi}$$  \hspace{1cm} (5.4)
By increasing the beam waist, the addressing range is also increased. However, as previously mentioned, the beam waist is limited by the size of the mirror. A compromise of speed and addressing range is required. In the following results, a beam waist of 60 $\mu$m is used for a mirror of radius 125 $\mu$m and resonant frequency of 260 kHz.

**Beam Waist and Steering Characterization**

Before aligning the beam steering system to the ion trap, a full characterization of the beam waist and addressing range was performed. The beam waist was measured at the proposed ion location with respect to the front viewport of the vacuum chamber. A beam waist of 1.5 $\mu$m at the proposed ion location was measured with a CCD camera and a microscope objective. Steering along one axis only with an beam...
Figure 5.9: Characterization of a single beam addressing range. The measured beam waist is 1.5 \( \mu \text{m} \) and adjacent sites are separated by 5 \( \mu \text{m} \). The solid line is a Gaussian fit and the points are the measured intensity profile.

separation of 5 \( \mu \text{m} \), five individual sites can be addressed with minimal overlap between the sites. Since the trap is mounted in the chamber with a 45° with respect to the MEMS device, the addressing range can be extended by a factor of \( \sqrt{2} \) by utilizing both tilt directions.

5.4 Individual Addressing of \( ^{171}\text{Yb}^+ \) Qubits Using MEMS Beam Steering

As previously mentioned, beam steering of the Raman laser is accomplished by using two one-dimensional MEMS mirrors (Kim et al., 2007) tilting in orthogonal directions. The mirrors are fabricated on a single substrate using Sandia’s SUMMiT V process (Smith et al., 1998) allowing for a single system to be scaled to multiple beams across a variety of wavelengths (Knoernschild et al., 2008, 2009). The final de-
Figure 5.10: Schematic of optical setup (both imaging and MEMS beam paths) as well as a microscope image of the ion trap highlighting the slot (the dark region) and control electrodes.

The sign of the mirrors consists of a 125 μm radius polysilicon plate with a ~30 nm thick aluminum coating which allows for maximum reflectance at 376 nm wavelength while minimizing the stress that induces curvature on the plate. By applying an actuation voltage between the grounded mirror plate and underlying electrode, the mirrors can be tilted by an angle $\theta$ (beam tilt angle of $2\theta$). The resulting output beam from the Fourier lens is demagnified and projected onto the ion location through the same 0.6 NA lens used for the ion imaging system. This is accomplished by using a dichroic filter that reflects the Raman beam (at 376 nm) and transmits the light scattered by the ion (at 369.5 nm). The Raman beam is perpendicular to the trap surface, allowing it to pass through the slot in the middle of the ion trap (Mount et al., 2013).

In order to align the addressing beams to the trapped ions, the imaging lens is first translated to image the surface of the trap. A weak beam is directed through the MEMS steering system and directed onto the trap. Using an EMCCD, we are able to see the scatter of the beam on the surface of the trap. The beam is then directed towards the trapping region and passed through the slot of the trap. The intensity
of the beam is increased and the beam is turned on for a time much longer than a
typical pi-time. The Raman beam is intentionally defocused in order to increase the
chance of the beam hitting the ion and inducing Raman transitions. Once a signal
is found, the focus of the beam is adjusted to minimize the pi-time of the Raman
transition.

5.4.1 Intensity Crosstalk Characterization

For the first experiment, we characterize the amount of optical crosstalk from the
co-propagating Raman beams on neighboring ion sites separated by approximately
7.4 µm (Crain et al., 2014). The two ions are first initialized to the |0⟩ state. The
Raman beam is then directed onto one of the two ions (site A) for a duration T. The
resulting state of the two ions is then determined by state-dependent fluorescence.
The same experiment is then repeated with the Raman beam directed onto the
second of the two ions (site B). Figures 5.11(a) and 5.11(b) show the probability of
the ions to be in the |1⟩ state as a function of the duration of the Raman beam, T.
The amount of time needed in order to transition the ion from the |0⟩ state to the |1⟩
state is \( \tau_{\pi,A} = 13 \mu s \) and \( \tau_{\pi,B} = 15 \mu s \) for ion A and ion B, respectively. The variation
between \( \tau_{\pi,A} \) and \( \tau_{\pi,B} \) is due to intensity variation of the Raman beams between the
two experiments. At the beginning of the scan, the step size is set to the amount of
time it takes to transition between the |0⟩ and |1⟩ states, so the data point should
be alternating between 0 and 1 for the ion that is being addressed. However, due to
either errors in calibrating that time and laser intensity drift, the data points start
to deviate from the 0 and 1 levels, resulting in aliasing. After 5 ms (~\( 350 \tau_{\pi,A(B)} \)),
the probability of the target ion to be in the |1⟩ state averages to 0.5 due to the
laser intensity drift, while that for the neighboring ion stays low (~0.005 for ion B
~0.024 for ion A). To improve the error from intensity drifts, compensated pulse
sequences can be used to perform the qubit gates (Mount et al., 2015a). From the
Figure 5.11: (a) The Raman beam is directed at ion A while ion B is prepared in the $|0\rangle$. The step size for the Raman beam duration is initially set to $\tau_{\pi,A} = 13 \mu s$, but because of intensity drift at the ion, $\tau_{\pi,A}$ varies slightly throughout the experiment. Therefore, the plot for ion A shows the envelope of the Rabi oscillations. (b) The Raman beam is directed at ion B, and ion A is prepared in the $|0\rangle$ state.
Figure 5.12: The Raman beam is first aligned to the location halfway between the two ions (ion A and ion B) and the π-times of each ion are measured. With the Raman beam kept at the same location, a single ion is loaded and its corresponding π-time is measured. The beam waist of the Raman beam can be estimated from the ratio of the three π-times since the spacing of the two ions and the optical power of the Raman beam is known. The estimated beam waist for this system is $\sim 3.3 \ \mu$m.

ratio of the Rabi frequencies between the target and neighboring ion, we estimate that the amount of intensity crosstalk at the neighboring ion is $1.3 \times 10^{-4}$ on ion B and $2.9 \times 10^{-4}$ on ion A.

In order to estimate the beam waist at the ion location, the Raman beam is parked at halfway between the location of the two ions, and $\tau_{\pi,A}$ and $\tau_{\pi,B}$ are measured (Figure 5.12). Leaving the Raman beam at the same location, a single ion is loaded to the middle position (location C) and its corresponding $\tau_{\pi,C}$ is measured. The power of the Raman beam and the spacing of the two ions is known, so the beam waist can be calculated from the ratio of $\tau_{\pi,A}$ ($\tau_{\pi,B}$) and $\tau_{\pi,C}$ assuming a Gaussian beam. From this measurement, we estimate the beam waist to be $\sim 3.3 \ \mu$m, which should lead to an intensity crosstalk of $< 5 \times 10^{-5}$. An imperfect Gaussian beam
shape and unwanted scatter (< −30 dB) could be the cause of the difference between
the measured and estimated crosstalk.

5.4.2 Switching Speed Characterization

In order to characterize the switching time between two neighboring ion sites, we
measure the response time of the MEMS by switching the Raman beam on and off
of a single ion (Crain et al., 2014). First, we align the Raman beam on a single ion
using voltage set #1. We also identify voltage set #2 that shifts the Raman beam to
a neighboring site, separated by the distance between two trapped ions (∼7.4 µm).
After initializing the ion to the |0⟩ state, the pulsed laser is turned on for \( \tau_{\pi,1} = 1.5 \mu s \) at time \( t \). The voltages applied to the MEMS electrodes are switched from
set #1 to set #2 at \( t = 0 \) (Figure 5.13 (a)). The state of the ion is then measured
by state-dependent fluorescence after the Raman π-pulse is complete. The response
time of the MEMS beam to move off the ion can be inferred by monitoring the
rate at which the Raman transition is suppressed (blue triangles in Figure 5.13 (b)).
Next, the experiment is repeated by re-aligning the Raman beam to hit the ion when
voltage set #2 is applied to the MEMS electrodes (\( \tau_{\pi,2} = 1.3 \mu s \)). For this case, the
beam starts off the ion when voltage set #1 is used, and then comes onto the ion
as the voltages are triggered to set #2. The rate at which the Raman transition is
activated (red dots in Figure 5.13(b)) indicates the time scale over which the MEMS
beam moves onto the ion. The total time it takes to switch the MEMS mirrors to a
neighboring ion site can be calculated from the time between the cases where both
ion sites experience a full π-pulse, less \( \tau_{\pi,1} \) (or \( \tau_{\pi,2} \)). The calculated switching time
from this data is approximately 1.1 µs. The slope of the response curve is limited by
the \( \tau_{\pi,1} \) we can achieve with our current optical power and beam waist.
Figure 5.13: (a) Timing diagram of the MEMS speed characterization experiment. The applied voltages for the MEMS electrodes are switched at time $t = 0$. The response time of the MEMS mirrors is characterized by varying the start time of the $\pi$-pulse, $t$. Time $t_m$ ($\sim 0.9 \mu s$) denotes the delay of the MEMS mirrors’ mechanical response to the applied voltage and $t_s$ ($\sim 2 \mu s$) denotes time needed for a full $\pi$-pulse incident on the ion after switching the MEMS. (b) Response time of the MEMS mirrors when switched between two neighboring ion sites. Region I is the case where the $\pi$-pulse finishes before $t_m$, which results in a full $\pi$-pulse on the ion site corresponding to voltage set #1. Region II corresponds to when the $\pi$-pulse extends past $t_m$ but ends before $t_s$, resulting in a partial $\pi$-pulse experienced by the ion site corresponding to voltage set #1. Region III corresponds to when the $\pi$-pulse begins before $t_m$ and ends after $t_s$, which results in a partial $\pi$-pulse on both ion sites corresponding to both voltage sets. Region IV is the case when the $\pi$-pulse is started after $t_m$ but before $t_s$, which results in the ion site corresponding to voltage set #2 experiencing a partial $\pi$-pulse. Region V is the case where the $\pi$-pulse starts after $t_s$, resulting in a full $\pi$-pulse on the ion site corresponding to voltage set #2. The time for the mirrors to switch completely from one ion site to the other is approximately $1.1 \mu s$. 
5.4.3 Sequential Single Qubit Gates

