Optical cavity integrated surface ion trap for enhanced light collection

Francisco Martin Benito

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Optical cavity integrated surface ion trap for enhanced light collection

by

Francisco M. Benito

B.S.E.E. Universidad Ricardo Palma, 1996
M.S.E.E. The University of New Mexico, 2011

DISSERTATION

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Dedication

A Victoria, Joaquín y Verónica
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Abstract

Ion trap systems allow the faithful storage and manipulation of qubits encoded in the energy levels of the ions, and can be interfaced with photonic qubits that can be transmitted to connect remote quantum systems. Single photons transmitted from two remote sites, each entangled with one quantum memory, can be used to entangle distant quantum memories by interfering on a beam splitter. Efficient remote entanglement generation relies upon efficient light collection from single ions into a single mode fiber. This can be realized by integrating an ion trap with an optical cavity and employing the Purcell effect for enhancing the light collection. Remote entanglement can be used as a resource for a quantum repeater for provably secure long-distance communication or as a method for communicating within a distributed quantum information processor. We present the integration of a 1 mm optical cavity with a micro-fabricated surface ion trap. The plano-concave cavity is oriented normal to the chip surface where the planar mirror is attached underneath the trap.
chip. The cavity is locked using a 780 nm laser which is stabilized to Rubidium and shifted to match the 369 nm Doppler transition in Ytterbium. The linear ion trap allows ions to be shuttled in and out of the cavity mode. The Purcell enhancement of spontaneous emission into the cavity mode would then allow efficient collection of the emitted photons, enabling faster remote entanglement generation.
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Chapter 1

Introduction

1.1 Overview

Information takes the form of physical attributes assigned to parameters which can be understood as real or abstract concepts. These physical systems contain encoded information in their states[37]. Classical physical information can be quantified by the number of distinguishable states described by a system. Similarly, in quantum information the physical information is stored in the state of a quantum system. The difference between these two types of information is that in classical information we can select a definite distinguishable state, roughly speaking, a true value, whereas quantum information has a continuous-like value which is accounted for by means of probabilities. Mathematically, the unit of classical information is depicted by the “bit” and for quantum information is depicted by the “qubit”[78] [65]. A bit is the representation of a two state system, such as true or false logic, on or off state, or any other attribute for these two values. Similarly, a qubit is the depiction of a two state quantum system, but differs from the classical two state systems by the fundamental quantum property of superposition. Hence, a two state quantum mechanical system
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\(|0\rangle\) and \(|1\rangle\) can be described as the linear combination of two independent states with different continuous amplitudes \(\alpha\) and \(\beta\). The \(\alpha\) and \(\beta\) amplitudes are real positive values and can vary continuously, as in:[53]

\[ |\psi\rangle = \alpha |0\rangle + \beta |1\rangle \]  

(1.1)

The information encoded in bits or qubits can be employed to process, transmit, and receive data between two parties. Classically, the bit of information is transmitted to or received from a second party through a physical transmission medium, for instance in a copper wire, where the information is encoded in electrical voltage, or in a fiber cable, where the information is encoded in photons. Likewise, a qubit will require a physical transmission medium to transport the quantum information, but the methods and techniques are not as straightforward as in classical information. The qubit, because of its quantum nature, has different fundamental features, which we summarize here:

- A qubit is in a superposition, which is observed as the interference of two or more states.

- Entanglement is the physical phenomenon when a pair or a group of particles interact with each other and become interlaced and behave as a single system. Entangled particles are correlated with each other even though they are separated spatially. \([25]\) \([64]\)

- A qubit cannot be copied or erased, non-cloning theorem, non-deleting theorem. \([77]\) \([55]\)

- A qubit can transfer its information with the aid of quantum teleportation. Quantum teleportation involves distributing entanglement and a classical bit of information. This classical information is used in the recovery of the original
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quantum state [13] [78] [53]. Another advantage of entanglement is that it allows eavesdroppers to be detected.

Researchers have demonstrated several different types of physical qubits including superconducting Josephson junctions[20] [46], atoms in optical lattices[16], quantum dots[52] [34], photons [57] and trapped ions [11].

Of these implementations trapped ions are one of the strongest contenders for realizing qubits. This qubit could be stored in different ways, such as in the internal energy structure of the valence electron [11], as in the two ground hyperfine states or between a ground state and a long lived excited state. These qubits receive the name of “hyperfine qubits” and “optical qubits”, respectively[36]. Two of the benefits of a hyperfine qubit are the particular sub-levels(clock states) that are well isolated from magnetic fields that could disturb them and long lived decay times.

Experimentally, trapped ion systems have demonstrated robust qubit [40] [31] performance including, long storage times and have a high fidelities for basic quantum computing operations, high fidelity understood as high accuracy. These qubits can be stored in a quantum register where quantum information can be stored as in a memory for classical computing.

Two or more ion qubits can process and transfer quantum information between them by means of their quantized motional states shared through their Coulomb interactions , which can be excited using laser light impinging on the ion. However, in a large chain of trapped ions the manipulation of individual qubits is more difficult due to single ion addressing errors from the laser’s pulses applied to induce transitions in the internal states of the ion during the quantum computations. Another major source of errors for a large chain of ions is the coupling of undesired motional modes,
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which are part of the trapped ion chain, but are not participating in the quantum operations[76].

A scheme to mitigate the errors due to the undesired motional modes in a long chain of trapped ions is to segment the ion trap by regions, such that the chain is separated and can be connected by moving the ions. One region could be used as a memory bank and the other used as the interaction region where the quantum computations occur. One way to realize this type of scheme is to transform a 3D linear Paul trap into a planar Paul trap, where several ion traps can be created and the ion can be transported from one region to another by applying voltage to particular control electrodes[31]. In turn, this architecture enables the connectivity of small units in order to build up a large scale ion trap for quantum computation.

One way to communicate from one of these units to another in a coherent way is via emitted photons of the trapped ions, where the quantum communication is achieved by teleporting these qubits of information. The scalable distribution of quantum information in a quantum network is also a prerequisite for the creation of a quantum repeater for secure long-distance communication[51] [24].

The entanglement of two trapped ions spatially separated by a large distance, requires first the entanglement of the trapped ion with its emitted photon[12]. The photons emitted are collected and coupled into a single mode fiber which is directed to a coincidence detection system comprised of a 50-50 beam splitter and photomultiplier tubes on the transmission and reflection output ports. If the photons are temporally matched they arrive at (the coincidence detection system at the same time), have the same spatial mode, and are matched in frequency and polarization, they can interfere at the beam splitter. In this way, a pair of qubits encoded into the hyperfine qubit states of a trapped ion separated by a large distance can be remotely
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entangled. In the experiment developed by Moehring et. al [49], for heralded entanglement, they demonstrated coincidence detection about every 8 minutes, between two qubits separated by 1 meter of distance and collecting the emitted photons using an objective lens with NA of 0.23. Moehring suggested that the best way to improve the entanglement process rate between qubits should be increasing the collection rate of emitted photons by each ion. This can be accomplished by the use of an objective lens with a large NA, in order to cover as much of the solid angle of the emitted photon. Recent experiments using objectives with a large NA = 0.63 [29] improved the light collection efficiency rate to 4.5 Hz, observing entanglement rates faster than the qubit decoherence times. However, the utilization of a large NA for light collection requires that the lens is closer to the ion, and it would be necessary to use additional lenses for correction of optical aberrations, making the optical system more bulky and difficult to scale. A second approach to increase the light collection efficiency uses the integration of an optical cavity along an ion trap. An ion located in the waist of the optical cavity experiences the inhibition or enhancement of its spontaneous emission properties. Moreover, most of the spontaneous emission by the ion inside the cavity would travel through the cavity mode and in this way we could collect in a more efficient manner the photon with encoded information emitted by the qubit.

This research work is focused on demonstrating a cavity-integrated in a micro fabricated surface ion trap for enhanced collection efficiency. In this proposal a planar linear trap designed and fabricated at Sandia National Laboratories was integrated with an optical cavity. The planar linear trap consists of two regions separated by 4.00 mm, a loading region where the ion is trapped and a cavity region to which the ion is transported for atom-field interaction. The planar linear trap is demonstrated to be robust and able to hold many ions. A moderate finesse optical cavity was used to increase the collection efficiency. When an excited ion is placed inside an optical resonator, the spontaneous emission rate into the cavity mode is enhanced,
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due to the Purcell Effect[59]. A trapped ion transition ($S_{1/2} \rightarrow P_{1/2}$) can be coupled to the cavity mode at a rate that can be comparable to that of free space modes.

The outline of this thesis is the following: Chapter 2 presents the classical theory of optical cavity resonators and the semiclassical model of the atom photon interface to understand the cavity design and results. Chapter 3 introduces the concepts for ion trapping needed to understand the designing device. Chapter 4 gives a detailed design, characterization and fabrication procedure of the cavity trap. Chapter 5 presents a detailed design, characterization and fabrication procedure of the surface linear ion trap. This chapter also includes a section with an explanation of the lasers used for the trapping experiment and the results of the cavity trap. Chapter 6 describes the experimental efforts at converting ultraviolet photons emitted by a calcium trapped ion to an infrared frequency. The last chapter presents conclusions and future experiments for this work.
Chapter 2

Optical Cavity

2.1 Overview

This section introduces the basic theory essential to understand the confinement of light in Optical Cavity Resonators. It begins with a review of Gaussian beams and their characteristic parameters, resonators, types of resonators, resonator stability and the resonant properties of passive optical cavities. At the end of this chapter the quantum theory of an atom in a cavity is outlined. All these definitions will be necessary for a complete understanding of the composition and parameters of the optical cavity that is integrated in the micro-machined ion trap.
2.2 Cavity Resonators Classical Theory

2.2.1 Gaussian Beam

A Gaussian beam consists of the electromagnetic radiation with transverse electric fields and intensity that are described by Gaussian functions. The solution of the Helmholtz equation is a Gaussian function describing the complex amplitude of the electric field, which propagates as an electromagnetic wave in the beam[63]:

$$E(r, z) = E_0 \frac{w_0}{w(z)} \exp \left( \frac{-r^2}{w^2(z)} \right) \exp \left( -ikz - ik \frac{r^2}{2R(z)} + i\zeta(z) \right)$$  \hspace{1cm} (2.1)

where,

- $r$ is the radial distance from the central axis of the beam
- $z$ is the axial distance from the beam’s waist
- $k$ is the wave number $\frac{2\pi}{\lambda}$
- $E_0$ is the electric field
- $\lambda$ is the wavelength of the electro magnetic field
- $w(z)$ is the radial distance from the center axis of the beam at which the field amplitude and intensity drop to $1/e$ and $1/e^2$, respectively, of their axial value
- $w_0$ is the beam’s waist size (radius)

From this equation we can find the following beam parameters as seen in Figure 2.1.

The spot size $w(z)$ represents the variation of the beam radius along the propagation direction

$$w(z) = w_0 \sqrt{1 + \left( \frac{z}{z_R} \right)^2}$$  \hspace{1cm} (2.2)

where the $z$ axis origin is defined to coincide with the beam waist.

The Rayleigh range ($z_R$) is the axial distance from beam waist where the area of
the beam cross-section is double.

\[ z_R = \frac{\pi w_0^2}{\lambda} \]  

(2.3)

The radius of curvature of the wavefronts comprising the beam is defined by,

\[ R(z) = z \left[ 1 + \left( \frac{z_R}{z} \right)^2 \right] \]  

(2.4)

The divergence of the beam is defined by the angle between the straight line and the central axis of the beam when \( z \gg z_R \), see Fig 2.2:

\[ \theta \approx \frac{\lambda}{\pi w_0} \]  

(2.5)
Chapter 2. Optical Cavity

2.2.2 Optical Resonators

An optical resonator is a system or device that builds up greater power at suitable frequencies. The resonance frequencies are called normal modes. The light beam travels at a constant velocity, reflecting back and forth between the mirrors of the optical cavity. Suppose that the length of the cavity is $L$, then the length of the round trip is $2L$. In order to cause resonance, the light needs to constructively interfere after a round trip, in other words the phase of a wave has to be equal to the initial phase after a round trip. For resonance, the wave has to satisfy the condition that the round trip distance $2L$ is equal to an integer number of the wavelength $\lambda$ of the wave.

$$2L = N\lambda, N \in 1, 2, 3, ...$$ (2.6)

When the wave velocity is $v$, the frequency is equal to $f = v/\lambda$, so the resonance
Chapter 2. Optical Cavity

frequencies are:

\[ f = \frac{Nv}{2L}, \quad N \in 1, 2, 3, \ldots \]  \hspace{1cm} (2.7)

2.2.3 Types of optical resonators

A cavity can be formed by two mirrors facing each other. The simplest type of cavity is formed by two plane parallel mirrors. It is known as the Fabry-Pérot cavity. Although, it is the simplest, it is not used in large scale lasers or setups due to the difficulty of alignment. They have to be aligned parallel to within a few seconds of an arc in order to avoid the walk-off of the intracavity beam. That is, the light will spill out of the cavity. In order to avoid the walk-off effect two concave spherical mirrors can be used in place of the two parallel mirrors or the cavity composed by a flat and a concave spherical mirror. The radiation pattern will be different for each type of cavity configuration as seen in figure 2.3,2.4,2.5. The patterns could be plane-parallel, concentric, confocal, hemispherical, or concave-convex. In the ideal plane parallel configuration the beam travels parallel without suffering any change in its paraxial shape. In the confocal configuration both the concave mirrors have the same focal point inside the cavity, at its center. Similarly, in the concentric configuration both concave mirrors share the same origin, but the beam waist is minimized. For the hemispherical configuration formed by a concave and a plane mirror the focal point is localized at the surface of the plane mirror when the radius of curvature of the concave mirror is equal to the cavity length. This is the configuration that we use for the integrated optical cavity.