Our final experiment measures the fidelity of two sequential single qubit gates on a pair of ions using quantum state tomography. Quantum state tomography reconstructs the full density matrix of the qubit state by projecting each qubit into the $|0\rangle$, $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, and $\frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle)$ bases (Altepeter et al., 2006). The density matrix of an arbitrary state is expressed as:

$$\hat{\rho} = \frac{1}{2} \sum_{i=0}^{3} S_i \hat{\sigma}_i$$

where the $\hat{\sigma}_i$ matrices are

$$\hat{\sigma}_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \hat{\sigma}_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \hat{\sigma}_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \hat{\sigma}_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

and the $S_i$ coefficients are given by

$$S_i \equiv \text{Tr}\{\hat{\sigma}_i \hat{\rho}\}.$$  

The $S_i$ values can be measured by projecting the ion in the three different bases (Altepeter et al., 2006).

We first prepare both qubits in the $|0\rangle$ state. The MEMS mirrors then tilt to aim the addressing beam at ion A and the Raman beam is turned on for the first single qubit gate operation. After the Raman beam is turned off, the MEMS mirrors aim the addressing beam at ion B. Then the Raman beam is turned on for the second single qubit operation. The Raman beam is redirected back to ion A and the qubit is rotated to one of the three measurement bases by applying the appropriate gate: $I$, $R_x(\pi)$, or $R_y(\pi)$. After rotating ion B to the same measurement basis, both qubits are measured using state-dependent fluorescence. This sequence is performed again with the same single qubit operations for each of the other two measurement bases.
Table 5.1: Table of various combinations of sequential single qubit gates on a pair of trapped ions and their corresponding gate fidelities measured using quantum state tomography.

<table>
<thead>
<tr>
<th>Gate A, Gate B</th>
<th>Gate Fidelities</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_x(\frac{\pi}{2}), I$</td>
<td>0.991(4), 0.9974(5)</td>
</tr>
<tr>
<td>$I, R_x(\frac{\pi}{2})$</td>
<td>0.9972(5), 0.991(4)</td>
</tr>
<tr>
<td>$R_x(\pi), R_y(\frac{\pi}{2})$</td>
<td>0.989(1), 0.992(4)</td>
</tr>
<tr>
<td>$R_x(\frac{\pi}{2}), R_x(\pi)$</td>
<td>0.989(4), 0.9913(9)</td>
</tr>
<tr>
<td>$R_x(\frac{\pi}{2}), R_x(\frac{\pi}{2})$</td>
<td>0.991(4), 0.992(4)</td>
</tr>
<tr>
<td>$R_x(\frac{\pi}{2}), R_y(\frac{\pi}{2})$</td>
<td>0.990(4), 0.992(4)</td>
</tr>
<tr>
<td>$R_y(\frac{\pi}{2}), R_x(\frac{\pi}{2})$</td>
<td>0.990(4), 0.992(4)</td>
</tr>
</tbody>
</table>

The fidelity is calculated using the following relation:

$$F(|\psi\rangle, \rho) = \sqrt{\langle \psi | \rho | \psi \rangle}$$  \hspace{1cm} (5.8)

where $\psi$ is the intended pure state and $\rho$ is the resulting arbitrary state. Table 5.1 shows different combinations of sequential single qubit gates on ion A and ion B along with the respective gate fidelities measured using state tomography. The fidelity of the preparation and measurement in the $|0\rangle$ state is 0.998 and the fidelity of measuring the $|1\rangle$ state is 0.991 in this experiment. The overall gate fidelities are currently dominated by our state preparation and measurement (SPAM) errors. In order to isolate the gate fidelities from SPAM errors, one can use randomized benchmarking technique (Knill et al., 2008; Mount et al., 2015a).

5.5 Discussion and Outlook

The measured intensity crosstalk and switching speed of the MEMS beam steering system show that this is a viable technology for the individual addressing of qubits in a trapped ion based quantum computer. The measured crosstalk of $< 3 \times 10^{-4}$ is on the order of error levels required for many of the quantum error-correction
Figure 5.14: Individual quantum state tomography of two trapped $^{171}\text{Yb}^+$ ions. These plots show the reconstructed real and imaginary parts of the density matrix for an ion that was driven by a $\pi$ gate with $0^\circ$ phase (top) and an ion that was driven by a $\pi/2$ gate with $90^\circ$ phase. The diagonals of the real part ($i = 0, j = 0$ and $i = 1, j = 1$) represent the state of the ion and the phase of the gate is captured by the imaginary part of the density matrix.

schemes (Steane, 2003; Raussendorf and Harrington, 2007). Other technologies that have been used to individually address trapped ion based qubits include microwave-driven gates on qubits in a magnetic field gradient (Piltz et al., 2014) and tightly focused static Raman beams using a multi-channel AOM (Debnath et al., 2016). For the microwave-driven gates the intensity crosstalk was measured to be on the order of $10^{-5}$, however, the qubit $|1\rangle$ state is defined as $|1\rangle \equiv ^2S_{1/2}|F = 1, m_f = 1\rangle$ (Piltz et al., 2014). Because this energy level is dependent on the local magnetic field, a magnetic field gradient can be used to break the degeneracy of the individual qubit
levels in a chain of qubits. While this does allow for individual addressing of the qubits, the qubits are now more susceptible to changes in the environment. Using a multi-channel AOM to perform static Raman gates provides an alternate solution for laser-driven individual addressing. A diffractive beam splitter is used to create an array of static Raman beams that can be individually shuttered by the multi-channel AOM. However, the main disadvantage for this type of system is controlling the optical quality of the addressing beams, and a poor quality beam has resulted in intensity crosstalk < 4% (Debnath et al., 2016).

As previously mentioned, this system has been designed to accommodate multiple independently controllable beams. This would allow for parallel operations as well as enabling two-qubit gates (such as a CNOT gate). This will require a slight redesign in the beam delivery system, but should be the logical next step for this type of system. In order to address a larger number of qubits, the MEMS mirrors can be redesigned to allow for a larger angular range, but that design change will also increase the response time of the mirrors. The switching speed that was measured in this work show that this is not the limiting factor for high speed algorithms, so a compromise can be made in future designs to allow for a larger addressing range. For now, however, combined with average error per single qubit gate using composite pulse sequence error compensation (3.6(3) × 10^{-4}) that has been demonstrated in our lab (Mount et al., 2015a), we have shown that laser-driven quantum logic gates using the MEMS beam steering system provides a scalable and viable solution to the individual addressing of single qubits.
6

Enhanced Photon Collection Through a Fiber

6.1 High Numerical Aperture Lens Model

For the work in this chapter, the scattered light emitted from a single trapped ion is collected by a high numerical aperture lens designed and manufactured by Photon Gear, Inc. This lens was designed specifically to have as large of an NA as possible with the current vacuum chamber designs as well as matching the image to the mode of a 0.07 NA single-mode fiber. The 0.6 NA of the lens covers 10% of the solid angle of the light scattered by the ion. The working distance of the lens is approximately 12 mm, so the lens is used exclusively with the UKAEA re-entrant viewport mentioned previously. The design of the lens was also dependent on the thickness of the UKAEA window, so its compatibility with other viewports is limited. The high NA lens features a very shallow depth of field of 5.25 \( \mu \text{m} \) and -4.08 \( \mu \text{m} \). The field of view is \( \pm 225 \mu \text{m} \) which allows for diffraction limited imaging of chains of ions. The overall magnification is 8.57 times as a result of matching the 0.6 imaging NA with the 0.07 NA of the single-mode fiber.

The alignment tolerances of the high NA lens were simulated by a graduate
student, Daniel Gaultney, in order to determine the requirements for optimal fiber coupling efficiency. The most sensitive degrees of freedom include the tilt and the axial translation of the high NA lens.

6.2 High NA Lens Optomechanics

Because of the strict alignment tolerances needed to couple the scattered photons from the ion into a single-mode fiber, particular care is taken to ensure the mechanical stability of the optical system. The high NA lens alignment to the ion requires five degrees of freedom: x, y, and z translation as well as pitch and yaw translation. Figure 6.2(a) shows the mechanical mount with the five controllable degrees of freedom that allows precise positioning of the high NA lens. The xyz translation is performed by a crossed-roller bearing translation stage (ULTRAAlign Precision Linear Stage, Newport). This stage provides 13 mm of linear travel with
Figure 6.2: CAD drawings of the optomechanics for both the high numerical lens (a) and the fiber (b). The high numerical lens is mounted on the translation stages with a 2” cage mount. The fiber is mounted using a 0.5” kinematic mirror mount.

angular deviation of less than 100 microradian about each axis. Thermal drift is minimized due to its large mass. The angular degrees of freedom are controlled by a tilt and rotation kinematic stage (Model #36, Newport). The tilt, rotation, and z translation (along the optical axis) are all actuated by miniature DC servo actuators (CONEX-TRA12CC, Newport). These closed-loop actuators provide a 12.5 mm travel range with 30 nm resolution. The uni-directional repeatability is 1 µm, but the bi-directional repeatability is only 3 µm. The actuators are controlled by the main Python control system.

The receiving fiber is mounted to a 0.5 inch kinematic mirror mount (Polaris Kinematic Mirror Mount, Throlabs) for tilt control. For translation, the fiber assembly is mounted to a three axis flexure stage (MBT616D, Thorlabs). This flexure stage is actuated by differential micrometers that provide 4 mm of coarse travel (500 µm/rev) and 300 µm of fine travel (50 µm/rev). One of the main advantages of flexure drives compared to traditional roller bearing design is the flexure translation prevents friction reducing drift. The optomechanical design of the fiber stage can be
seen in Figure 6.2.

6.3 High NA Lens Alignment and Aberration Correction

Before attempting to couple the photons scattered from the ion into a fiber, a coarse alignment of the high numerical lens to the ion is performed. The first step in the alignment is to roughly measure the height of the lens to match the height of the ion from the top of the optical table. The lens is then positioned into the re-entrant viewport and brought into light contact with the glass window. By feel, one can roughly adjust the vertical and horizontal tilt of the lens so that it is flush with the front surface of the viewport. Once the angles are roughly adjusted, the mechanical assembly is bolted to the table and the lens is translated away from the viewport using the micrometers. A UV LED is used to illuminate the surface of the trap, and the lens is positioned such that the image of the surface of the trap is focused onto an EMCCD (Andor iXon) with 16 µm pixels. Using distinguishing features on the trap such as alignment marks and electrodes, the lens is translated to align with the expected trapping region. The lens is then translated away from the trap 70 µm to match the height of the ion from the trap. Using this procedure, the lens should project the image of the ion onto the EMCCD, though roughly aligned (out of focus, aberrations, etc.). Once the camera position is roughly known, the EMCCD is replaced with a CMOS camera (Guppy Pro F-503B) with 2.2 µm pixels. The initial camera placement is performed with the EMCCD because the CMOS camera does not have as much sensitivity in the UV, therefore requiring a longer acquisition time to detect an adequate number of photons from the ion.

Now that the lens is roughly aligned to the ion, finer steps are needed to fully correct for the residual aberration. Figure 6.3 shows the schematic of the different ways used to image the ion in order to adequately characterize the aberrations as well as fiber couple the scattered photons. A 50/50 pellicle beamsplitter (BS1) is
Figure 6.3: Schematic for the alignment of the high NA lens as well as the fiber coupling of the photons scattered by the ion. BS1 is used to direct the scattered photons onto the PMT in order to monitor the ion while the alignment is performed. Cam1 is used for the initial alignment of the high NA lens, and then the second imaging stage along with Cam2 is inserted to finely adjust the high NA lens alignment. The ion is imaged from the back of the vacuum chamber through the 0.15 NA objective and onto Cam3. Light from the fiber stage is then directed through the vacuum chamber and its image is overlapped with the ion’s on Cam3. At this point, small adjustments can be made to detect a fiber coupling signal from the ion.

used to direct half of the photons to a PMT and half to the CMOS camera (Cam1). At this imaging point, the ion is magnified by \( \sim 8.6x \), so the diffraction limited spot size is approximately the size of a single pixel on the CMOS camera. After the first rough alignment, however, the image will most certainly not be diffraction limited so additional alignment can be performed to a certain extent.

A second stage imaging system (not shown in figure) is inserted to magnify the image of the ion by another factor of \( \sim 25 \). Due to the larger ion image, the EMCCD can be used to record the image in order to have a higher sensitivity. In order to diagnose the aberrations present in the system, the second stage imaging system can be translated along the optical axis to provide a series of images at the EMCCD. By analyzing how the image of the ion (nominally a point source) changes as it is moved through the focus of the lens, we can match these images with simulations from Zemax with various tilts and decenter of the high NA lens, as shown in Figure 7.
Figure 6.4: Images of the ion as the detector is moved through the focus of the image. The step size between the captured images is approximately 125 µm.

Figure 6.5: Simulation using Zemax Optic Studio of the through focus image of the ion with introduced tilt/decenter misalignment of the high NA lens.
Figure 6.6: (a) Aberrated image of a single ion as seen through a misaligned high NA lens. (b) Image of the ion after proper alignment of the high NA lens.

6.4 and Figure 6.5 respectively. The pellicle beamsplitter (BS2) can be replaced with a mirror to direct the light from the ion to a different second stage of imaging and the EMCCD (Cam2). The second stage of imaging consists of an asphere lens (f = 11mm, Thorlabs A220TM-A) which magnifies the image of the ion ~480x at a location 500 mm away from the asphere.

The most prevalent aberrations in the system come from coma, defocus, and astigmatism. Figure 6.6 (a) shows an image of the ion after the 480x imaging stage with significant aberration. Comatic aberration due to off axis alignment is identified by the distortion or the tail. To correct for this, the high NA lens tilt and corresponding x/y translation is adjusted until the distortion is only along either the x or the y axis. The same adjustments are performed for the orthogonal direction so that any visible distortion is gone. The remaining aberrations are astigmatism and defocus. The astigmatism can be identified by the fact that rays in different planes focus in different image planes. This can be caused by unintentional curvature of
any of the optical surfaces that cause the optical system to be axisymmetric. This could be due to warping of the vacuum window or warping of the lenses during their assembly or integration with the optomechanics. In order to correct for the astigmatism in this system, a cylindrical lens is inserted before the first image plane. By measuring the difference in length along the optical axis at which the tangential rays and sagittal rays focus, the astigmatism is simulated in the Zemax model as a curvature of the vacuum window. The radius of curvature and placement of the cylindrical lens is then optimized to correct the astigmatism. The cylindrical lens is mounted on a rotation stage in order to match the curvature of the lens with the angle of the astigmatic aberration. Figure 6.6 (b) shows the resulting corrected image of the ion. The final aberration, defocus, can be optimized by translating the high NA lens along the optical axis and minimizing the image on the camera. However, the final adjustments are made by maximizing the fiber coupling of the scattered photons.

6.4 Fiber Coupling Alignment

Once the high NA lens is aligned sufficiently, the alignment of the fiber to the ion is performed. The first step is to align the 0.15 NA objective to image the ion through the 1.33” viewport on the back flange and onto a camera. The NA of the back objective is limited by the long distance from the ion to the back viewport (~65 mm). For the initial fiber alignment, 370 nm light is coupled into the detector side of the fiber such that the light is directed onto the ion trapping location. The high NA lens is translated towards the ion in order to image the surface of the trap with Cam1. The fiber stage is positioned such that the 370 nm light from the fiber is imaged onto the surface of the trap and can be seen by Cam1. The fiber position is then adjusted to send the light through the slot in the center of the trap between the two center DC electrodes that indicate the center of the trapping region. The 370 nm light will travel through the chamber and out of the 1.33” viewport on the back
flange, collected by the 0.15 NA imaging objective, and focused onto Cam3. The fiber stage is adjusted to overlap the 370 nm light from the fiber with the image of the ion. Then, the high NA lens is translated along the optical axis to minimize the spot size of the fiber light. The output of the fiber is then mounted to the face of a PMT with a 6 nm bandpass filter. At this point, the fiber stage is carefully adjusted until photons are detected through the fiber by the PMT.

Optimizing the fiber coupling includes adjusting all twelve degrees of freedom: x/y tilt for fiber and lens, x/y/z translation for fiber and lens, and rotation and z translation of the cylindrical lens. With the cylindrical lens and optical filter in the image path, the image of the ion cannot easily be checked with the second stage imaging without losing all of the optimization work. To profile the beam without using the cameras, we measure the fiber coupling percentage as a function of the fiber position. Figure 6.7(a) and Figure 6.7(b) show the x and y count rate of the collected photons from the ion with the fiber at different axial locations as a function of radial displacement. The solid lines are Gaussian fits to the data. This data was taken without the cylindrical lens and astigmatism correction, so the focus of the two profiles occurs in different axial locations. Figure 6.7(c) and Figure 6.7(d) show the same plots with data after correcting the aberrations of the image.