2.2.4 Stability

After we learn about the different optical cavity configurations it is important to know about the stability of them. Stability in this context means that the beam size does not grow without limit; instead it is refocused into the cavity every time it completes a round trip. By using the ray transfer matrix analysis method, it is possible to calculate a stability criterion as a function of the cavity length and curvature of the mirrors[67] [47].

\[
0 \leq \left( 1 - \frac{L}{R_1} \right) \left( 1 - \frac{L}{R_2} \right) \leq 1
\]

(2.8)

where L is the cavity length. The factor \(1-\frac{L}{R_{1,2}}\) is termed the stability parameter and is represented by the \(g_{1,2}\) value.
Chapter 2. Optical Cavity

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{confocal.png}
\caption{Confocal}
\end{figure}

\begin{equation}
0 \leq (g_1)(g_2) \leq 1
\end{equation} \hfill (2.9)

Relating the g parameter to the Gaussian beam parameters above we find:

\begin{equation}
w_0^2 = \frac{L\lambda}{\pi} \sqrt{\frac{g_1g_2(1-g_1g_2)}{(g_1 + g_2 - 2g_1g_2)^2}}
\end{equation} \hfill (2.10)

\begin{equation}
z_R = \frac{g_1g_2(1-g_1g_2)}{(g_1 + g_2 - 2g_1g_2)^2} L^2
\end{equation} \hfill (2.11)

The radius of curvature of the mirror as a function of the length and the g value is:

\begin{equation}
R_{1,2} = \frac{L}{1 - g_{1,2}}
\end{equation} \hfill (2.12)
By keeping the cavity length $L$ constant, then the stability values of $R$ can be plotted in a $g_1$ and $g_2$ map, corresponding to the axes of the the plane(Figure 2.6). The cavity is stable if the points $g_1$ and $g_2$ are positive and limited by the area formed by the parabola and the positive axis, or if the points $g_1$ and $g_2$ are negative and limited by the area formed by the parabola and the negative axis.

### 2.2.5 Source of optical resonator loss

There are two main sources of loss in optical resonators[67]:

1. inherent losses due to reflectance imperfections at the mirrors and
2. losses due to absorption and scattering in the medium between the mirrors.

The round trip power attenuation factor associated with the second process is defined by $e^{-2\alpha d}$, where $\alpha$ is the absorption coefficient of the medium and $d$ is the cavity length. For mirrors of reflectance $\mathcal{R}_1 = r_1^2$ and $\mathcal{R}_2 = r_2^2$ the wave intensity decreases...
by the factor $R_1 R_2$ in the course of two reflections, one at each mirror for a single round trip. Therefore, the intensity attenuation factor is:

$$r^2 = R_1 R_2 e^{-2\alpha d}$$  \hfill (2.13)

where $\alpha$ represents the effective total distributed loss coefficient. Thus,
Chapter 2. Optical Cavity

\[ \alpha_{m1} = \frac{1}{2d} \ln \left( \frac{1}{R_1} \right) \]  
\[ \alpha_{m2} = \frac{1}{2d} \ln \left( \frac{1}{R_2} \right) \]

are the loss coefficients for the two mirrors. \( \ln(1/R) \) is termed the \( \delta \) notation for cavity losses. The transmission intensity through the cavity is given by:

\[ I_T = \frac{T_{max} I_{inc}}{1 + \left( \frac{2F}{\pi} \right)^2 \sin^2 \left( \frac{\pi \nu}{\lambda_{FSR}} \right)} \]

From this equation we can find three parameters used to characterize an optical cavity. They are the finesse \( \mathcal{F} \), the free spectral range \( \nu_{FSR} \), and the linewidth \( \kappa \). The \( \nu_{FSR} \) is the measure of the spacing between two successive axial resonator modes with Gaussian shape. The linewidth is the width in frequency of the optical mode spectrum, typically the full width at half maximum. The finesse is a measurement of the quality of the optical cavity, and is defined by the ratio between the \( \nu_{FSR} \) and the linewidth. Also, the finesse defines the sharpness of the resonance peaks. Assume that we can have an ideal mirror with reflectance close to 1, then the finesse is defined by[28]:

\[ \mathcal{F} = \frac{2\pi}{\mathcal{L}} \]

where \( \mathcal{L} = T_1 + T_2 + l_1 + l_2 \) is the total loss of the cavity, \( T_1 \) and \( T_2 \) are the transmission loss and \( l_1 \) and \( l_2 \) are the passive losses of the mirrors. Scattering and absorption of the mirrors are included in the passive loss parameters, which are determined mainly by the surface roughness in the dielectric coating.
Chapter 2. Optical Cavity

The next parameter in the transmission intensity equation is the free spectral range, which is defined by:

\[ \nu_{FSR} = \frac{c}{2L} \]  

(2.18)

The third basic cavity property that can be characterized is the linewidth, which is defined by:

\[ \kappa = \frac{\nu_{FSR}}{2F} \]  

(2.19)

2.2.6 Resonance properties of passive optical cavities

Further analysis of an optical cavity shows that only part of the incident signal is reflected off the mirror \( (M_1) \) Fig.2.7. The portion of the incident light confined in the cavity is called the circulating signal, and the other fraction of the incident light is transmitted through the second mirror \( (M_2) \). The incident, reflected, and transmitted signals are capable of being measured, but the circulating or intracavity beam cannot be measured directly. However, its properties can be inferred from the transmitted and reflected beams. Knowing the properties of the intra-cavity beam are essential in cavity QED experiments, because the circulating intensity inside the cavity interacts with the confined ion. Analyzing what happens at the input mirror \( (M_1) \), the circulating signal \( (E_{cir}) \) consists of the vector sum of that portion of the incident signal \( (E_{inc}) \) which is transmitted through the input mirror \( (M_1) \) and has the value of \( jt_1E_{inc} \), plus a contribution representing the circulating signal \( E_{cir} \), which left this same point one round trip earlier and is back to the same point after bouncing off the second mirror \( (M_2) \). We can express the circulating signal just inside the mirror \( M_1 \) as:
Chapter 2. Optical Cavity

Figure 2.7: Optical resonator

\[ E_{\text{cir}} = jt_1 E_{\text{inc}} + g_{\text{rt}}(w) E_{\text{cir}} \] (2.20)

where \( g_{\text{rt}} \) is the net complex round trip gain for a wave making one complete round trip in the cavity. However, we have to consider losses intrinsic to the mirror materials as well. Using \( \alpha \) as the absorption coefficient, the signal amplitude causing a round trip signal reduction is \( e^{-2\alpha L} \), where \( L \) is the length of the cavity. Also, the signal will suffer a phase shift represented by \( e^{jwL} \). After considering these losses factors, one can represent the complex round trip gain as:

\[ g_{\text{rt}}(w) \cong r_1r_2e^{2\alpha_o L - \frac{jwL}{c}} \] (2.21)

The round trip gain will be less than unity. The phase accumulated by the circulating field traveling a distance \( 2L \) is \( \phi \). This phase is given by:
Chapter 2. Optical Cavity

\[ \phi = 2kL = 2\pi \nu \frac{2L}{c} = 2\pi \frac{\nu}{\nu_{FSR}} \quad (2.22) \]

From the above equation we can find the factor \( \frac{E_{\text{cir}}}{E_{\text{inc}}} \)

\[ \frac{E_{\text{cir}}}{E_{\text{inc}}} = \frac{jt_1}{1 - r_1r_2e^{\frac{-i\nu_{FSR}}{\nu}}} \quad (2.23) \]

Using a similar analysis for the input mirror (M_1) at the second mirror (M_2), one can find the transmitted signal intensity as a function of the circulating signal.

\[ \frac{E_{\text{cir}}}{E_T} = \frac{1}{jt_2e^{\frac{-i\nu_{FSR}}{\nu}}} \quad (2.24) \]

The intensity of the fields are proportional to the square of the electric field. Therefore:

\[ \frac{I_T}{I_{\text{inc}}} = \frac{(t_1t_2)^2}{(1 - (r_1r_2)^2)(1 + \frac{4r_1r_2 \sin^2(\frac{\nu}{\nu_{FSR}})}{1-(r_1r_2)^2})} \quad (2.25) \]

\[ \frac{I_{\text{cir}}}{I_{\text{inc}}} = \frac{t_1^2}{|1 - g_r t(w)|^2} \quad (2.26) \]

In this work, the cavity trap supports the interaction between a trapped ytterbium ion and a photon. This experiment explores the reciprocal action between an isolated ion in a cavity with high reflecting mirrors for enhanced light collection. The cavity mirrors and their separation length define the mode structure, which will be tuned in resonance or nearly resonant with the transition between two levels of the ytterbium trapped ion. The study of the interaction between an ion and the cavity is known as cavity quantum electrodynamics. The effect that is presented in this thesis is the
Chapter 2. Optical Cavity

alteration of the atomic radiative parameter modifying the spontaneous emission rate of the trapped ion.
Chapter 3

Ion Trapping

3.1 Earnshaw’s Theorem

The first requirement for this experiment is to isolate a charge from the environment, here we produce an harmonic potential, where the ion minimize its potential energy and finds a stable state of static equilibrium. The Earnshaw theorem states that a system of electrical charges cannot be in stable static equilibrium in using only static electric fields. This section will explain and demonstrate the Earnshaws theorem for a system of charged particles and extend the idea to a single particle based on the work of W. Jones [30].

The virial theorem relates the time average of the kinetic energy to the time average of the potential energy for a system of particles. The total forces exerted on a particle consist of the sum of the internal forces and the external forces. The virial for a pair of charges is:

\[
\overrightarrow{F}_{12} \cdot \overrightarrow{r}_1 + \overrightarrow{F}_{21} \cdot \overrightarrow{r}_2 = \overrightarrow{F}_{12} \cdot (\overrightarrow{r}_1 - \overrightarrow{r}_2) = \overrightarrow{F}_{12} \cdot \overrightarrow{r} \tag{3.1}
\]
Chapter 3. Ion Trapping

The electrostatic force for two charged particles obeys Coulombs law

\[ \vec{F}_{12} = \frac{kQ_1Q_2}{r^3} \]  

(3.2)

Replacing Couloms force \( F_{12} \) in the first equation, the virial contribution is found in terms of the charges. The potential of the pair of charges is \( U \) and can be extended for all the other particles by finding the potential energy for each pair of particles. The total internal potential energy is given by the sum of all the mutual potential energies. Setting \( \vec{F}_{\text{ext}}(i) \) to be an external force applied to a single particle, the total external force is:

\[ \sum_i \vec{F}_{\text{ext}}(i). \vec{r}_i \]  

(3.3)

If the system is in static equilibrium the internal and external forces exerted to a particle must be equal.

\[ U + \sum_i \vec{F}_{\text{ext}}(i). \vec{r}_i = 0 \]  

(3.4)

In order to show that, assume that the system is in static equilibrium with no need of external forces, \( U=0 \). Now, consider an external force applied to a couple of particles while keeping the external forces equal to zero for the other particles. Lets analyze the following cases:

- A force of equal magnitude and antiparallel to the \( r \) direction is applied to a pair of particles, then the energy potential \( U \) becomes positive and increase.
Chapter 3. Ion Trapping

Figure 3.1: Electrostatic field assumption

- A force of equal magnitude and parallel to the r direction is applied to a pair of particles, then the energy potential $U$ becomes negative and decrease.

If the system is in static equilibrium as has been assumed, any external force exerted on the system will create a restoring force that will pull the particles to their equilibrium positions. It means that the energy potential always increase to compensate for any applied external forces. Our assumption is incorrect, because in the second case the potential energy becomes negative, so the system cannot be in static equilibrium.
3.2 Ion trapping

Suppose that there is a single charged particle which is in static equilibrium by applying external electrostatic forces. The field at the single charged particle is described by an electrostatic potential $\phi$ with lines perpendicular and towards the single charge. If the single charge is removed from that position, the field lines will not keep the direction towards where the single charge was in rest, because the positive charge lines are going to seek a negative charge to terminate. However, an electrostatic potential can describe a saddle region profile where a single charge would be in an unstable equilibrium[22] [56].

As it is seen in the figure 3.2, the potential has a paraboloid shape dictated by
Chapter 3. Ion Trapping

the electrode geometry[26].

\[ \phi \simeq (\alpha x^2 + \gamma z^2) \quad (3.5) \]

To generate this saddle shape around a charged particle a quadrupole field is needed. The field applied forms a harmonic potential which traps and ati-traps in two dimensions.

If the potential is harmonic then the Laplacian of the potential is zero. The Laplace equation \( \nabla^2 \phi = 0 \) requires that the constants \( \alpha \) and \( \gamma \) sum to zero. Analyzing this condition:

\[ \phi = \frac{\phi_0}{2r_0^2} (x^2 - z^2) \quad (3.6) \]

In our particularly simple geometry this field can be generated by four hyperbolically shaped electrodes linearly extended in the y direction. Then field strength is:

\[ E_x = \frac{\phi_0}{r_0^2} x, \quad E_z = \frac{\phi_0}{r_0^2} z, \quad E_y = 0 \quad (3.7) \]

If a positively charge ion is located at the center of the quadrupole potential the ion will oscillate harmonically in the x direction, but will move away from the center in the z direction and will be lost. In order to avoid this behavior the potential applied needs to oscillate in time. A radio frequency oscillating voltage will create a time averaged potential and dynamically trap the ion.

A 3D quadrupole rf trap[45] is designed to create a single trapping point but experiences problems when trapping more than one ion. For instance, two trapped ions in this quadrupole rf trap are repelled by their mutual Coulomb force from the
center of the confinement region, resulting in micromotion. But if instead of generating a single point trap a linear trap is generated, the ions are trapped along a line by the rf quadrupole potential. In this manner two or more ions can move freely in the axial direction by applying voltages to particular control electrodes. This modified designed of the quadrupole ion trap is called the linear rf Paul trap[58].

A linear rf Paul trap is similar to a quadrupole mass filter which consists of four parallel rods. The rf voltage is applied to two diagonally opposite cylindrical rods and the other two rods are grounded. The linear trapping region is at the center and along the rod axis. To trap the ion in the axial direction a DC potential is applied at both ends of the rods. The time varying potential close to the trap axis can be written[60]:

\[
V = \frac{V_0}{2} \left[ 1 + \frac{x^2 - y^2}{\alpha R^2} \right] \cos(\Omega t) \tag{3.8}
\]

where R is the distance from the axis to the surface electrodes, Ω is the rf frequency, and α is a geometry factor. If Ω is a very high frequency, the ion of mass \( m \) and charge \( q \) is trapped in an effective pseudopotential:

\[
\phi = \frac{qV_0^2}{4m\Omega^2 R^4} (x^2 + y^2) = \frac{m\omega_r^2}{2q} (x^2 + y^2) \tag{3.9}
\]

\[
\omega_r = \frac{qV_0}{\sqrt{2m\Omega R^2}} \tag{3.10}
\]

In the center of the trap axis the static potential can be approximated by the harmonic potential.

\[
\phi_s = \frac{m\omega_z^2}{2q} \left[ z^2 - \frac{x^2 + y^2}{2} \right] \tag{3.11}
\]
Chapter 3. Ion Trapping

where \( z_0 \) is half the length of the central region of the trap, \( \kappa \) is a geometric factor and

\[
w_z = \sqrt{\frac{2\kappa q U_0}{m z_0^2}}
\]  \hspace{1cm} (3.12)

The total potential due to the rf electrodes and DC caps near the center of the trap is given by adding equations 3.8 and 3.11. If we return to the actual oscillating potential Newton's second law of motion allows us to calculate the force exerted on the charge at the center of the trap.

\[
\vec{F}(xz) = m.\vec{\ddot{r}}(xz) = -\nabla \phi(xz)
\]  \hspace{1cm} (3.13)

The equation of motion for an ion in this electric field is found by solving the Mathieu differential equations[44]:

\[
\frac{d^2 x}{d\tau^2} + (a_x + 2q_x \cos(2\tau))x = 0
\]  \hspace{1cm} (3.14)

\[
\frac{d^2 z}{d\tau^2} + (a_z + 2q_z \cos(2\tau))z = 0
\]  \hspace{1cm} (3.15)

where [4]:

\[
a_x = a_y = -\frac{1}{2} a_z = -\frac{4Q\kappa U_0}{m z_0^2 \Omega^2}
\]  \hspace{1cm} (3.16)

\[
q_x = -q_y \frac{2QV_0}{m R^2 \Omega^2}, \hspace{1cm} q_z = 0
\]  \hspace{1cm} (3.17)
3.3 Ion trapping stability

The solution of the differential equation can be separated in two regimes: Stable, where the motion of the ion oscillates in the plane with limited amplitude, and unstable, where the amplitude of the motion of the ion grows until it is untrapped. In the stable region an a-q map can be traced with the trap parameters as is shown in the figure 3.3[39] [56]. The a parameter is in function of the DC voltage and the q parameter is in function of the RF voltage. We can adjust the values of a and q to bring the ion to a much more stable region. These equations and parameters are needed for design a linear Paul trap. The actual experiment uses a surface linear trap designed and fabricated in a silicon wafer using standard MEMS fabrication process[43]. To create a similar quadrupole potential in a surface linear trap, the four rod geometry is modified by moving one of the rf electrodes and one of the DC control electrodes into the surface plane. The rf electrodes are located on either side of a DC control electrode at the center of the trap that can be used to vertically position the ion at the rf null while the outer DC electrodes provide axial confinement for the ion. It will be shown in a later section that the fabrication of this trap requires a multilayer process with vias through out the trap for interconnections.
Figure 3.3: Trap stability region
Chapter 4

Experimental cavity

4.1 Cavity design

In designing a moderate finesse optical cavity, we chose mirrors such that the coating of the fused silica substrate is highly reflective at 369 nm, the mirror has the smallest radius of curvature available, the area of the exposed substrate to the trapped ion is minimum, the cavity length is minimal, the mirror substrates do not disturb the trapped ion inside the cavity region, and the trapped ion is as close to the waist of the cavity mode as possible[10]. These design criteria led us to choose a half symmetric cavity with a curved mirror with a 5 mm radius of curvature. The flat mirror is attached underneath a hole in the ion trap chip with a 105 µm of diameter. It is a 2 mm x 2 mm flat fused silica substrate coated for high reflectivity(HR) at 369 nm with a transmission of 250 ppm. The curved mirror has a transmission of 6000 ppm with the same coating of the flat mirror. The curve mirror is called the out coupling mirror where most of the photons will leave the cavity. The mirrors are HR coated by Advanced Thin Films(ATF), which was the only coating company that could guarantee coatings with the required specifications. In order to have a stable
resonator, the cavity length should be the less than 5 mm. Another important constraint is related to the dielectric surface in the mirror, which can accumulate charges that could disturb the trapped ion and potentially push it from its rest position [27]. Hence, the mirrors need to be separated at a far enough distance where the ion is less susceptible to these dielectric charges. These two constraints guide us to design a cavity with a length of approximately 1 mm.

The collection efficiency is given by the following equation[69] [21]:

\[
P_{\text{coll}} = \frac{T_{\text{out}}}{L} \left( \frac{2\kappa}{2\kappa + \gamma} \right) \left( \frac{2C}{1 + 2C} \right)
\]

(4.1)

Here \( T_{\text{out}} \) is the outcoupler transmission, \( L \) is the sum of all photon loss mechanisms (mirror, absorption, scattering losses, and transmission), \( \kappa \) is the electric field decay rate of the cavity, \( \gamma \) is the linewidth of the excited atomic state, and \( C \) is the cooper-
Chapter 4. Experimental cavity

Table 4.1: Summary of cavity design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcoupler transmission</td>
<td>1500 ppm</td>
</tr>
<tr>
<td>Coherent coupling rate $g$</td>
<td>$2\pi \times 9.1$ MHz</td>
</tr>
<tr>
<td>Cavity half width $\kappa$</td>
<td>$2\pi \times 26.2$ MHz</td>
</tr>
<tr>
<td>Atomic linewidth $\Gamma$</td>
<td>$2\pi \times 19.6$ MHz</td>
</tr>
<tr>
<td>Cooperativity, $C$</td>
<td>0.16</td>
</tr>
<tr>
<td>Outcoupling efficiency</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Activity is a standard measurement of how well the field and atom system are coupled. It is important to note that the cavity QED in the strong coupling regime requires $C \gg 1$, but in this work the cavity-ion system will be in the bad coupling regime, enough for our purposes of light collection and light enhancement[33].

As we have seen the atom-field coupling $g$ is inversely proportional to the cavity mode volume. Therefore, one way to increase the cooperativity of the atom-cavity system is to build a cavity with small mode volume which can result in a relatively large enhancement of the spontaneous emission rate. However, the realization of a small cavity volume can be problematic to the trapped ion, because the charges accumulated on the dielectric mirrors could attract or repel the trapped ion from its stationary position.

The system parameters for obtaining a $\sim 12\%$ of collection efficiency are summarized in Table 4.1 and the numerical results plot at Figure 4.2.

The cavity finesse is defined by[28]:

$$F = \frac{2\pi}{\mathcal{L}}$$

(4.2)

where $\mathcal{L} = \mathcal{T}_1 + \mathcal{T}_2 + l_1 + l_2$ is the total loss of the cavity, $\mathcal{T}_1$ and $\mathcal{T}_2$ are the transmission loss and $l_1, l_2$ are the passive loss of the mirrors. Scattering and absorption of the mirrors are included in the passive loss parameters, which are determined mainly.
Chapter 4. Experimental cavity

Figure 4.2: Plots of the cooperativity and collection efficiency as a function of outcoupler transmission and cavity length. The star represents our chosen conditions by the surface roughness in the dielectric coating [32]. Taking into account these constraints, the physical and the manufacturing limitations of the mirror coating, surface roughness of the substrates, and placement in the ion trap chip, the cavity is designed to have a finesse of approximately 150. The calculation of the collection efficiency for the experimental cavity requires the knowledge of the total losses, finesse, cavity length, free spectral range and beam waist. All these parameters were characterized with different transmission mirrors as will be shown in section 4.2.3.

4.2 Mechanical design

The cavity has to have a small volume mode as possible, where the waist is going to be located approximately at the ion position. A half symmetric cavity normal to the planar micro machined trap is constructed with a concave mirror and a flat mirror HR coated for 369 nm. The flat and concave UV fused silica substrates were bought from Lattice Electro Optics (LEO). The size of both type of substrates were 7.75
Chapter 4. Experimental cavity

mm in diameter and 4 mm in thickness and a surface roughness , which is defined as the peak to valley deviation from flatness, of 3-5 Årms and $\frac{L}{10}$ wave at 633 nm by vendor specs. The concave mirror is molded at the center of a fused silica substrate with a radius of curvature of 5 mm, and a diameter of 1.5 mm. It was molded in a substrate piece with a diameter of 7.75 mm. Both mirrors where coated by Advanced Thin Films (AFT) with a reflectivity of approximately 99.945% at 369 nm for the flat substrate which has a target of transmission of approximately 250 ppm, and total losses of 300 ppm and a reflectivity > 99.925% at 739nm at 0 degree. The curved mirror has similar characteristics but with a transmission of 6000 ppm. The last material deposited in the coatings is $SiO_2$. After the substrates where coated by ATF, they were sent to Perkins Precision to machine down the surface facing the ion. For the curved mirror, it was first reduced to a diameter of 4 mm and then the curve mirror side coned down to a diameter of about 2 mm. The curved side of the mirror is exposed to the trapped ion and forms the optical cavity. The flat mirrors were cut into a square shape with dimensions of 2 mm by 2mm and mounted to the back of the ion trap chip. A square shaped pit of 2 mm by 2 mm is etched in the back side of the chip, where the flat mirror is inserted and attached with UHV epoxy. The distance from the coating side of the mirror to the top of the chip surface is about 50 µm.

4.3 Cavity assembly

The flat mirror is fixed while the concave mirror is movable to adjust the cavity length, so it needs to be mounted in a flexure structure that allows the cavity length to be scanned vertically. A flexure mount was designed to accommodate the curved fused silica mirror and a small piezo actuator, which permits scanning the cavity
Chapter 4. Experimental cavity

Figure 4.3: Flexure mount model

length. The flexure mount consists of two pieces joined at one end. The low part of the flexure mount is fixed and is mounted and glued on the ceramic pin grid array (CPGA). The top part of the structure is movable, and holds the curved mirror. The flexure mount has dimensions of approximately 25.5 mm long, 7 mm wide where the piezo is placed and 9 mm wide on the opposite side. It is 5 mm high on the piezo side and 3.8 mm high on the junction side. At the center there is a through hole of approximately 4 mm diameter that is used to hold the mirror. The flexure mount is made of oxygen free copper, which was chosen because it is a good conductor, minimizes oxidation, is extremely ductile, and is ultra-high vacuum (UHV) compatible. The piezo used is a chip miniature piezo PL055.31 from Physik Instrumente (PI). The dimensions are 5 mm x 5 mm x 2 mm with a 2.2 μm travel range. It is UHV compatible (minimal outgassing) and allows high bake out temperatures up to 150°C, it has a capacitance of 250 nF, and an operating voltage from -20V to 100V.
An additional structure was designed to allow optical access to the cavity locking the laser from the side. The same structure is used to collect photons from the excited trapped ion. This turning mirror mount is designed to hold a planar mirror which is reflective at 45 degree. This simple structure is made of stainless steel. The dimension of the turning mirror mount is approximately 33.5 mm long, 6.15 mm wide and 14 mm high.