6.5 Single-mode Fiber Coupling Efficiency Calibration

The single-mode fiber coupling percentage is experimentally measured by comparing the total system efficiency of the photon collection using free-space propagation and through a single-mode fiber. For this experiment, the HOA trap is used to trap a single $^{174}$Yb$^+$ ion 75 µm above the surface. The high NA lens directly images the ion and collects 10% (0.6 NA) of the scattered photons from the ion. Initially, the ion is focused through an iris and a 6 nm bandpass filter onto the PMT. The iris acts as a spatial filter to block any scattered light from the laser beam clipping on the trap.
Figure 6.7: (a) Count rate as a function of displacement of the fiber in the $x$ direction. The data for each axial position of the fiber is fitted to a Gaussian curve. The focus of the image in the $x$ plane along the axial direction can be determined by the minimum waist of the Gaussian fit. (b) Count rate as a function of displacement of the fiber along the $y$ direction. Poor Gaussian fits to the measured data indicate residual aberration in the $y$ plane of the image. By comparing the axial location where the minimum waist occurs with the location for the $x$ plane, it is evident that astigmatism is present in this system. (c) and (d) show the same two experiments, but after aberration correction.
as well as any background light from the environment. For detection of the photon through a single-mode fiber, the photons from the ion are instead coupled into the single-mode fiber using the methods described above. The fiber acts as a spatial filter much like the iris, so no additional spatial filtering is needed. An identical 6 nm bandpass filter is used to filter the 935 nm scatter from the repumping beam clipping the edge of the trap. The end of the fiber is then directed onto an identical PMT as before.

The $^{174}$Yb$^+$ isotope can be modeled as a simple two-level system with a scattering rate on resonance of

$$R_{174Yb} = \varepsilon \left( \frac{\Gamma}{2} \right) \left( \frac{I/I_{sat}}{1 + I/I_{sat}} \right)$$

where $\varepsilon$ is the collection efficiency, $I_{sat} = 51 \text{ mW/cm}^2$, $\Gamma = 2\pi \times 19.6 \text{ MHz}$. All units in this work are SI units, and the intensity is defined to be $I = cn\varepsilon_0|E|^2/2$, where $c$ is the speed of light, $n$ is the refractive index of the medium, $\varepsilon_0$ is the vacuum permittivity, and $|E|$ is the electric field. By varying the intensity of the detection beam and measuring the scattering rate, the collection efficiency can be calculated by fitting the data to Equation 6.1.

Figure 6.8 shows the effective scattering rate for the detection of the photons by the PMT and the fiber-coupled photons with a PMT. Each point in the plot is the average number of measured photons in a set detection period for 300 experiments. The ion is first cooled with 370 nm light red detuned of the resonant transition. Then, the cooling beam is turned off and the resonant 370 nm detect beam is turned on. During this time interval, the FPGA counts the number of pulses received from a detector. After the 300 experiments for a single point, the power of the detection beam is increased by increasing the signal power to the AOM. After the scan, the data is fit to Equation 6.1 and the collection efficiency is extracted. By measuring the collection efficiency of the free-space PMT and the PMT through the fiber, we
Figure 6.8: The measured effective scattering rate of a single $^{174}$Yb$^+$ ion as a function of detect beam power. The fit curve for each data set is the scattering model of a simple two-level system: $a(bP/(1 + bP))$, where $a = \varepsilon \Gamma / 2$ and $bP = I/I_{\text{sat}}$.

are able to determine the fiber coupling percentage. The total fiber coupling for a single-mode fiber is calculated to be $\sim 24\%$. The $^{174}$Yb$^+$ ion emits an equal fraction of sigma- and pi-polarized light and the single-mode fiber rejects the pi-polarized light, so the total fiber coupling percentage for sigma-polarized light is $\sim 48\%$. This is a significant improvement over the current state-of-the-art experiments coupling scattered light from a $^{171}$Yb$^+$ ion into a single mode fiber, which was previously $\sim 14\%$ (Hucul et al., 2015). The $b$ coefficient in the fit equation describes the saturation power of the atomic transition. Ideally, the $b$ fit values would be identical for each experiment, but intensity fluctuations or beam pointing errors can cause this value
to change from scan to scan. However, in the time scale of a single scan, the fitted value for the saturated power coefficient is determined to be constant.

6.6 Superconducting Nanowire Single Photon Detectors

Previous qubit state detection experiments have been performed using PMTs as the single photon detector (Noek et al., 2013). The main disadvantages of using PMTs is their low quantum efficiency (QE) and their relatively high dark count rate ($R_{DC}$). The QE of the PMT was specified to be 32% and the $R_{DC}$ of the detector was measured to be 6.5 Hz. To help overcome these limiting factors, the National Institute of Standards and Technology (NIST), the Jet Propulsion Lab (JPL), and Lincoln Labs have recently developed fabrication processes to pattern nanowire-sized superconducting materials to be used as photon detectors (Beyer et al., 2015; Najafi et al., 2015). The superconducting nanowire single photon detector (SNSPD) can be designed for specific wavelengths to have high detection efficiency (DE), low $R_{DC}$, and low detection jitter. In this work, the DE describes the conversion efficiency of an incident photon to a measured detection pulse. For the application of photon detectors in ion trap quantum computing experiments, the main focus will be on the DE and $R_{DC}$.

In a normal conductor, the flow of electric current can be visualized as a stream of individual electrons moving through an ionic lattice. The electrons can collide with particles in the lattice and transfer energy to the lattice which is converted into heat. This loss of energy is the phenomenon of electrical resistance and the heat transfer is Joule heating. However, superconducting materials exhibit zero electrical resistance. When a material is superconducting, the flow of electrons is now described as bound pairs of electrons (Cooper Pairs) instead of individual electrons. The formation of the Cooper Pairs is dependent on the thermal energy of the lattice. If the energy of the lattice ($kT$) is larger than the energy required to produce the Cooper Pairs,
Figure 6.9: (1) Under normal conditions and operating below $T_c$, the nanowire is superconducting. (2) An incident photon is absorbed by the SNSPD and (3) creates a local hot spot in the wire. (4) This hot spot spreads throughout the device and raises the device temperature above $T_c$. The device becomes resistive, which can be measured with an appropriate readout circuit. The cooling system returns the SNSPD back below $T_c$ and the device returns to its original superconducting state (Natarajan et al., 2012).

than the material becomes normal and the flow of electrons is impeded. This critical temperature ($T_c$) is typically below 10 K for the commonly used superconducting materials. The superconducting nature of the material is also dependent on the amount of current supplied to the device. The critical current ($I_c$) describes the current at which the material will become resistive.

The SNSPD is cooled below its $T_c$ and is biased with a DC current that is close to $I_c$. A single photon incident on the detector breaks local Cooper Pairs in the device which reduces the $I_c$ to less than the DC bias current. This forms a localized non-superconducting region in the device. This hotspot has a finite resistance which translates to a voltage drop that can be measured by a detection circuit. As the SNSPD cools, it is able to detect another incoming photon. The DE is optimized by the selection of material and the geometry of the nanowire (Engel et al., 2013; Marsili et al., 2012). The optical bandwidth of the detector is also dependent on the geometry, but it can be further optimized by constructing a resonant structure on the device. For the following work, the detector material is molybdenum silicide (MoSi).
Figure 6.10: Picture of the cryostat system and the three cooling stages. The SNSPDs are attached to the coldfinger at the bottom of the structure.

6.6.1 Cryostat System

As mentioned above, the SNSPDs need to operate at cryogenic temperatures below 10 K. Specifically for the device used in the following experiments (MoSi), the $T_c$ is $\sim$3.4 K. Standard closed-cycle cryocoolers can reach 4 K, so an additional cooling system is needed to reach temperatures below $T_c$. The system used in these experiments consists of two refrigeration systems: a Sumitomo Gifford-McMahon (GM) style closed-cycle system (4 K base temperature) and a single-stage sub-Kelvin $^4$He cooler from Simon Chase Cryogenics ($<1$ K base temperature). The GM cooler allows compressed helium regulated by an external compressor unit to quickly expand in a volume that is enclosed in a thermally conductive material and is in contact with the sample mount. The heat is removed from the sample stage through isothermal
expansion and is expelled out of the cryo-system. The first stage of this cooling system has 5 W of cooling power at 45 K, and the second stage has 200 mW at 4.2 K.

The sub-Kelvin cooler from Simon Chase Cryogenics uses evaporative cooling to reach temperatures below 1 K. The system is first cooled to 4 K by the GM cooler. Low pressure $^4$He is absorbed by a charcoal cryopump when the temperature reaches below 40 K. After absorbing the $^4$He in the initial cool down to 4 K, the charcoal is heated to 40 K. Since the charcoal pump is thermally isolated from the rest of the cooling system, the released $^4$He will liquify when it reaches the part of the system that is below its critical temperature. A gas-gap heat switch is activated to allow the liquid helium to flow to the coldfinger, which is in contact with the sample stage. The helium will then boil off and cool the sample to less than 1 K. Once all of the helium is boiled away, the cycle will need to be started again with the heating of the charcoal pump. The sub-Kelvin cooler has $\sim 100 \, \mu m$ of cooling power at 1 K.

6.7 SNSPD Detector Efficiency Calibration

The DE of the SNSPD is experimentally measured by comparing the total system efficiency of the photon collection using a PMT and the SNSPD. The total system efficiency is calculated by measuring the scattering rate of the $^{174}$Yb$^+$ ion as a function of the detect beam power, using the same setup and experimental procedure as detailed in section 6.5. In order to increase the detection efficiency, the 1.5 $\mu m$ core single-mode fiber was replaced with a 10 $\mu m$ core multi-mode fiber. Figure 6.11 shows the effective scattering rate for the detection of the photons by the PMT, the fiber-coupled photons with a PMT, and the fiber-coupled photons with two different SNSPDs with the same structure and material. Table 6.1 shows a summary of the collection efficiencies of each of the measurement methods.

For this experiment, the fiber coupling percentage is measured to be $\sim 63\%$. To
Figure 6.11: The measured effective scattering rate of a single $^{174}\text{Yb}^+$ ion as a function of detect beam power. The fit curve for each data set is the scattering model of a simple two-level system: $a(bP/(1 + bP))$, where $a = \varepsilon\Gamma/2$ and $bP = I/I_{sat}$.

determine the detector efficiency of the SNSPDs, use the equation

$$
\varepsilon_{sys} = \varepsilon_{PG}\varepsilon_{FC}\varepsilon_{fiber}\varepsilon_{det}
$$

(6.2)

where $\varepsilon_{sys}$ is the total system efficiency (shown in Table 6.1), $\varepsilon_{PG}$ is the collection percentage of the 0.6 NA lens (10%), $\varepsilon_{FC}$ is the previously mentioned fiber coupling percentage, $\varepsilon_{fiber}$ is the fiber and connector efficiency (73.1(8)%), and $\varepsilon_{det}$ is the detection efficiency. Using these measured values, the detection efficiency of the two SNSPDs are calculated to be $68.5\% \pm 1.2\%$ and $69.3\% \pm 1.1\%$, respectively.

It has been shown that the SNSPD detectors provide more than a factor of
Table 6.1: Summary of the collection efficiencies of various detection methods.

<table>
<thead>
<tr>
<th>Detection Method</th>
<th>Detection Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free-space PMT</td>
<td>2.310% ± 0.038%</td>
</tr>
<tr>
<td>Fiber PMT</td>
<td>1.469% ± 0.025%</td>
</tr>
<tr>
<td>Fiber SNSPD_1</td>
<td>3.184% ± 0.038%</td>
</tr>
<tr>
<td>Fiber SNSPD_2</td>
<td>3.253% ± 0.037%</td>
</tr>
</tbody>
</table>

two improvement on the overall detection efficiency of the system. Not only does the SNSPD provide a greater detection efficiency, this optical setup also exhibits a significant decrease in the dark count rate (< 100 mHz compared to 10’s of Hz for the PMT). These two factors make this detector technology very promising for high speed and high fidelity state detection.

6.8 State Detection Through an Optical Fiber

For this experiment, we trap a single $^{171}$Yb$^+$ ion over the central slot in the Sandia HOA trap and couple the scattered photons into a multi-mode fiber using the high NA lens. The large core of the multi-mode fiber (10 $\mu$m) allows for efficient coupling of both the $\pi$- and $\sigma_+,-$-polarizations of the $^{171}$Yb$^+$ ion. The ion is first prepared to the $|0\rangle$ state by applying a field resonant with the $^2S_{1/2}|F = 1\rangle \rightarrow ^2P_{1/2}|F = 1\rangle$ transition. The light resonant with this transition is generated by adding sidebands to the 370 nm cooling beam with a 2.1 GHz EOM. The 7th sideband (14.7 GHz) of this modulation is close to resonance with the $^2S_{1/2}|F = 0\rangle \rightarrow ^2P_{1/2}|F = 1\rangle$ transition, so the EOM power is optimally tuned to reduce the power in this sideband by minimizing the carrier. The carrier and sidebands can be measured using an optical cavity. The resulting error from the 7th sideband pumping out of the $|0\rangle$ state is $\tau(10^{-6})$ (Noek et al., 2013). Once the ion is pumped to the $|0\rangle$ state, a microwave field resonant with the hyperfine transition of the ion can be applied to rotate the ion to the $|1\rangle$ state. State-dependent florescence is then used to determine the state of the ion.
Figure 6.12: Typical histograms of the dark and bright state of the ion. This data was taken with a 500 $\mu$s detection interval with 11.4 mW/cm$^2$ beam intensity. The inset on the dark state histogram plot shows the events where the ion was pumped out of the dark state during the detection interval. The rate at which this happens depends on the beam intensity and the detection time. The bright state histogram can be modeled as a Poissonian distribution, with a tail corresponding to the events where the ion pumps dark at some point during the detection interval.

6.8.1 Magnetic Field Calibration

In order to achieve the optical scattering rate, the magnetic field strength and direction at the ion location is tuned. Coils are mounted to the top, sides and front of the vacuum chamber to provide magnetic field control in all three directions. The number of turns and the size of the coils are calculated to provide a sufficient magnetic field strength (typically $\sim$5 Gauss). The magnetic field at the ion location can be determined by measuring the Zeeman relative splitting of the three $^2\text{S}_{1/2}|F = 1\rangle$ levels. The frequency difference between $^2\text{S}_{1/2}|F = 1, m_f = 0\rangle$ and the $^2\text{S}_{1/2}|F = 1, m_f = \pm 1\rangle$ is $\delta_{\text{Zeeman}} = 1.4$ MHz/G. First, individual coils are adjusted one at a time to minimize the Zeeman splitting, which determines the coil current.
at which the magnetic field is zero for that direction. The top and side coil currents are fixed to set the magnetic field strength in that direction to be zero. The front coil current is then adjusted to produce a Zeeman splitting of 5 MHz.

### 6.8.2 Scattering Rate Calibration

The state detection process is dependent on three separate scattering rates: the scattering rate of the $|1\rangle$ state ($R_o$), the bright pumping rate ($R_b$), and the dark pumping rate $R_d$. The optimized scattering rate of the ion in the $|1\rangle$ state is given by the expression:

$$R_{o,\text{opt}} = \left(\frac{1}{3}\right) \left(\frac{\Gamma}{2}\right) \left(\frac{s_o}{1 + \frac{2}{3}s_o + \left(\frac{2\Delta}{\Gamma}\right)^2}\right)$$  \hspace{1cm} (6.3)

where $\Gamma = 2\pi \times 19.6$ MHz is the linewidth of the $^2P_{1/2}$ state, $s_o = 2\Omega^2/\Gamma^2$ is the on-resonance saturation parameter with a Rabi frequency $\Omega$, and $\Delta$ is the detuning of the detection from the $^2S_{1/2}|F = 1\rangle \rightarrow ^2P_{1/2}|F = 0\rangle$ cycling transition. The optimal scattering rate assumes a Zeeman splitting and detect beam polarization that minimizes the effects of coherent dark states (Noek, 2013; Berkeland and Boshier, 2002). For this work, the Zeeman splitting is fixed by the magnetic field strength at the ion to be $\delta_{\text{Zeeman}} = 2\pi \times 5.0 \text{MHz}$.

The dark pumping rate describes the rate at which the ion will pump to the $|0\rangle$ state after being initialized to the $|1\rangle$ state:

$$R_d \approx \left(\frac{2}{3}\right) \left(\frac{1}{3}\right) \left(\frac{\Gamma}{2}\right) \left(\frac{2\Omega^2}{\Gamma^2}\right) \left(\frac{\Gamma}{2\Delta_{\text{HFP}}}\right)^2$$  \hspace{1cm} (6.4)

for which $\Delta_{\text{HFP}} = 2\pi \times 2.1$ GHz is the hyperfine splitting of the $^2P_{1/2}$ energy level (Noek, 2013). The bright pumping rate is the rate at which the ion will off-resonantly pump to the $|1\rangle$ state after initially prepared in the $|0\rangle$ state and is expressed as:

$$R_b \approx \left(\frac{2}{3}\right) \left(\frac{\Gamma}{2}\right) \left(\frac{2\Omega^2}{\Gamma^2}\right) \left(\frac{\Gamma}{2(\Delta_{\text{HFP}} + \Delta_{\text{HFS}})}\right)^2$$  \hspace{1cm} (6.5)
where $\Delta_{HFS} = 2\pi \times 12.6$ GHz is the hyperfine splitting of the $^2S_{1/2}$ energy level (Noek, 2013).

The three scattering rates can be experimentally measured by preparing the ion in the $|1\rangle$ state and varying the detection time over which photons are collected. The average number of photons collected over a time $\tau$ can be fit to the function:

$$\bar{n}(\tau) = \int_0^\tau \varepsilon R_0 p_1(t) dt$$

(6.6)

with the conditions

$$\begin{cases}
\dot{p}_1 = R_b p_0 - R_d p_1 \\
p_0 + p_1 = 1
\end{cases}$$

(6.7)

where $\varepsilon$ is the detection efficiency and $p_{0,1}(t)$ are the probabilities of the ion in the $|0\rangle$ and $|1\rangle$ state, respectively. Solving the system of equations and the integral gives the following fit equation:

$$\bar{n}(t) = \left( \frac{\varepsilon R_0}{R_d + R_b} \right) \left( R_b + f - \frac{R_b}{R_d + R_b} \right) \left( 1 - e^{-(R_d+R_b)t} \right)$$

(6.8)

where $f$ is the bright state preparation fidelity. Figure 6.13(a) shows an example of the average number of photons detected for a given time with a set detection beam intensity. By fitting Equation 6.8 to this data, the dark pumping rate, bright pumping rate, and effective scattering rate can be extracted for the given detection beam intensity. The intensity of the detection beam is then varied to calculate more rates, and the resulting data for the dark, bright, and scattering rates can be seen in Figure 6.13 (b), (c), and (d), respectively.