In addition to simply knowing that the flexure mount is capable of holding the upper curved mirror at the correct height, it is also important to know the mechanical resonances of the mount. The mechanical resonance of the structure fully assembled with the mirror and the piezo needs to be sufficiently high such that it will not interfere with the cavity length locking bandwidth. An optical measurement of the mechanical resonance was done using a Michelson interferometer, by illuminating the back of the curved mirror with a collimated 780 nm laser, very small displacements can be
measured, mainly limited by the stability of the mechanical components. Figure 4.5 is a picture of the apparatus used. One arm of the interferometer holds the flexure mount with the mirror and piezo; this is the movable arm of the system. The other arm just contains a fixed flat mirror with HR reflectivity coating at 780 nm. At the center of the interferometer is a beam splitter that divides the incoming 780 nm laser light in the two arms. At the opposite side of the fixed flat mirror is a Thorlabs silicon amplifier photo detector PDA36A with a wavelength range of 350-1100 nm and variable gain. The instability of the mechanical components cause the signal amplitude of interest detected by the photodetector to be comparable to the noise amplitude. A lock-in amplifier was therefore used to extract the small signals. The piezo is scanned in frequency using a ramp signal and the magnitude response is
measured using the lock-in amplifier. The results show that the lowest resonance is about 3.7 KHz, which is sufficiently high for locking the cavity mount.

The curved and flat mirrors were analyzed using a white light interferometer. A white light interferometer is a tool that does topography measurements of a sample. It is a type of Michelson interferometer that uses white light to scan the height of a test object, in our case to test the surface roughness. The interferometer used for this test was limited to about 1 nm rms roughness. The results of this analysis are shown in the figures below, whereby it is seen that the rms surface roughness of the LEO mirror is < 1 nm and has a 5 mm radius of curvature as is expected based on the manufacturing specifications.

Figure 4.6: Mechanical resonance
Chapter 4. Experimental cavity

4.3.1 Mirror placement

Bottom mirror

The trap was backside etched to remove a 2.2 mm x 2.2 mm square shape where the 2mm x 2mm mirror piece of HR coated flat fused silica mirror is inserted. It was held in place with a small probe and glued using Epotek H77 epoxy, which is UHV compatible. The mirror placement was then analyzed with a white light interferometer to measure the distance of the mirror below the top metal layer as well as the possible tilt of the mounted mirror. For the cavity mode to hit the ion, the bottom mirror must be less than 2.7 degrees from parallel. As seen in the figure 4.9, the assembled setup has < 0.2 µm tilt across the cavity hole of 105 µm diameter.
Chapter 4. Experimental cavity

Hence, the mirror is located about 50 µm below the top surface and is tilted less than 0.1 degrees.

Figure 4.8: Flexure mount assembly

Upper mirror

The mounting of the upper mirror requires a more delicate procedure. First, the curved mirror has a cylindrical shape after milling. An open collar of approximately 4 mm diameter is glued to the substrate with a few drops of 3M 2216 epoxy, which is UHV compatible. Once the epoxy is cured the mirror with the collar attached is mounted into the flexure structure and is glued once again using the 3M 2216 epoxy. The collar allows rough positioning of the mirror on top of the flexure mount.
Chapter 4. Experimental cavity

Table 4.2: Summary of cavity design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcoupler transmission</td>
<td>6000 ppm</td>
</tr>
<tr>
<td>Coherent coupling rate $g$</td>
<td>$2\pi \times 4.77$ MHz</td>
</tr>
<tr>
<td>Cavity half width $\kappa$</td>
<td>$2\pi \times 23.8$ MHz</td>
</tr>
<tr>
<td>Atomic linewidth $\Gamma$</td>
<td>$2\pi \times 19.6$ MHz</td>
</tr>
<tr>
<td>Cooperativity, $C$</td>
<td>0.05</td>
</tr>
<tr>
<td>Outcoupling efficiency</td>
<td>0.14</td>
</tr>
</tbody>
</table>

4.4 Mirror characterization

The mirrors were characterized in the lab to measure their finesse, linewidth and free spectral range. Several mirrors with different diameter, radius of curvature and transmission losses were characterized using two different cavities. The first cavity type was built using a piezo cylinder from American Piezo Ceramic (APC). The dimensions of the piezo are OD: 38 mm, ID: 34 mm, length: 25 mm. It included a pair of cap features that were designed to hold mirrors with a diameter of 7.75 mm. with retaining rings inside them. Additional caps were built to hold the milled mirrors at 4 mm. These caps were made of stainless steel. Two 28 AWG wires were glued to the internal and external walls of the piezo cylinder using Torr-Seal epoxy for applying voltage. This cylindrical piezo and caps form a cavity length of 2 mm.Figure 4.10.

The second type of cavity was built using the flexure mount structure and the milled mirror with a diameter of 4 mm. The procedure for the construction of this type of cavity is the same as for the final cavity.Figure 4.11. Mode matching to the cavity using the 369 nm laser light was performed using a two lens configuration. The UV light was collimated and then sent through a telescope which focuses the incoming beam size to approximately the cavity waist. The two lenses that form the telescope were mounted on a single axis translational stage for easy adjustment of the beam
Chapter 4. Experimental cavity

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Substrate</th>
<th>Shape</th>
<th>RoC-dia(mm)</th>
<th>Tx(ppm)specs</th>
<th>Cone down</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fused silica</td>
<td>concave</td>
<td>25-7.75</td>
<td>250</td>
<td>NO</td>
</tr>
<tr>
<td>2</td>
<td>Fused silica</td>
<td>concave</td>
<td>25-7.75</td>
<td>250</td>
<td>NO</td>
</tr>
</tbody>
</table>

Table 4.4: Cavity N° 2, Finesse 1168, wavelength = 369 nm

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Substrate</th>
<th>Shape</th>
<th>RoC-dia(mm)</th>
<th>Tx(ppm)specs</th>
<th>Cone down</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Fused silica</td>
<td>concave</td>
<td>5-7.75</td>
<td>1500</td>
<td>NO</td>
</tr>
<tr>
<td>4</td>
<td>silicon</td>
<td>flat</td>
<td>25.4x25.4</td>
<td>250</td>
<td>NO</td>
</tr>
</tbody>
</table>

waist size and position. The focal length of the lenses and the distance between them and the cavity mode were calculated using the ABCD matrix method.

A batch of substrates with different radius of curvature, diameter and shape were characterized. The results for several of these cavities are presented in Tables 4.3-4.8. The cavity parameters for the final cavity with a $F$ of 150 are shown in table 4.2.

### 4.5 Cavity trap system assembly and test

The completed cavity trap system was assembled in a portable clean space. To assemble the fully cavity system on the micro machined surface trap, the flexure mount holding the curved mirror and the piezo must be aligned to the cavity hole on the surface trap and glued on the CPGA. A fixture was designed and fabricated to hold the fully mounted flexure for alignment. The fixture held the flexure mount from its four corners using tipped nylon set screws. Additionally, the fixture has an

Table 4.5: Cavity N° 3, Finesse 1227, wavelength = 369 nm

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Substrate</th>
<th>Shape</th>
<th>RoC-dia(mm)</th>
<th>Tx(ppm)specs</th>
<th>Cone down</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Fused silica</td>
<td>concave</td>
<td>5-7.75</td>
<td>1500</td>
<td>NO</td>
</tr>
<tr>
<td>6</td>
<td>Fused silica</td>
<td>flat</td>
<td>na-4</td>
<td>250</td>
<td>YES</td>
</tr>
</tbody>
</table>
Chapter 4. Experimental cavity

Table 4.6: Cavity N° 4, Finesse 950, wavelength = 369 nm

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Substrate</th>
<th>Shape</th>
<th>RoC-dia(mm)</th>
<th>Tx(ppm)specs</th>
<th>Cone down</th>
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</tr>
<tr>
<td>8</td>
<td>Fused silica</td>
<td>flat</td>
<td>na-4</td>
<td>250</td>
<td>YES</td>
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</tbody>
</table>

Table 4.7: Cavity N° 5, Finesse 650, wavelength = 369 nm

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<tr>
<th>Mirror</th>
<th>Substrate</th>
<th>Shape</th>
<th>RoC-dia(mm)</th>
<th>Tx(ppm)specs</th>
<th>Cone down</th>
</tr>
</thead>
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<tr>
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<td>concave</td>
<td>5-4</td>
<td>1500</td>
<td>YES</td>
</tr>
<tr>
<td>10</td>
<td>silicon</td>
<td>flat</td>
<td>2X2</td>
<td>250</td>
<td>NO</td>
</tr>
</tbody>
</table>

aperture on top that allows access to the curved mirror with the alignment laser. This fixture has a threaded hole at one of its extremes that is used for attaching to an XYZ stage. The stage permits the movement of the flexure mount in all three space dimensions for proper alignment to the cavity hole. The CPGA with the micromachined trap was mounted on a 100 pin socket which in turn was mounted on top of a beam splitter. In one of the output ports of the beam splitter a photodetector was installed and in the second output port a camera was placed to monitor the transmitted modes from the formed cavity. The verification of the alignment was performed with 780 nm laser light coupled into the optical cavity. The laser light from an APC fiber passes through a Thorlabs collimator package F810APC-780, which expands and collimates this laser beam. The expanded beam passes through two lenses mode matching optics which focus the beam size to about 25 µm at the optical cavity waist. Additionally, two steering mirrors on the optical setup provided fine control of the beam position in the cavity. Using this technique and a weak input beam, modes were observed after adjusting the position of the curved mirror on top of the cavity hole where the flat mirror was glued. After

Table 4.8: Cavity N° 6, Finesse 400, wavelength = 369 nm

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Substrate</th>
<th>Shape</th>
<th>RoC-dia(mm)</th>
<th>Tx(ppm)specs</th>
<th>Cone down</th>
</tr>
</thead>
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<tr>
<td>11</td>
<td>Fused silica</td>
<td>concave</td>
<td>5-4</td>
<td>1500</td>
<td>YES</td>
</tr>
<tr>
<td>12</td>
<td>silicon</td>
<td>flat</td>
<td>2X2</td>
<td>250</td>
<td>NO</td>
</tr>
</tbody>
</table>
Chapter 4. Experimental cavity

assembly of the cavity ion trap system, it was inserted into the vacuum chamber and baked at 100°C for a couple of weeks in order to reach UHV pressure. More about the details of baking is explained in a later section.
Chapter 4. Experimental cavity

Figure 4.9: White light interferometer
Figure 4.10: Curved mirror characterization
Figure 4.11: Curved and flat silicon mirror
Chapter 4. Experimental cavity

Figure 4.12: Cavity assembly set up
Chapter 5

Ion trap experiment

5.1 Vacuum chamber

A trapped ion is very delicate and cannot be perturbed by other particles. Ideally, the ion requires a particle free environment. Although the ideal case is impossible to reach, the atoms can be isolated in an ultra high vacuum chamber where the pressure is about $10^{-11}$ Torr\[61\]. At this pressure the mean free path of a particle is on the order of kilometers, such that collisions occur in minutes. The goal is to achieve long trapping times much greater than the duration of a single experiment.

The vacuum chamber built for this experiment uses only UHV compatible materials. All pieces including the spherical octagon, flanges and fittings, are stainless steel 316L. The stainless steel 316L is more resistant to corrosion and pitting. View ports were used to gain optical access inside the spherical octagon. The view ports are made of stainless steel 304 and have hermetically sealed quartz glass windows. Additional hardware components are added inside the spherical octagon to hold the chip trap and its accessories. In this section the components needed to achieve UHV
Chapter 5. Ion trap experiment

Figure 5.1: UHV chamber

are going to be explained and in the following sections more details about the other components will be given.

The spherical octagon has a cross fitting where an ion pump, a titanium sublimation pump and an ion gauge are attached. Additionally, this vacuum chamber is connected to a turbo molecular pump through a bakeable valve. The turbomolecular pump is used to obtain and maintain high vacuum during the bake. This pump is based on transferring momentum to the molecules in a determined direction by successive impacts against a solid moving surface. The rotor spins at high speed kicking the molecules and push them from the chamber to the backing pump. Usually, using turbo pumps pressures of about $10^{-7}$ Torr or $10^{-8}$ Torr are reached.
The ion pump is used to achieve pressures at the ultra high vacuum range. The operating mechanism consists of ionizing the residual gas molecules inside the vacuum chamber. An electric field is applied to these ionized particles which leads them towards a titanium surface in the ion pump. When the ionized molecules hit the titanium surface they react and are adsorbed. Thus, they are removed from the vacuum environment. The titanium sublimation pump is also used to reach ultra high vacuum inside the chamber. It works like the ion pump, but has titanium filaments that are heated in vacuum. These heated filaments sublimate titanium, which is deposited on the walls surrounding the filaments. The residual gas around the pump reacts with the sublimated titanium particles and is adsorbed on the surface walls.

In the experiment, the spherical octagon has a bakeable valve that is connected to a turbomolecular pump (Pfeiffer TMU 071-P) via a bellow. Previous to the chamber bakeout, the titanium sublimation, the ion gauge, and the ytterbium oven are activated for degassing. Afterwards, the vacuum chamber is heated to 110°C to remove gases and water particles that are adsorbed by the internal walls in the chamber. The bakeout at 110°C is set to protect the coating on the cavity mirrors and avoid possible degradation of them during the this process. Because, the chamber is not baked at high temperatures, the bakeout process takes between 7 to 10 days, before observing a pressure at about $10^{-8}$ Torr using only the turbo pump.

Once the pressure inside the chamber reaches the $10^{-8}$ Torr pressure the bakeable valve is closed, the turbo pump is turned off and the ion pump and gauge are activated. After a couple of days, when the pressure in the chamber has reached the bottom, the oven is cooled down to ambient temperature. The pressure measured by the ion gauge after the vacuum chamber is at ambient temperature is about $10^{-9}$ Torr. The chamber is then moved from the oven to the optical table where the ti-
ion trap experiment

Tantum sublimation pump is fired a few times (every 4 hours) until an ultra high vacuum pressure of about $10^{-11}$ Torr is reached\[54\].

\section*{5.2 RF coupling}

The ion trap requires an oscillating electrical field at radio frequency to create a pseudo potential surrounding the ion. This RF field is delivered by a high voltage source of about 250V at a frequency of about 25 MHz that is coupled onto the micro-fabricated silicon chip. The RF source and the RF load (electrodes of the chip) are not impedance matched. The most convenient way to impedance match the source and the load is with a RCL circuit, where the majority of power is delivered to the RF load electrodes with a small reflection power. The RF load electrodes are modeled as a circuit with resistance and capacitance. Thus, an inductor is necessary to complete the RCL impedance match circuit\[68\]. This circuit has multiple functions, first as an impedance matching element, second as a filter with a narrow bandpass for the desired RF, and third as a voltage amplifier. One possible way to transfer the full power onto the ion trap chip would be using a coaxial $\lambda/4$ resonator at the desired RF frequency. However, this solution would require a very long coaxial resonator of about 3 meters for an RF frequency of 25 MHz, which is impractical for experimental reasons. Another solution, is a helical resonator, which acts as a coaxial $\lambda/4$ resonator, but it is dimensionally compact. The inner conductor is a single helix which is surrounded by a conductive cylindrical enclosure. The helix is connected to the RF electrode in the ion trap chip and the cylindrical enclosure is connected to RF ground. For the RF input an antenna with a coil of small diameter and length at the center is used to inductively couple to the large helix. The antenna cap with the coil is used to adjust the impedance matching of the RF source and the RF load electrodes in the chip. The figure 5.2 shows the helical resonator with the
cap attached on it. The material used for this RF resonator is copper and the length of the cylindrical enclosure is about 6 in with a diameter of approximately 3 in. The cavity traps have a total capacitance between RF hi and ground of 7 pF, including the package (which adds 4 pF). Depending on the vacuum chamber, the feedthrough, internal RF wiring, and socket can add an additional 6 pF, bringing the total capacitive load to 17 pF.

In an ideal quadrupole trap, the trap secular frequency is given by:

$$\omega_{sec} = \frac{qV}{\sqrt{2\Omega_{rf}mR^2}}$$

(5.1)

where $q$ is the charge of the trapped particle, $V$ is the voltage amplitude, $\Omega_{rf}$ is the applied rf angular frequency, $m$ is the mass of the particle, and $R$ is electrode distance. This can be simply modified to calculate the secular frequency in the cavity trap by substituting $R$ for a characteristic distance. The characteristic distance corresponds to the distance at which hyperbolic electrodes operating at the same voltage and frequency would generate the same secular frequency as in the surface trap. The characteristic distance for the cavity trap in the linear region (not over the hole) is $R=237 \mu m$. By substituting $R$ with this number the user can calculate the secular frequency they are generating for a particular voltage, drive frequency, and ion species. The trap depth can be expressed as:

$$d = \alpha \frac{1}{2} m \cdot \omega_{sec}^2 \cdot R^2, \alpha = 0.014$$

(5.2)

where the factor $\alpha$ is required to account for the specifics of the surface trap geometry. In terms of practical trap depth (defined as the ability to stay trapped following a collision with a particle of energy $E$, this assumes that the stability parameter does not exceed 0.5.
These devices have been safely operated with RF amplitudes of up to 300 V, but could possibly be operated at higher voltages if necessary. This would have to be tested by the user. At SNL we have successfully trapped and shuttled ytterbium ions with a voltage amplitude of 250 V and drive frequency of 25 MHz.

This RF resonator was tested by connecting it to a network analyzer through a directional coupler which is used to transfer RF power to the chip electrodes and observe the back reflection signal from the trap. The network analyzer scans the frequency in a range where the RF can is in resonance and applies a standing wave that travels through the helix; at the resonance frequency a dip is observed in the reflected signal. Adjusting the inductive coupling with the RF antenna, results in a much lower dip, which means that the back reflection is minimized and the input power that is being transferred to the ion trap is maximized.
Chapter 5. Ion trap experiment

The Q factor of the RF resonator is the ratio between the energy stored in the inductor and the energy dissipated per cycle of RF. The Q is measured using the network analyzer. It is equivalent to the resonant frequency divided by the difference between the upper and lower frequencies at 3 dBm. attenuation(full width half max).

5.3 Ytterbium source

The source of atoms is a small oven that consists of a sample of ytterbium loaded in a miniature stainless steel tube (McMaster-Carr 5560K46) needle that is about 20 mm long and 0.82 mm in diameter. The oven is attached to a kapton wire through a piece of tungsten sheet by spot welding. The oven is heated by passing current through the kapton wire to the bottom of the stainless steel source where the ytterbium sample is deposited. The heat generates ytterbium vapor that is expelled outside the needle oven. This thin oven is pointed towards the center of the 105 $\mu$m loading hole in the cavity trap. The ytterbium neutral atoms travel thru the loading hole to the top side of the trap where they are ionized using the two photon technique as is explained in...
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the section 5.3.

Figure 5.4: Ytterbium source. a) stainless steel needle with spot welded kapton wire, b) chip back side with ytterbium spots deposited in order to align the needle

5.4 Imaging system

The micromachined ion trap is placed facing up inside the vacuum chamber. Above it there is a reentrant viewport window that permits imaging the trap from the top and reduces the separation distance between the trap and the outside of the vacuum chamber. The distance from the trap surface to the top of the view port window is about 35 mm. A homemade objective was built. It consists of 5 lenses of 1 in diameter for correcting aberration, has a numerical aperture of approximately 0.25, a long working distance of about 35 mm, and a focal length of about 190 mm measured
Chapter 5. Ion trap experiment

from the last lens. The overall imaging system has a 5X magnification. The objective lens is supported by an XYZ stage for positioning control and focusing on the trap. For the construction of the objective the lenses were separated using plastic spacers made with a 3D printer.

![Objective Diagram]

Figure 5.5: Objective

5.5 Detection system

The detection system for a trapped ion consists of two elements, a high sensitivity CCD camera and a photomultiplier tube. The camera is used to visualize the the surface trap, align the laser beams on top of it, and observe the ion fluorescence when initially loading. The camera model is the Andor Luca, an electron multiplying CCD. This camera combines single photon sensitivity with a quantum efficiency of about 35% of photon capture at 369 nm. This EMCCD technology allows the amplification of one single photon up to 1000 times. In the experiment, this camera permits the visualization of the fluorescence emitted by a trapped ytterbium ion by using a 369 nm filter with a +/- 10 bandwidth from Semrock. The camera is focused at the ion
on top of the loading hole region. In order to find the loading hole, first a laser beam is crashed into the surface of the micromachined ion trap around the center. Using the camera XYZ stage, it is moved around until the laser beam is located. After the position is identified, the laser beam and the camera positions are adjusted until the loading hole is found.

### 5.6 Filter board

![Printed circuit board](image)

**Figure 5.6:** Printed circuit board. Board material is Rogers 4350-B UHV compatible. the PCB was fabricated with no silk and no mask.
Chapter 5. Ion trap experiment

The micromachined ion trap has two RF electrodes traveling along the trap axis crossing the loading and cavity holes; on the sides of the RF electrodes are many DC electrodes for ion confinement in the axial direction. The separation between the RF electrodes and DC electrodes is about 10.5 µm. Parasitic capacitance leads to RF voltage pick up on the DC electrodes and disturbs the trapped ion. A low pass filter in-vacuum printed circuit board was designed and constructed to filter any possible pick up signal from the RF source. Each of the 96 DC control electrodes has a passive low pass filter with a cut off frequency of 100 KHz.

A single passive low pass filter consist of a 158 ohm resistor and a 10 nF capacitor. In order to accommodate the roughly 200 passive components in a 60 mm x 70 mm board, SMD 0402(0.4 mm x 0.2 mm) parts were chosen. The capacitor is a multilayer ceramic material X8R (C1005X8R1H103K050BB), which is temperature stable from $-55^\circ C$ to $155^\circ C$ with a 15% variation of its value at this temperatures. Similarly, the resistor (CRCW0402158KFKE) has the same temperature stability range as the capacitor. For the in-vacuum printed circuit board the material chosen was the Rogers laminate 4350-B. The Rogers 4350-B is composed of hydrocarbon ceramic woven glass which provides very low outgassing at temperatures up to $125^\circ C$ and a thickness of 0.34. The final 2 layer PCB has the pads and traces made of copper (1.5 oz.); no mask or silk was added to the PCB to avoid adding unnecessary materials inside the UHV chamber that could outgas. Additionally, the PCB has an array of thru holes that allows the ZIF socket to be mounted and soldered in place. The solder employed was Kester lead free and composed of 96.5% tin, 3% silver and 0.5% copper (Sn96.5Ag3.0Cu0.5). To connect the PCB with the exterior of the chamber, it was connected thru a 100 pin adapter designed to be attached to the flange.
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5.7 Ion trap chip mounting

The microfabricated ion trap is mounted in a ceramic pin grid array (CPGA) package where the RF and DC electrodes are wire bonded from the chip bond pads to the CPGA pads. This type of package has the pins arrayed on one side of the package, for easy mounting to the socket. A great advantage of using the CPGA package is the flexibility to interchange traps by only removing it from the socket and keeping the rest of the vacuum chamber unchanged. The CPGA (CPG10018) was acquired from Spectrum Semiconductor Materials.

![Chip mounting](image)

Figure 5.7: Chip mounting

The CPGA is connected to a zero insertion force (ZIF) socket for easy insertion. A ZIF socket is an array of receptacle pins, where their positions are controlled by a lever that drives all the receptacles with the same pressure to their opened or closed positions. The receptacle pins are made of a copper alloy with beryllium and gold
plating. The ZIF structure is made of a thermoplastic polymer called polyether ether ketone (PEEK), which is an insulator and resists high temperatures.

5.8 Ion trap fabrication

For this experiment, a linear surface ion trap fabricated in the MESA fab at Sandia National Laboratories was used[70][48]. This trap is geometrically similar to surface traps fabricated with other alternate techniques besides aluminum on silicon dioxide, including printed circuit board, gold on quartz [66][17][1][41][18][71]. The principal feature of the Sandia trap design is the minimization of the exposed dielectrics in the surface trap to the ion. This feature helps to reduce the influence of the undesired stray fields to the ion[27]. To accomplish the reduction of dielectric exposed in the surface trap, Sandia’s design used an array of DC and RF conductor electrodes that are supported by oxide pillars. The oxide underneath is etched, reducing the amount of dielectric below the electrodes and leaving a few microns of the electrode overhanging. The surface trap is fabricated using MEMS fabrication process with multiple metal layers. The design also requires having a lower metal layer which contains the bond pads allowing the interconnection of the chip with the CPGA package. The bottom metal layer also serves as a ground plane to limit RF coupling loss to the silicon substrate. Additional metal layers buried between top electrodes and the bond pads plane are needed to complete the interconnection and routing of the bond paths terminals to the top electrodes.

A silicon on insulator (SOI) is used as the substrate for developing the ion trap structure[73]. The bottom metal layer consists of aluminum layer of about 1 µm which was deposited in the SOI substrate and planarized. Above the first metal layer, a layer of silicon dioxide is grown through plasma enhanced chemical vapor
Chapter 5. Ion trap experiment

deposition (PECVD) process. Each 2 \( \mu \text{m} \) layer of oxide is etched and planarized to create via trenches which are filled with tungsten in the next process step. The vias are fabricated for interconnecting the metal layers. Several layers of oxide are grown and etched to build up the insulating layer. A top metal layer is deposited to form the trap electrodes. The separation between electrodes is about 10.5 \( \mu \text{m} \). Finally, part of the oxide layer underneath the top metal layer is wet etched forming the overhanging electrodes. Additionally, two holes of 105 \( \mu \text{m} \) diameter and separated about 4 mm were etched in the silicon substrate allowing the loading of atoms from the backside of the trap and forming the optical cavity.

Control electrodes require capacitors to shunt to ground RF signals, which couple via the parasitic capacitance between the RF electrode and the control electrodes. This can be achieved in the cavity trap using an interposer chip with a trench capacitor for each control channel, only for the 96 control version.