6.8.3 State Detection Using Photon Time of Arrival

As previously mentioned, the standard state detection technique is state dependent florescence. With this method, a threshold is set to determine how many detected
Figure 6.13: (a) The average number of photons detected as a function of detection time for a beam intensity of 11.4 mW/cm$^2$. The fit of this data contains the information for the dark pumping, bright pumping, and effective scattering rate of the ion at this beam intensity. The (b) dark pumping, (c) bright pumping, and (d) effective scattering rates can be plotted as a function of beam intensity.

photons constitutes the ion to be in the bright state. With a sufficiently high scatter rate ($\varepsilon R_o$) and a dark count rate ($R_{DC}$) and bright pumping rate slow compared to the detection interval, the threshold can be set to zero. In this case, if a single photon is detected during the detection interval, then the qubit state is determined to be in the $|1\rangle$ state.

The errors associated with this state detection method can be classified as either a detection error of the bright state or a detection error of the dark state. The probability to detect zero photons for a given detection time ($t$) from an ion that is
initialized to the $|0\rangle$ state is

$$P_{t,d}(n = 0) = \frac{R_b}{\varepsilon R_o - R_b} e^{-R_{dc}t} \left[ e^{-R_b t} - e^{-\varepsilon R_c t} \right]$$  (6.9)

where $n$ is the number of scattered photons. Similarly, the probability to detect zero photons from an ion that was initialized to the $|1\rangle$ state for a given detection time ($t$) is

$$P_{t,b}(n = 0) = \frac{R_d}{\varepsilon R_o + R_d} e^{-R_{dc}t} \left[ 1 - e^{-(\varepsilon R_o + R_d)t} \right]$$  (6.10)

Therefore, the state detection error for the $|0\rangle$ state is $1 - P_{t,d}$, and the state detection error for the $|1\rangle$ state is $P_{t,b}$. The derivation of these probabilities can be found in Appendix A.

To experimentally measure the detection error probabilities in our system, we perform 100,000 experiments each for the case of the ion initialized to the $|0\rangle$ state and to the $|1\rangle$ state. To initialize the qubit to the $|0\rangle$ state, the 2.1 GHz sideband is added to the cooling beam for 60 $\mu$s. To initialize the qubit to the $|1\rangle$ state, we turn on the 2.1 GHz sideband for 60 $\mu$s to pump it to the $|0\rangle$ state, and then use the microwave to transition the qubit to the $|1\rangle$ state. In order to minimize the amount of amplitude error from either power drifts or poor $\pi$-time calibration, the B2 compensation sequence is used (Wimperis, 1994; Mount et al., 2015a). The B2 compensation sequence is able to correct amplitude errors $O(\varepsilon^2)$, where $\varepsilon$ is the fractional error of the applied signal (Merrill and Brown, 2014). The B2 consists of three extra rotations in addition to the initial rotation:

$$R(\theta_t, \phi_t) \xrightarrow{B2} R(\theta_t, \phi_t)R(\pi, \phi_t + \phi_{B2})R(2\pi, \phi_t + 3\phi_{B2})R(\pi, \phi_t + \phi_{B2})$$  (6.11)

where $\theta_t$ and $\phi_t$ are the target rotation and phase, respectively, and

$$\phi_{B2} = \cos^{-1}\left(\frac{-\theta_t}{4\pi}\right)$$  (6.12)
Figure 6.14: (a) The detection error probability of the ion prepared in the dark and bright state as a function of detection time for a given detection intensity. The dashed lines show the analytic solution for a measured dark pumping, bright pumping, and effective scattering rate assuming ideal state preparation for each case.

One of the disadvantages of using a compensated pulse sequence is the increase in time it takes to perform a gate. For the B2 sequence, the total time is related to the total rotation angle, $\theta_{total} = 4\pi + \theta_t$, so $t_{total} = \theta_{total}/\Omega$ where $\Omega$ is the Rabi frequency.

Once the ion is initialized to the appropriate state, the detect beam is turned on for 500 $\mu$s, and the total number of photons detected by the SNSPD as well as each individual photon's arrival time with respect to the beginning of the detect interval is recorded by the FPGA. The FPGA uses a 200 MHz clock to record the arrival times, resulting in a 5 ns timing resolution. After the data is recorded, the arrival time of the first photon in each of the 100,000 experiments is extracted. For the
\[ |0\rangle \text{ state, the state detection error for a particular detection interval is determined by the number of photons that arrive before that time. For the } |1\rangle \text{ state, the state detection error corresponds to the amount of photons that did not arrive by a particular detection time. Figure 6.14(a) shows both the } |0\rangle \text{ and } |1\rangle \text{ detection error probabilities as a function of detect time for a particular detection beam intensity (11 mW/cm}\ ^2\text{). Figure 6.14(b) shows the average detection error as a function of time for varying detection beam intensities. Figures 6.14(a) and (b) also include the analytical curves using Equations 6.9 and 6.10 using the rates experimentally measured in the previous section. The time at which the minimum detection error probability occurs corresponds to the optimal maximum wait time, } t_{\text{max}} \text{. At this point, the bright state error has reached a lower limit, and the dark state error will continue to rise due to the bright pumping rate (} R_b \text{) and dark counts.}

The current experiment is limited by the state preparation of the qubit. The dark state error can be caused by inefficiently pumping out of the } ^2\text{D}_{3/2} \text{ level with the 935 nm laser. During initialization, the ion has a 0.5\% probability of decaying from the } ^2\text{P}_{1/2} \text{ level to the } ^2\text{D}_{3/2} \text{ state. Ideally, the 935 nm laser excites the ion from the } ^2\text{D}_{3/2} \text{ level to the } ^3[3/2]_{1/2} \text{ state (lifetime of 37.7 ns), and the ion decays back to the } ^2\text{S}_{1/2} \text{ levels and into the cycling transition with a 98.2\% probability. However, if this occurs at the end of the initialization stage, the ion will pump out of the } ^2\text{D}_{3/2} \text{ level after the 2.1 GHz sideband is turned off, resulting in the ion left in the } |1\rangle \text{ state. The lifetime of the ion in the } ^2\text{D}_{3/2} \text{ is 52 ms, which is longer than the experimental time, so it will not decay to the } ^2\text{S}_{1/2} \text{ state without the stimulated emission from to the 935 nm light during the detection interval. If the 935 nm light is detuned from the } ^2\text{D}_{3/2} \rightarrow ^3 [3/2]_{1/2} \text{ transition or the polarization of the 935 nm beam is not optimal, then the pumping becomes less efficient. Figure 6.15 shows the dark and bright state detection error probabilities with an analytical fit curve with the state} \]
Figure 6.15: (a) The bright and dark state detection error probability as a function of detection time for a given detection beam intensity (11 mW/cm$^2$). Each curve is generated by measuring the time of arrival of the first photon in each of the 100,000 experiments. (b) Average detection error probability for varying detect beam intensities as a function of detection time. The dashed lines in each plot show the analytic solution for a measured dark pumping, bright pumping, and effective scattering rate. The state preparation is the only free parameter.
preparation error as the only free parameter:

\[
\text{DarkStateError} = (1 - \varepsilon_{\text{prep,}d})P_{t,d}(n > 0) + \varepsilon_{\text{prep},d}P_{t,b}(n > 0)
\]  

(6.13)

and

\[
\text{BrightStateError} = (1 - \varepsilon_{\text{prep,}b})P_{t,b}(n = 0) + \varepsilon_{\text{prep},b}P_{t,d}(n = 0)
\]  

(6.14)

where \(\varepsilon_{\text{prep,}(d,b)}\) is the corresponding state preparation error. The fit for the dark state preparation error is 3.3(3) \(\times 10^{-4}\), and the fit for the bright state preparation error is 1.44(5) \(\times 10^{-3}\).

The average detection time can be determined by averaging the time it takes to determine the state as bright and the time it takes to determine the state is dark. For the dark state, it will always take the maximum time, \(t_{\text{max}}\). However, for the bright state, the average detection time is proportional to the effective scatter rate (\(~1/(\varepsilon R_o)\)). For long \(t_{\text{max}}\), this will reduce the average state detection by approximately a factor of two, but this factor will decrease as \(t_{\text{max}}\) becomes closer to \(1/(\varepsilon R_o)\). Figure 6.16 shows the detection error probability of 200,000 experiments as a function of the average detection time for different detection beam intensities. For a detection beam intensity of 11 mW/cm\(^2\), the average detection time is 23.7 \(\mu s\) with 99.885(7)% detection fidelity. Increasing the detection beam intensity to 38 mW/cm\(^2\), the average detection time decreases to 15.0 \(\mu s\), but the detection fidelity decreases to 99.824(9)%. Table 6.2 compares these results the state detection using a single photon threshold with a two-event discrimination (TED) method, which at the time exhibited the highest fidelity and fastest speed for state detection of a ion qubit, used in a previous experiment (Noek et al., 2013).