![Chip cross section](image.png)

Figure 5.8: Chip cross section
Chapter 5. **Ion trap experiment**

Each trench capacitor has a capacitance $C = 1.05 \text{ pF}$, with a variance $<1\%$. They are meant to be operated at up to $20 \text{ V}$, but the breakdown voltage is $> \pm 30 \text{ V}$. The stray inductance, which can undermine the ability to shunt the RF off the control electrodes, is $0.05 \text{ nH}$, much smaller than the $1 \text{ nH}$ inductance that the wirebonds otherwise would have added. The lead resistance of $4 \ \Omega$ is comparable to the wirebond lead resistance. The shunt capacitors can also be provided by the users inside or outside the vacuum chamber using standard ceramic chip capacitors.

### 5.9 Ion trap operation

After the vacuum chamber, has reached a pressure of about $3 \times 10^{-11} \text{ Torr}$, the system is ready to begin to try ion trapping. The RF can is connected and optimized to deliver the voltage of about $250 \text{ Vpp}$ at $25.5 \text{ MHz}$ to the RF rail electrodes. The DC voltage is applied symmetrically to 3 electrodes on each side of the loading hole and the center electrode. These DC voltages varied between $-3.5 \text{ V}$ and $+3.5 \text{ V}$ around the loading hole, but they can varied from $-6 \text{ V}$ to $+6 \text{ V}$ during shuttling. A current of $3.8 \text{ A}$ is applied to the stainless steel needle to generate ytterbium vapor. The stream of atoms out of the source has a tight diameter of approximately $800 \ \mu\text{m}$ which travels through the loading hole.

To verify that the stainless steel oven is aligned with the loading hole, it was heated by applying few amps of current until a flux of neutral atoms came out of the oven and through the hole. The atoms above the surface of the trap absorbed photons from the $399 \text{ nm}$ laser which promoted the valence electron from the S state to the P state. From the P state the electron decays to the S state and emits a photon which is observed on the Andor camera. The $399 \text{ nm}$ laser frequency is scanned to find the
Chapter 5. Ion trap experiment

Once the neutral atoms are present in the trap loading region, the atoms are photoionized by a two photon absorption technique using a laser at 399 nm (751525.549 GHz) with 20 mW and 369 nm (739 nm lock 405645.775 GHz) with 20 mW. The lasers are set to the resonance frequencies of ytterbium 174. All lasers are set and aligned above the loading hole, approximately 100 µm above the surface. The 399 nm light promotes the electron to the excited P state and the 369 nm laser promotes the electron to the continuum. A repump laser at 935 nm (32571.975 GHz) with about 500 uW is aligned to the same position as the other lasers.
5.10 Compensation and shuttling

The next goal achieved was shuttling the ion into the cavity hole where the experiment takes place. The RF potential forms a quadrupole null where the ion is trapped. This quadrupole null resembles a tube that runs along the trap axis, where the ion is going to be trapped. The null point is located approximately 100 µm above the surface. The quadrupole null allows trapping in the radial directions, while trapping in the axial direction is controlled by the DC electrodes that run outside the RF electrodes in the trap chip. The solution table which was calculated with a custom boundary element modeling for all 96 DC electrodes.

The ion is compensated for micro-motion by applying DC offset to the center and outer electrode. The secular frequencies were measured by scanning the frequency
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of an oscillating field in the range of the secular frequencies. In this experiment the RF output was coupled to a direct digital synthesizer (DDS) source that provides the oscillating field needed to observe the variation of photon scatter of the trapped ion in a frequency range of 100KHz to 4MHz. The output of the coupler is amplified and connected to the RF can. The cooling laser is red detuned by 20 MHz of its optimal cooling frequency to avoid losing the ion during the frequency scan. The response of the tickle frequency is identified by an increase of the fluorescence. Once the secular frequencies have been identified, an additional voltage is applied to the near by electrode to minimize the ion micromotion.

Figure 5.11: Experimental setup

The shuttling solutions were calculated using a custom boundary element method
Chapter 5. Ion trap experiment

solver developed at Sandia. Control voltages up to 20 V are safe with an interposer, though the trap interposer has a 30 V breakdown limit for each control channel. Exceeding this limitation is very likely to result in a short to ground in the trench capacitor for that channel. A current-voltage characteristic corresponding to a diode is indicative of a short between metal and silicon. A strictly ohmic short is usually caused by direct metal to metal shorts either on chip or in the wiring. If no interposer is used the applied control voltages can approach the RF voltage (∼300 V). Figure 13 shows the electrode labels for the cavity trap. In this figure the RF trace comes off to the left, which defines a specific orientation. This can also be determined from the direction indicated by the gold tab on the package. The axial frequency resulting from an applied control voltage set is:

\[
\omega_{\text{axial}} = \sqrt{\frac{D U q}{m}},
\]  

(5.3)

where D depends on the particular unit voltage set (the geometry, electrodes used, etc.), U is the scale of the voltage applied, q is the charge of the ion, and m is the mass of the ion. The secular frequencies in the radial directions will be impacted by the addition of the control voltages.

Using the compensation voltages for the loading hole as an initial parameter, the ion was transported a few hundred microns and returned to the loading hole repeatably. The goal was to shuttle the ion to the cavity hole which is located at 4 mm away from the loading hole. When the ion was shuttled to a particular distance and did not return to the loading hole, the compensation voltages on the center electrode were adjusted along the path. The ion traveled to about 3 mm without needing to compensate the voltage in the center electrode. But when the ion was moved close to the top cavity mirror region, the ion was lost and did not return to the loading hole. We suspect that the charged dielectric mirror becomes charged and attracted the ion
Chapter 5. Ion trap experiment

when it travel around this region by adding few hundred of millivolts to the center electrode, the ion was pulled down from the curved mirror. The robust solution was found through several iterations of this procedure.

5.11 Lasers

In addition to the RF and DC voltages required for ion trapping, lasers are necessary for photoionization of the neutral atoms in the trap region, slowing down the motion of the trapped ion, and repumping the ion back to the cooling cycle when it decays to a metastate. Due to the demands of very stable lasers to realize all of these wavelengths, it is necessary to understand the techniques for laser locking.

In this thesis the element chosen for the experiments is ytterbium. Ytterbium neutral atoms are photoionized using two lasers with wavelengths at 369 nm and 399 nm. The 399 nm laser drives the electron from $2S_{1/2} \rightarrow 2P_{1/2}$ and the 369 nm laser drives the electron to the continuum. Doppler cooling for ytterbium requires a laser with wavelength of 369 nm. Similarly to the photoionization process the 369 nm laser drives the cooling transition $2S_{1/2} \rightarrow 2P_{1/2}$ to Doppler cool the trapped ion. When the ion is in the $2P_{1/2}$ excited state, it has a small probability to decay into the metastate $D_{3/2}$, stopping the cooling cycle. The ion needs to be returned to the cooling cycle, by repumping with a 935 nm laser. Once the ion is in this excited state it will decay into the $2S_{1/2}$ state, thus returning to the cooling cycle. Figure 5.12. [54].

For the lasers above an accurate and sensitive wavemeter is needed to measure the laser wavelengths. The wavemeter is calibrated externally using a stabilized Rubid-
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Figure 5.12: Yb energy levels

Ium atomic transition with narrow linewidth. The 399 nm and 935 nm lasers are stabilized using the wavemeter PID controller. A 780 nm laser was used to stabilize the trap cavity with the Rubidium atomic transition. The 369 nm laser is generated by doubling a 740 nm laser which is stabilized via a transfer cavity lock.

The transfer cavity locking technique in our lab is used to stabilize the Doppler cooling laser for the ytterbium transitions and also the stabilize the Doppler cooling laser for calcium transitions for another experiment [79]. This section will focus on explaining the general transfer cavity technique. Basically, the transfer cavity tech-
Chapter 5. Ion trap experiment

A stabilized reference laser with a fixed and known frequency. The laser is stabilized to a Rubidium atomic reference. After obtaining this stable reference laser, it is directed to a transfer cavity for locking the cavity length. The locking is done by servo controlling the piezo attached to one of the mirrors. Finally, the experimental lasers are locked to a resonance of the transfer cavity.

A laser of wavelength \( \lambda \) is coupled into an assembled cavity of length \( L \). There exists constructive interference when:

\[
2L/\lambda = n \quad (5.4)
\]

where \( n \) is an integer. Maxima interference of two consecutive modes is represented by:

\[
(n + 1) - n = \delta n = +/ - 1 \quad (5.5)
\]

when the cavity length is scanned, a new maximum is spaced by:

\[
\delta L = \lambda / 2 \quad (5.6)
\]

with \( \lambda \) fixed. Now if the frequency is shifted and the cavity length is kept fixed, then the change in the laser frequency between two resonances is:

\[
\delta f = f' - f = c/2L \quad (5.7)
\]

This quantity is known as the free spectral range. From this equation, it can be observed that the change in cavity length or mirror position \( \delta L \) depends on the
Chapter 5. Ion trap experiment

wavelength and the frequency changes depends on the cavity length. Suppose that two collinear lasers $\lambda_A$ and $\lambda_B$ are aligned into the cavity. If the cavity length is scanned each wavelength will undergoes constructive interference at different cavity lengths. However, because $\lambda_A$ and $\lambda_B$ are different they will occur with an offset. Now, consider the case where that one of the lasers is frequency stabilized and the second laser is not. If $\lambda_A$ is stabilized, its transmission maxima serves as a length reference for the etalon in units of length $\lambda_A/2$. Having a fixed $\lambda_A$ mode of our stable laser, a drifting nB fringe of $\lambda_B$ can be located close to the $\lambda_A$ mode. If the $\lambda_B$ changes, the corresponding transmission peak will shift by a $\delta\lambda$. It is very clear that a change in relative spacing will be observed between these two frequencies. Using this idea, a PID controller can be implemented to scan the laser B to change the target fringe separation between these two lasers. The implementation of the transfer cavity is represented in figure 5.13.

The 739 nm laser is locked using a transfer cavity, which uses a stable 780 nm laser as reference laser, which in turn is locked using an error signal derived from saturated absorption spectroscopy of atomic rubidium[42]. The rubidium is an alkali metal with one valence electron in its most outer shell. The transition between the $5S_{1/2} \rightarrow 5P_{1/2}$ is driven by the 780 nm laser resonance and can absorb and emit photons when on resonance. The spin-orbit interaction will split the 5S and 5P states in fine structures as follows:
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\[ 5S, l = 0, s = 1/2 \]
\[ |l - s| < j < l + s; j = 1/2 \]
\[ ^2sL_j \rightarrow ^2 S_{1/2} \]

\[ 5P, l = 1, s = 1/2 \]
\[ j = 1/2, 3/2 \]
\[ ^2P_{1/2}, ^2P_{3/2} \]

Moreover, some atoms have nuclear spin I, which interacts with the total angular momentum J. This interaction generate the hyperfine structure. The nuclear spin of rubidium state isotope is I=3/2 , then:

\[ 5^2S_{1/2}, I = 3/2, J = 1/2 \]
\[ I - J < F < I + J, F = 1, 2 \]
\[ 5^2P_{1/2}, I = 3/2, J = 1/2 \]
\[ I - J < F < I + J, F = 1, 2 \]
\[ 5^2P_{3/2}, I = 3/2, J = 3/2 \]
\[ I - J < F < I + J, F = 0, 1, 2, 3 \]

The transitions analyzed in the optical setup are the \( D_2 \) lines with transitions from \( 5^2S_{1/2} \rightarrow 5^2P_{3/2} \). The transitions on the \( D_2 \) lines follow the selection rules described by:

\[ \Delta J = 0, \pm 1 \quad \Delta M_J = 0, \pm 1 \] (5.8)
Parity change

\[ \Delta l = \pm 1 \]

Any \( \delta n \)

Any \( \delta L = 0, \pm 1 \)

\[ \Delta S = 0 \]

\[ \Delta F = 0, \pm 1 \]

\[ \Delta M_F = 0, \pm 1 \]

The rubidium hyperfine structure is resolved using the saturated absorption spectroscopy technique. For this technique the 780 nm laser beam is split in two beams that are traveling in opposite direction through the rubidium atoms. One of the beams has a weak intensity, whereas the other beam has a strong intensity that saturates the transition in the rubidium sample. The weak beam is the probe and the strong beam is the pump. When the rubidium atom is traveling towards one of the

![Figure 5.13: Rb lock and transfer cavity](image-url)
Chapter 5. Ion trap experiment

beams, the frequency seen by the atom will be higher. This is the Doppler effect. Thus, the atom traveling with a certain velocity \( v \) towards one of the beams and away from the other will perceive two photons shifted in frequency by the Doppler effect. If the atom is traveling on the same axis of the beams, but approaching one of them the frequency will be upshifted. Conversely, the frequency of the opposite beam will be downshifted. However, the atom will not see any change of the laser frequency in any directions perpendicular to the beam axis. Therefore, both beams will excite atoms and will modify the absorption distribution. If the laser frequency is equal to the transition frequency of the rubidium atom, both beams will excite atoms that have the same velocity component \( v = 0 \). In this case the pump beam has already saturated the rubidium atoms, so the probe beam not be significantly absorbed and higher laser intensity will travel through the atoms to the detector. Figure 5.13.