6.9 Discussion and Outlook

While this experiment has shown more than a factor of two increase in coupling into a single mode fiber from previous experiments (Hucul et al., 2015), there are still areas
Figure 6.16: Average state detection error probability as a function of average detection time for different intensities of the detection beam. The average state detection error was determined from the result of 200,000 experiments. The error bars indicate the 1/e confidence interval.

that can be improved. The first improvements to this system should be to eliminate the fiber connector loss, use wavelength-optimized SNSPDs, and use larger NA fibers for better fiber coupling. Instead of using two fibers connected at the input of the cryostat system to deliver the photons to the SNSPD, a single continuous fiber can be used. The ~70% measured detector efficiency for the SNSPD can be increased for 370 nm light by optimizing the device structure and the materials used for the resonant structure that encapsulates the device. In conjunction with this, the device itself can be fabricated to have a larger active area which will allow for the use of larger core, high NA multi-mode fibers. The larger core fibers will allow for looser tolerances for the fiber coupling, which should, in turn, increase the overall coupling percentage.
Table 6.2: Summary and comparison of the average state detection times and errors for various detection beam intensities.

<table>
<thead>
<tr>
<th>Intensity (mW/cm²)</th>
<th>Time (µs)</th>
<th>Fidelity</th>
<th>Intensity (mW/cm²)</th>
<th>Time (µs)</th>
<th>Fidelity</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>53.4</td>
<td>99.879(7)</td>
<td>5</td>
<td>165.4</td>
<td>99.891(7)</td>
</tr>
<tr>
<td>11</td>
<td>23.7</td>
<td>99.885(7)</td>
<td>8</td>
<td>99.8</td>
<td>99.915(7)</td>
</tr>
<tr>
<td>23</td>
<td>16.6</td>
<td>99.862(8)</td>
<td>17</td>
<td>45.7</td>
<td>99.897(7)</td>
</tr>
<tr>
<td>38</td>
<td>15.0</td>
<td>99.824(9)</td>
<td>36</td>
<td>28.1</td>
<td>99.856(8)</td>
</tr>
</tbody>
</table>

Preliminary results show that by changing the 10 µm core fiber to a 50 µm core fiber with a larger NA, the fiber coupling increases from ~63% to ~95%. This implies that the fiber coupling in the previous experiments was limited in part by the NA of the fiber. The downside to using larger core fibers will be that this could increase the background counts, but proper light shielding and alignment should mitigate these concerns.
The results of this thesis suggest that a quantum computer based on trapped ions has a viable path towards scalability. This work provides a foundation on which future quantum information experiments can be based. The work in Chapter 3 highlights some of the hardware advancements that we made to make the ion trapping system more scalable. This includes minimizing the failure due to non-repeatability of the construction of particular components. For example, the vacuum chamber, custom back flange, and the UHV PCB allow for a simple blueprint to be followed in order to assemble a full quantum register. Hand-assembly of one hundred wires to create a vacuum compatible connector is no longer needed. The work developing the readout circuit for a 32-channel PMT also created a reliable and compact solution for the detection of single ions in a chain. Another common way to detect the state of individual atoms was to use the EMCCD and monitor the number of counts in a specified region for each ion. Although it does produce the results needed, this is a bulky and expensive solution.

One of the main scalable hardware demonstrations of this thesis was the MEMS based beam steering system. One of the challenges of implementing a trapped ion
based quantum computer is the addressability of single qubits. Although individual
addressing has been demonstrated in other systems, other technologies have suffered
from either high crosstalk (Debnath et al., 2016) or are not compatible with the
qubit scheme proposed for our quantum computer (Piltz et al., 2014). For the work
in Chapters 5 and 6 we proposed and demonstrated a scalable beam steering system
that enables individual addressing of qubits with minimal crosstalk (Crain et al.,
2014). This system is scalable in the sense that not only can a single laser beam
independently address multiple qubits, the system can be extended to steer multiple
beams independently (Knoernschild et al., 2009). The system demonstrated in this
thesis shows that the error on the neighboring qubits due to crosstalk of the address-
ing beam is less than the single qubit gate error demonstrated in similar experiments
in this lab (Mount et al., 2015a) and is below the error threshold for quantum error
correction schemes (Steane, 2003; Raussendorf and Harrington, 2007).

The last chapter details the steps necessary to extend local qubit operations to
long-distance operations by providing a fiber optic channel for the scattered photons
of a single ion. We are able to couple ~60% of the collected light by the high NA lens
into an optical fiber by fine control over the optomechanics of the lens and fiber. For
this work, these photons were used to demonstrate high speed, high fidelity state
detection using SNSPD. While previous experiments were limited in part due to the
low quantum efficiency of PMTs (Noek et al., 2013), SNSPDs can be designed to
have a much higher detection efficiency. With this technology, we can wait for only
a single photon to determine the state of the ion without the negative consequences
of high dark count rates or long detection times due to low detector efficiency.

7.1 Future Potential

Like the computing technologies that preceded the quantum computer model, this
first pass at a scalable solution is certainly not the most optimal. From the chal-
lenges and disadvantages learned from these sets of experiments, we can start to gain a better perspective on what it will take to finally realize a trapped ion-based quantum computer. For example, although the hardware for our vacuum chambers has improved significantly from previous generations, it is unrealistic to think that a full-scale quantum computer that requires hundreds or thousands of qubits can be built around such a large structure. The reason why the vacuum systems are as large as they are is mainly due to the vacuum pumps required to reach the pressures necessary for stable ion trapping and computations. One way that we propose to eliminate the need for these large pumps is by integrating the ion trap with a cryostat system. The ion trap can be packaged and sealed on its standard CPGA in a low vacuum environment (not necessarily UHV) and is placed within a 4 K cryostat system. A passive charcoal pump is placed inside the vacuum package beside the ion trap to help pump residual gasses at the low temperature. This means that the hardware required to provide an adequate vacuum environment for ion trapping is now the size of the cold finger housing of the cryostat and the compressor, but the compressor could be shared by other systems.

One of the other issues with the current system is the stability of the optics required for imaging and fiber coupling a trapped ion. Either due to mechanical vibrations or more likely thermal drifts, the large optomechanics used to align the high NA lens and fiber coupling will drift over time. This problem can also be addressed by moving to a more compact ion trapping system. The current setup requires an 8” beam height off of the optical table, which results in large and potentially unstable mounts. One of the other main issues with the current optical setup is that we have twelve degrees of freedom just for the fiber coupling alignment alone. We have identified the critical degrees of freedom that are required to maximize the fiber coupling of the photons from the ion, so future designs can be tailored to minimize the amount of degrees of freedom. For example, the $x$ and $y$ position of the high NA
Figure 7.1: Schematic of connected quantum registers in order to perform quantum interactions between qubits in separate registers. The coupled photons from each quantum register are sent to an optical cross-connect switch. The cross-connect directs pairs of photons onto beam splitters for interference. Heralded entanglement between remote qubits occurs with the coincident measurement of the photons on the output detectors.

lens is fairly insensitive, especially when compared to machining tolerances. If the position of the ion is known relative to some machined surface, the high NA lens can be attached to a mount that is machined to place it in the correct $x/y$ plane. Also, with further investigation, the source of the astigmatism in the imaging optics should be identified, eliminating the need for the cylindrical lens. With proper machining and planning, the tilt of the fiber should also not be a concern while aligning the fiber coupling setup. This results in only actuating the $z$ and the two tilt angle of the high NA lens and the $x/y/z$ of the fiber. If these are controlled with closed-loop actuators, then the alignment process can in principle be automated.

The last step in realizing a full quantum register in our lab is to demonstrate remote entanglement to couple remote trapped ion quantum registers (Figure 7.1, or initially, demonstrate entanglement between the ion qubit and its scattered photon. As mentioned in Chapter 1, the communication qubit in the quantum register emits a photon who has two distinguishable states (either frequency or polarization)
Figure 7.2: (a) An ion prepared in the $|0\rangle$ state is transitioned to the $^2S_{1/2}|F = 1, m_f = 1\rangle$ state via a fast Raman gate. (b) The ion is then resonantly excited to the $^2P_{1/2}|F = 1, m_f = 1\rangle$ state with a $\pi$-polarized pulse, where it then (c) spontaneously emits a photon through one of the three decay channels. The $\pi$-polarized photon is filtered by the single-mode fiber and the other two photons form the frequency basis of the photonic qubit.

which is entangled with the ion qubit. For example, an entangled state between the communication qubit an the emitted photon could be:

$$|\psi\rangle = |0\rangle |\nu_0\rangle + |1\rangle |\nu_1\rangle$$

(7.1)

where $|\nu_0\rangle$ and $|\nu_1\rangle$ are the two distinguishable frequency states of the emitted photon.