The 780 nm laser diode is a Toptica tunable external cavity diode laser (ECDL) model DL 100. The ECDL configuration is used to reduce the laser linewidth of the free running laser diode and have better control of the wavelength tuning and avoid frequency mode hops[75][62]. In the ECDL Littrow configuration (Figure 5.14) the light emitted requires a collimation lens with very short focal length to have a laser beam with the same diameter over a long distance. This beam hits a reflection grating which is diffracted into a few orders. The first diffraction order is sent back to the the laser diode forming a cavity with a length of a few centimeters between the laser diode and the grating. The new cavity is longer than that diode laser cavity thus having a smaller emission linewidth. The second diffraction order goes to the experimental setup through a collimated lens.
Chapter 5. Ion trap experiment

5.12 Trapping

The Doppler laser cooling system consists of a master diode laser, a tapered amplifier and a doubling cavity system. The laser used is a Toptica TA/DL SHG pro. The master diode used in the system is a diode laser mounted in an ECDL configuration similar to the ECDL described in the above section. The light emitted by the laser diode is collimated and propagated to a disperse holographic grating. The first order diffracted beam goes back to the diode laser forming a cavity that is used to reduce the linewidth of the laser. The grating is mounted in a movable stage that allows adjustment of the angle of incidence to tune the laser frequency. The optical power of the master diode laser is about 25 mW, which is not enough to convert to UV frequency in a second harmonic generator. A high power source is needed after the master diode laser. Therefore, a tapered amplifier is added in the optical path before directing the laser into the SHG crystal. A tapered amplifier is a semiconductor diode laser that can deliver high power in a short range of frequencies. A few milliwatts of power seeded to a tapered amplifier can result in a couple watts of power output. Subsequently, this amplified laser travels through mode matching optics that adjust the spatial beam to the waist of the cavity. The resonant cavity where the doubling
Chapter 5. Ion trap experiment

crystal is located has a bow tie shape. The waist of the cavity is at the center of the
doubling crystal. In this way, maximum conversion efficiency is obtained. Similarly,
to the other laser configurations the master laser is locked using the Pound-Drever-
Hall technique. At the output of the cavity the doubled laser at 369 nm is coupled
to a polarization maintaining laser fiber. At the other side of the fiber it is split in
three arms using polarizing beam splitter cubes. The power is controlled using half
waveplates at the entrance of each beam splitter cube. Two of the arms are used
directly for cooling the trapped ion and the third arm is propagated through a New
focus electro optical modulator at 2.1 GHz. The third laser arm is used to align
and characterize the cavity trap at 369 nm. The characterization of the cavity is
explained in detail in the cavity section.

5.13 Cavity ion trap experiment

The surface ion trap is designed to create a trapping region along the axis parallel
to the surface. The two RF electrodes run through the chip, both with the same
oscillating voltage. In between the RF electrodes travels a DC electrode that controls
the vertical position of the ion. Along these electrodes there are 72 outer electrodes,
36 per each side, that control the ion position along the chip and allow the shuttling
of the ion from the loading hole to the cavity hole. Each outer electrode has a width
of 128 $\mu$m and a separation between of them of 10.5 $\mu$m. The loading and cavity
hole have a diameter of 105 $\mu$m. The distance between the two holes is 4 mm. The
cavity assembly is attached to the CPGA with epoxy (3M 2126) and the pressure in
the vacuum chamber is low enough (3 x10$^{11}$ Torr) to store ions for hours.

The RF resonator is coupled into the cavity through an electrical feedthrough and
minimized the back reflection power of the total applied power. The DC voltage
Chapter 5. Ion trap experiment

applied to the electrodes is delivered using a controllable digital DC power source with low noise.

The stainless steel ytterbium oven source is connected to the exterior of the vacuum chamber through an electrical feedthrough which also had the piezo wires. The oven source is heated by applying a current source of 3.8 amps for about 2 minutes to evaporate some ytterbium atoms that will flow through the loading hole. The 369 nm and 399 nm laser shutters were open for approximately one minute for photo-ionization. During this time the ionized atom was trapped at the RF null, immediately afterwards the 399 nm shutter was closed and kept the cooling and repumping laser activated.

Ion trapping is optimized by fine tuning the position of the laser cooling and repumping lasers until maximum fluorescence was achieved. Afterwards, the ion was shuttled by a few electrodes by trying not heat it. The oscillating field creates a “tunnel-like” shape along the principal axis of the trap, where the ion is transported from one loading region to the cavity region. A first approach allowed the ion to be
Chapter 5. *Ion trap experiment*

transported from the loading hole to the cavity hole back and forth with no need of cooling and repumping lasers. However, this approach did not allow holding the ion for very long times in the cavity region. A second approach using the cooling and repumping lasers in a position far from the loading hole allowed holding the ion for several minutes without losing it.
Chapter 5. Ion trap experiment

Figure 5.17: Cavity linear trap schematic

The ion is loaded on the top surface of the cavity trap. It is transported and held at electrode 7 by setting a second set of lasers (cooling and repumping) on that position. Knowing the pitch between the electrodes (∼138.5 µm) the lasers are set to the next electrode where is held. Thus, the ion is transported and held one at electrode at time underneath the copper flexure mount. Using this approach the ion is moved five electrodes with no errors. However, when the ion is moved closer to the center of the mount, the ion was not held. We suspected that the rf field created along the linear trap is modified when it travels underneath the mount. Thus, when we tried to hold the ion around the center of the mount, it is disturbed and lost it.

Simultaneously, the cavity coupling required some optical elements to focus and mode match the laser beam size to the cavity mode waist. A 780 nm laser is used to lock the cavity to the correct cavity length for the $S_{1/2} \rightarrow P_{1/2}$ transition of the ytterbium ion. A 369 nm laser drives the $S_{1/2} \rightarrow P_{1/2}$ transition in the ion, thus it is desirable to lock the cavity to the distance where the cavity is at resonance for 369 nm modes using the 780 nm laser. It is accomplished by coupling the 780 nm laser
and 369 nm into the cavity and modulating the 780 nm laser until the sidebands overlap the 369 nm mode. The 780 nm laser is modulated with a fiber EO at 10.8 GHz to overlap one of the sidebands with the 369 nm mode. The reflected beam goes to a Pound-Drever-Hall electronic setup for locking the cavity to the right cavity length[7]. Figure 5.18.

Figure 5.18: PDH lock technique
Chapter 6

Frequency translation

6.1 Overview of the project

This chapter describes the experimental efforts at converting the ultraviolet frequency of an emitted photon by a calcium ion to an infrared frequency[72]. Ion trapping is a leading technology for the realization of a quantum computer. Researchers in this field utilize a variety of elements for encoding information including Be, Yb, Ca, Sr, Mg, as well as other ions. A qubit encoded in one element cannot be directly entangled with a qubit encoded in a different element because of the energy differences. If we want to interconnect these qubits encoded in different elements, an interface is necessary to convert and match the energy of their emitted photons for entanglement.

The plan in this experiment is that a calcium ion is trapped and the light is collected using a objective with an NA= 0.35 and coupled to a single mode fiber. The coupled photons are directed into a nonlinear crystal located inside an optical cavity where the UV photons are mixed with a red pump laser converting the UV photon to an intermediate wavelength visible photon. When the UV photons travel through
Chapter 6. Frequency translation

the crystal, their electric field interacts with the material’s atomic dipoles, making them oscillate. If the material is homogenous and is not susceptible to the photon’s wavelength, they pass through the material with no change in their wavelength. However, if the material is susceptible to the photons wavelength and lack of inversion symmetry, the atomic dipoles will oscillate with nonlinear response adding harmonic frequencies to the photon natural frequency. When the electromagnetic waves of two photons interact in a material their frequency output response is modified. In this nonlinear process the magnitude of the electromagnetic waves is characterized by the $\chi^{(2)}$ coefficient. For this second order interaction three possible scenarios are presented [2] [14].

- Two input photons with the same frequency are mixed in a nonlinear crystal to create a photon with double the input frequency. This process is called second harmonic generation (SHG).

- Two input photons with different frequencies are mixed in a nonlinear crystal to create a photon with a frequency equal to the sum of the input frequencies. This process is called sum frequency generation (SFG)[3].

- In the third case the annihilation of two input photons occurs, generating a third photon that is the difference of the two input photons. This process is called difference frequency generation (DFG)[3].

6.2 Design and Experimental results

For this experiment the DFG method is used, which mixes the photons collected from the calcium ion and a high power pump laser. When two or more photons with different wavelengths travel through a nonlinear material for mixing, their relative
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Phase will change along the material. This phase mismatch limits the generation of the photons by mixing these two photons. One technique to overcome this issue is quasi-phase matching, where the phase mismatch is controlled by reversing periodically the orientation of the crystal. By inverting the crystal orientation the relative phase is kept constant, increasing the generation of photons. This period depends on the interacting photon wavelengths. The 397 nm photon emitted for the calcium ion is mixed with a 914 nm pump laser for generating 702 nm photons. For this case the poling period for first order QPM is approximately 3.1 µm. The target value for converting 397 nm to 702 nm is:

$$S_2 = \frac{\pi^2 \omega_2}{4 \omega_3} S_0 = \frac{\varepsilon_0 c n_1 n_2 n_3 \lambda_1 \lambda_3}{32 d_{eff}^2 L^2}$$ (6.1)

$$S_2 = \frac{(8.85 e^{-12} \cdot 3 e^8 \cdot 2.28 \cdot 2.14 \cdot 2.16 \cdot 702 e^{-9} \cdot 397 e^{-9})}{32 \cdot (11.6 e^{-12})^2 \cdot L^2}$$ (6.2)

A build-up cavity is designed to increase the power of the 914 nm pump laser in the crystal. The pump power needed to observe nonlinear conversion is approximately 20W. If the input pump power is about 100 mW a cavity with a buildup of 200 times is needed to achieve the required power. The cavity design has a bow tie configuration with two concave mirrors and two flat mirrors[67]. The three parameters that control the cavity performance are the mirror separation, the mirror radius of curvature and the coatings. The geometry of the cavity defines the Gaussian beam parameters. The mirrors have a radius of curvature of 150 mm. The mirrors selected are broadband coated for reflecting 914 nm wavelength at 99.9% reflectivity. The crystal is 30 mm long and is placed in between the in-coupler and out-coupler mirrors. The Rayleigh range is calculated to be the length of the crystal.

The input mirror coupling reflectivity is such that the cavity is impedance matched, by setting the reflectivity equal to the other losses in the cavity mirrors. The surface
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<table>
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<tr>
<td>L2</td>
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<td>Index of refraction of crystal at</td>
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<tr>
<td>Mirror reflectivity</td>
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</tr>
<tr>
<td>Build-up</td>
<td>292</td>
</tr>
</tbody>
</table>

Table 6.1: Cavity parameters for conversion in ppLT [74]

ion trap was fabricated at Sandias MESA fab[70]. The fabrication of this trap is similar to the surface trap used for the cavity experiments, but at the center of the trap there is a rectangular slot where the neutral calcium atoms are loaded. The ion is trapped about 80 µm above the surface. The ion trapping procedure is the same as for the ytterbium ions, as is explained in the previous sections. To transfer the photon emitted by the trapped calcium ion to the bow tie cavity, the photon is coupled to a single mode optical fiber. However, coupling the photon to the fiber requires a custom imaging objective. Similar, to the objective lenses used in the ytterbium trapping experiment this design employed five lenses, each 2 inches in diameter. This objective has a working distance of 43 mm and an NA of 0.35.

The lens had an expected coupling efficiency of 0.40, due to aberrations and spot size mismatch with the fiber mode field diameter and an additional system efficiency of 0.63, due to absorption losses. All this results in a total coupling efficiency of 0.253. The expected percentage of light collection is 3.2% from the $4\pi$ emission of light from the ion. Thus 0.81% of photons emitted by the ion were expected to be coupled into the fiber.

The objective was mounted on a five axis adjustment stage to have full control of
Chapter 6. Frequency translation

Figure 6.1: Objective

the x,y,z, tip and tilt position of the lens. An additional goal of this experiment was verifying that the photons emitted by a single ion trapped are indistinguishable by observing the intensity correlation, the second correlation function $g^{(2)}$, with a Hanbury-Brown-Twiss (HBT) interferometer. The $g^{(2)}$ measurement shows the

Figure 6.2: Assembled lens stack
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probability of observing a second photon at a time $t$ after the first photon has been observed. The results of this measurement indicate the nature of the photon. If the photon is due to thermal and non coherent light the $g^{(2)}$ is maximum at $t=0$, but decreases as the time increase. For coherent light, $g^{(2)}$ probability is independent of time and the smallest value occurs at $t=0$, a process known as anti-bunching.

![Histogram of the number of events per time between detector clicks.](image)

Figure 6.3: Histogram of the number of events per time between detector clicks. The data (circles) were normalized by dividing average count number per bin at long delay times. The fit is to Eq. 6.3, which describes expected photon statistics for an overdriven ion.