In order to produce this entangled state (Figure 7.2), the ion is first pumped to the $|0\rangle$ state. A fast Raman transition is then used to rotate the qubit to the $^2S_{1/2}|F = 1, m_f = 1\rangle$ state. From there, a $\pi$-polarized resonant pulse excites the ion to the $^2P_{1/2}|F = 1, m_f = 1\rangle$ state where the ion will either spontaneously emit a photon to back to the $^2S_{1/2}|F = 1, m_f = 1\rangle$ state or to one of the two qubit states ($^2S_{1/2}|F = 1, m_f = 0\rangle$ or $^2S_{1/2}|F = 0\rangle$). The $\pi$-polarized light will be filtered by the single mode fiber, so we are left with the two frequency distinguishable photons.

While polarization distinguishable qubits have been demonstrated in other labs (Maunz et al., 2007; Hucul et al., 2015), the remote atom-atom entanglement generation has been partly limited by the light collection. The probability at which the
two remote ions are entangled by simultaneously emitting a photon and interfering the photon on a beamsplitter is expressed as

\[ P_{\text{ent}} = p_{\text{bell}} \left[ P_{\pi} P_{S_{1/2}} D_{\text{eff}} T_{\text{fib}} T_{\text{opt}} \frac{\Omega}{4\pi} \right]^2 \]  

(7.2)

where \( p_{\text{bell}} \) is the probability of selecting two of the four Bell states of light, \( P_{\pi} \) is the probability of exciting the ion with the resonant laser pulse, \( P_{S_{1/2}} \) is the probability to decay from the \( ^2P_{1/2} \rightarrow ^2S_{1/2} \), \( D_{\text{eff}} \) is the detector efficiency, \( T_{\text{fib}} \) is the fiber coupling percentage and transmission, \( T_{\text{opt}} \) is the transmission of the optical components, and \( \frac{\Omega}{4\pi} \) is the solid angle collected by the imaging lens (Hucul et al., 2015). With our improved light collection and detection methods, we could reasonably expect to increase the 4.5 sec\(^{-1}\) entanglement rate by an order of magnitude due to the increase in fiber coupling (\( \sim 60\% \) compared to \( \sim 14\% \)) and the increase in detector efficiency (\( \sim 70\% \) compared to \( \sim 35\% \)) (Hucul et al., 2015).

Overall, the work I performed in this thesis provides a path towards scalable quantum information processing using trapped ions. The system built and characterized can represent a single quantum register with all of the necessary resources to perform local gates as well as high fidelity readout and provide a photonic link. The main fundamental advancements shown in this thesis include individual addressing of qubits with low crosstalk and high efficiency fiber coupling of scattered photons from a trapped ion into an optical fiber for fast state detection. Our lab has also made significant progress toward multi-qubit gates not mentioned here, and with a fully functional second system, we will have the necessary resources to create a photonic link between two independent quantum registers. With the other advancements mentioned above, this work shows a promising path towards a fully scalable quantum computer architecture.
Appendix A

Derivation of Analytic State Detection Error Probabilities

When analyzing the bright and the dark state (|1⟩ and |0⟩) photon detection, the histograms can be represented by simple Poissonian distributions:

\[
P(k \text{ events in interval}) = \frac{\pi_b^k e^{-\pi_b}}{k!}
\]  \hspace{1cm} (A.1)

where \( \pi_b = (\varepsilon R_o + R_{dc})t \) and \( \pi_d = R_{dc}t \) for an effective scattering rate \( (\varepsilon R_o) \) and dark count rate \( (R_{dc}) \). However, this simple model does not fully describe the detection probability if the ion transitions during the detection interval. We can assume that the probability that the ion transitions more than once during a detection interval is small, so we can analytically calculate the new distributions.

We can start by specifying an initial photon collection rate given by \( R_1 \), a state transition rate \( R_t \) that changes the ion from its initial state to one that has a photon collection rate \( R_2 \). Assuming that all photon collection and state transition events are Poissonian, the probability of detecting \( n \) photons in a detection interval \( t \) is
given by:

\[ P(n; t, R_1, R_2, R_t) = \sum_{k=0}^{n} \int_{0}^{t} d\tau P_p(k; R_1\tau)\tilde{p}(\tau, R_t)P_p(n - k; R_2(t - \tau)) \]  

(A.2)

where \( P_p(n; \bar{n}) \) is the Poissonian probability of detecting \( n \) photons given \( \bar{n} \) expected photons, and \( \tilde{p}(t, R) = \frac{d}{dt} (1 - e^{-Rt}) = Re^{-Rt} \) is the probability density for a non-zero number of Poissonian events. This integral can be explained as the probability of detecting \( k \) photons in a detection interval \( \tau \) with a collection rate \( R_1 \) before the ion transitions to a state with a collection rate of \( R_2 \), and then in the remaining time \( t - \tau \), collecting \( n - k \) photons. With the proper probability equations inserted into equation A.2, we get:

\[ P(n; t, R_1, R_2, R_t) = \sum_{k=0}^{n} R_t e^{-R_2t} \int_{0}^{t} d\tau \frac{(R_1\tau)^k(R_2t - R_2\tau)^{nk}}{(k!(n - k)!)}e^{-(R_1 + R_t - R_2)\tau} \]  

(A.3)

By performing integration by parts, we find that only the terms where \( k = 0 \) and \( k = n \) remain. Solving total sum and integral gives:

\[ P(n; t, R_1, R_2, R_t) = \left( \frac{R_t}{R_1 + R_t - R_2} \right) ^n \left[ e^{-R_2t} \sum_{k=0}^{n} \frac{(R_1 + R_t - R_2)^k(R_2t)^k}{k!(R_1 - R_2)^k} - e^{-(R_1 + R_t)t} \sum_{k=0}^{n} \frac{(R_1 + R_t - R_2)^k(R_1t)^k}{k!(R_1 - R_2)^k} \right] \]  

(A.4)

The sum of all of the terms in this distribution is equal to the total probability of undergoing a non-zero number of transitions. The total probability distribution for state collection is given by the sum of the transition distribution and the Poissonian distribution and is weighted by the probability of having zero transition events:

\[ P(n; t, R_1, R_2, R_t) = P_t(n; t, R_1, R_2, R_t) + e^{-R_2t}P_p(n; R_1t) \]  

(A.5)

In order to determine the photon detection probability for the \( |1\rangle \) and \( |0\rangle \) state, we can substitute in the appropriate rates into Equation A.4. For the bright state, the
ion starts in the detection cycling transition so \( R_1 = \varepsilon R_o + R_{dc} \) and can transition to the dark state at the dark pumping rate \( R_d \). Once in the \(|0\rangle\) state, the only detection events will come from dark counts, at a rate of \( R_{dc} \). If the ion is initialized to the dark state, the probability of detecting counts is dependent on \( R_{dc} \) until it transitions to the bright state rate, which occurs at the bright pumping rate, \( R_b \). From there the detection probability is again dependent on the rate of the detection cycling transition plus the dark count rate. The full expressions for the probability of detection \( n \) counts in a detection time interval \( t \) is:

\[
P_{t,b}(n) = \frac{R_d e^{-R_{dc}t}}{\varepsilon R_o + R_d} \left( \frac{\varepsilon R_o}{\varepsilon R_o + R_d} \right)^n \left[ \sum_{k=0}^{n} \frac{(\varepsilon R_o + R_d)^k (R_{dc}t)^k}{k!(\varepsilon R_o)^k} - e^{-(\varepsilon R_o + R_d)t} \sum_{k=0}^{n} \frac{(\varepsilon R_o + R_d)^k (\varepsilon R_o + R_{dc}t)^k}{k!(\varepsilon R_o)^k} \right] \tag{A.6}
\]

and

\[
P_{t,d}(n) = \frac{R_b e^{-R_{dc}t}}{\varepsilon R_o - R_b} \left( \frac{\varepsilon R_o}{\varepsilon R_o - R_b} \right)^n \left[ e^{-R_{bt}t} \sum_{k=0}^{n} \frac{(\varepsilon R_o - R_b)^k (R_{dc}t)^k}{k!(\varepsilon R_o)^k} - e^{-(\varepsilon R_o - R_b)t} \sum_{k=0}^{n} \frac{(\varepsilon R_o - R_b)^k (\varepsilon R_o + R_{dc}t)^k}{k!(\varepsilon R_o)^k} \right] \tag{A.7}
\]


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Biography

Stephen Gregory Crain was born in Little Rock, AR on September 9th, 1987 and spent his childhood in Conway, AR. He graduated from Conway High School in 2006 and went on to pursue a degree in electrical engineering at the University of Arkansas. While attending the University of Arkansas he worked for Dr. Magda El-Shenawee and her computational electromagnetics group. Stephen earned his B.S. in Electrical Engineering in 2010 with honors and decided to pursue his doctorate at Duke University. Stephen entered Duke University as a NSF Graduate Research Fellow and John T. Chambers Fellow and began his work with Dr. Jungsang Kim. While in Dr. Kim’s group, Stephen worked on various projects in the effort to design an scalable quantum computer. Stephen’s projects included designing and constructing a MEMS-based beam steering system for the individual addressing of trapped ions as well as the coupling of scattered photons from a single trapped ion into an optical fiber. Stephen finished his PhD work in the spring of 2016.