In this measurement photons collected from the calcium ion are sent to a beam splitter. At the transmitted and reflected output ports of the beam splitter a photomultiplier (PMT Hamamatsu H6240-01) is positioned in a HBT setup. The time arrival of the photons detected from one PMT are correlated in time with the photons collected by the second PMT using a PicoHarp 300 time-correlated single photon counter, set to 256 ps resolution. The results of this experiment are shown in the figure 6.3 with a resulting $g^{(2)}(0) = 3$ with no background subtraction of the signal.
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These were taken for an integration time of 12000 seconds with an average count rate of 9x10$^3$ per PMT. Another feature visible in the plot shown includes the the Rabi oscillations of the ion as is described by:

\[ g^{(2)} = 1 - e^{-\frac{3\gamma t}{4}} \left[ \cos(\Omega t) + 3\gamma.4.\Omega.\sin(\Omega t) \right] \tag{6.3} \]

where $\gamma$ is the natural linewidth of the transition and $\omega$ is the Rabi frequency at the specific detuning.

For the frequency conversion a third order quasi-phase matched (QPM) periodically poled lithium tantalate (ppLT) crystal was chosen. The poling period is approximately 3 $\mu$m with a length of 30 mm manufactured by Deltronic Crystal. The bow tie cavity utilized 0.5 mirror substrates from CVI/Melles Griot. The mirrors were coated by Evaporated Coating Inc with anti-reflection (AR) coatings for 397 nm and high reflective coating (99.9%) for 914 nm. The mirror coatings were measured applying a normal incident beam to be 99.8% and found the cavity build up to be 292. The bow tie cavity was locked to the 914 nm pump laser via the Pound-Drever-Hall (PDH) stabilization technique[7].

The cavity optical table was mechanically decoupled from the table using sorbothane isolation material which allows the cavity to remain locked for hours. The crystal was located between the in-coupler and out-coupler mirrors and mounted in a machined aluminum jig that sits on a five axis translation stage to align the crystal to the internal beam of the cavity. The mount is heated via a kapton heater and a thermo-electric cooler. The crystal mount sustains a stabilized temperature of 125$^\circ$C which is required to adjust the QPM pole length. The pump laser is an external cavity diode laser (ECDL). It employed a Thorlabs (M9-915-300) diode with a maximum output power of 300 mW, coupled to a fiber optical cable The power delivered to
the cavity is about 100 mW. A dichroic beam splitter is used to overlap the pump and ion photon. Unfortunately, frequency conversion could not be observed because a higher power pump laser was required. The calculations for the mW power laser required a first order nonlinear crystal, but we used a third order poling because of the technical challenges to manufacturing a first order periodic poling length.
Figure 6.5: Cavity transmission signal. The cavity transmission trace is shown in blue. The PDH error signal that is used to stabilize the cavity is shown in green. The PDH is offset for clarity.
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Figure 6.6: Setup for imaging the ion and coupling light to the fiber. Here, a pellicle beam splitter could send light to a secondary lens for imaging on the camera and the fiber or it could be removed to send all of the light to the fiber for maximum coupling. a) Image of a single calcium ion b) Thunderbird trap.
Chapter 7

Conclusions

A micro cavity setup was designed, built, characterized and mounted onto a surface linear ion trap designed and fabricated by Sandia National Laboratories. Also the linear ion trap was characterized, before being mounted to the micro-cavity. The cavity ion trap integration is presented and discussed in detail in this thesis.

During the development of the experiment several optical schemes were used for mounting and characterizing the micro cavity. Several optical resonators with different lengths were built to characterize the mirrors with various radii of curvature and transmission losses. An optical setup for cavity mode matching was built in a portable clean room (Sentry Air System) for mirror mounting into the flexure device. Also the cavity alignment and mounting to the ion trap chip was performed in this clean space. The cavity ion trap system was tested by finding Gaussian modes, prior to installing it into the vacuum chamber.

An ultra high vacuum chamber was constructed to suit the cavity ion trap. Also, a custom bottom flange was designed to accommodate a view port, which allows access to the transmission of the cavity beam; two electrical feed throughs that pro-
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Provide current and voltage to the stainless steel oven and cavity piezo; and a 100 pin connector that delivers the DC voltage to the control electrodes. In order to reduce the amount of cross-talk between the rf signal and the DC electrodes, every control electrode has a passive low pass band filter integrated in a UHV compatible printed circuit board.

Once the cavity ion trap system was built, the linear ion trap was characterized by loading and trapping ytterbium ions. In addition, the trapped ion was shuttled along the cavity axis repeatedly. The optical resonator was characterized by coupling 780 nm and 369 nm light and measuring the finesse. The cavity was locked using the 780 nm laser to the $S_{1/2} \rightarrow P_{1/2}$ transition of the ytterbium ion.

Additionally, during these years at graduate school I participated in two more experiments. In one of these experiments, a new ion trap chamber was built and characterized using calcium atoms. A new objective lens with large NA and long working distance was designed and built. The photon emitted by the calcium ion were coupled into a single fiber for coupling into a ring cavity for frequency translation. $g^2$ measurement were realized in this experiment demonstrating the quantum photon nature. The other experiment was the characterization of ultra smooth micro mirrors fabricated in a silicon slab for cavity quantum electrodynamics experiments with neutral atoms.

In summary, this thesis were focused on integrating optics with atom traps. The experimental considerations and the detailed construction of an optical resonator integrated with a surface linear trap is presented. The optical micro cavity is aligned by monitoring the modes on the transmission side instead of the reflection. It is difficult finding high quality mirrors for ultraviolet light, and in addition the UV light damages the coating, if it is exposed to UV for a long time or at applied high
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power. This exploratory experiment has helped to understand better techniques to assemble a cavity trap, the limitations of working with UV light and the potential use of this system for quantum entanglement.

7.1 Future outlook

The integration of an optical resonator on an ion trap is a necessary scheme to interconnect separates traps and also for transmitting quantum information through photons entangled with the trapped ions. This thesis explained in detail the efforts to implement an optical resonator normal to a surface trap. However, new challenges appeared during the implementation and integration of the cavity trap system.

The first challenge was coupling of the UV laser light into the micro cavity by observing the back reflection. It was difficult to achieve, because the back reflection has a small SNR caused by the absorption of the silicon mirror plus the losses in the curve and silicon slab mirror at UV. This makes difficult the coupling of the UV light, with the modes buried into the noise. To overcome this, we replaced the silicon mirror with a flat fused silica mirror that allowed observation of the cavity transmission. The larger SNR of the transmitted light allowed a rapid alignment of the laser light into the cavity and the trap hole of 105 \( \mu \text{m} \) of diameter.

A second issue is the limitation of producing a high reflectivity coating for the cavity mirrors at UV wavelengths. In this experiment we designed the cavity to be resonant with the ytterbium ion optical transition at 369 nm. It would be better to use a different element such as barium for the qubit creation. Using barium ions, the cavity would be designed to couple the optical transition between the \( S_{1/2} \rightarrow P_{1/2} \) states at 493 nm [23]. It is very feasible to obtain excellent coating mirrors at this
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wavelength (finesse $> 8e^4$) [19].

Another problem mount is the lack of visibility of the ion once it travels underneath the cavity flexure mount. The mount did not allow complete control and effective alignment of the cooling and repumping laser beams at the cavity region. One way to overcome this issue would be to reduce the mirror diameter from 4 mm to 2 mm, and design a flexure mount. The milling of the curved fused silica mirror to a 2 mm diameter has been demonstrated previously. This new mount will allow reduce distance from the loading hole to the cavity hole, allow visibility of the ion until just the edge of the cavity mirror, and reduce the amount of copper material on top of the surface ion trap. Moreover, the cavity trap would be installed in a smaller octagon chamber that would permit to reduce the working distance of the objective lens and the distances of the lasers for cavity coupling, ion cooling, photoionization and repumping.

A different approach would consist of a cavity aligned horizontally to the surface ion trap. Such a design would allow complete visibility of the trapped ion along the trap axis. To accomodate this design, we would use coned down mirrors, like the one used in this thesis, and mount them on the CPGA ceramic. The ceramic would have trenches milled by a laser that would permit the placement and alignment of the mirrors. Both mirrors can be mounted on shear piezos, but would have only one of them in operation at the time. Once the cavity passed the testing protocol, a linear trap would be designed around it for integration of the system. A similar approach to the horizontal cavity could be realized using fiber tips coated for barium transitions at 493 nm [15], in this case the cavity would use trenches etched on silicon slab for alignment of the fibers. This fiber would be driven by MEMS actuators.
Appendices

A  Ultrasmooth microfabricated mirrors for quantum information 5
Appendix A

Ultrasmooth microfabricated mirrors for quantum information

This section explains the work developing an ultra high reflectivity micromirror in a silicon slab for quantum information systems on an atom chip[6]. The figure of merit for an atom cavity system is typically described by the single atom cooperativity, $C_1 = \frac{g_0^2}{\kappa \gamma}$, in some cases it is desirable to be in the strong coupling regime with $C_1$ larger than unity[5]. Here $g_0$ is the vacuum Rabi frequency which quantifies the atom photon coupling strength, $\gamma$ is the atoms natural linewidth and $\kappa$ is the damping rate of the cavity field. To maximize the cooperativity we seek to enhanced the cavity finesse $F$. The finesse is a function of the reflectivity which depends on the surface roughness, so it is necessary to optimize the smoothness resulting from the mirror fabrication process. The reflectivity limit due to surface roughness is quantified by the scattering factor $SF = e^{-\left(\frac{16\pi \sigma}{\lambda}\right)^2}$, where $\sigma$ is the roughness of the mirror surface and $\lambda$ is the wavelength of the light.

Achieving high reflectivity with a micromirror on a silicon surface requires minimizing the roughness of the surface, and depositing a high reflectivity coating. Mirrors that are nearly spherical may be formed in a silicon surface by isotropic wet etch-
Appendix A. Ultrasmooth microfabricated mirrors for quantum information

Figure A.1: Micro cavity

ing or through an aperture in a lithographically defined mask[35] [50]. For these micromirrors, wet etching was employed through lithographically defined circular apertures in a silicon dioxide hard mask. Mirror diameter and surface roughness scale with the aperture size for a give time; consequently the best surface roughness results were obtained with the smallest mask openings of 1 μm, and resulted in mirror diameters of about 70 μm. Fluorine (F) radicals are generated using NF$_3$ in a chemical downstream etch mode[9] [8]. After removing the silicon dioxide hard mask the mirrors are smoothed first using an inductively coupled plasma etch with SF$_6$ then by two consecutive oxidation smoothing cycles in which 2 μm of oxide was thermally grown at 1050°C with steam for 13 hours and then removed using HF etching. Consistent with the work in [38], the mirror surface was visually rough after F etching. After plasma smoothing the surface roughness was measured by AFM to be 6.2-8.5 Årms in a spatial wavelength band of 2 nm to 1 μm. The oxidation smoothing further reduced the surface roughness to a final value of 2.2 Årms. These results were consistent across the surface of a given 150 mm silicon substrate and over several substrates.
A scanning electron microscope image of a cross section of a finished micromirror fabricated using this process is shown in figure A.4. This mirror structure has a depth of 9.5 µm and a chord of 70.5 µm, indicating a RoC of 68 µm. However, subsequent cavity measurements show that the RoC is in fact 251 µm in the region defining the cavity mode, suggesting that the micromirror is aspheric with a slightly flattened bottom. Characterization of the mirror surface roughness after smoothing was performed by acquiring AFM images at the center of the mirror, found by turning off real time background subtraction, and restricting image processing to a linear background subtraction. The post smoothing roughness of 2.2 Årms supports, in principle, a reflectivity of 99.9988% and a cavity finesse of $\mathcal{F}=260\,000$ assuming a second mirror of equal performance. The mirrors are coated via an ion beam sputtering technique at 780 nm, with a dielectric mirror stack consisting of silicon dioxide and tantalum oxide layers. After coating, a slightly increased mirror surface roughness of 2.6 Årms is measured, which is attributed to native oxide formation on
Appendix A. Ultrasmooth microfabricated mirrors for quantum information

the Si surface before coating.

The optical properties of the micromirrors were determined using the experimental setup shown in the figure A.2. A half symmetric cavity was formed using a micromirror and a planar super polished fused silica mirror with an identical coating. Light from a 780 nm diode laser with a 2 MHz linewidth is coupled to the cavity through the planar mirror. A nonpolarizing beam splitter redirects a portion of the light reflected from the cavity to a fast photodiode. The transmission signal is inaccessible due to absorption by the silicon substrate. The cavity length was scanned with piezo actuators attached to the micromirrors substrate. A cavity finesse of 64 000 was measured with a contrast of 55% for a cavity length of 58 µm.

To measure the cavity length and radius of curvature a 2 GHz sidebands to the light was added with a fiber based phase modulator. The cavity length is determined by $\text{FSR} = \frac{c}{2L}$. The RoC is determined through the spacing of the $TEM_{00}$ and $TEM_{10}$ modes. These modes are separated in frequency by: 

$$ \delta v = \frac{c}{2\pi L} \cos^{-1}\sqrt{1 - \frac{L}{\text{RoC}}} $$

The RoC within the region of the mirror interacting with the cavity mode is independent of cavity length at the level of 251 +/- 17 µm for cavity lengths from L=19 to 123 µm. Using these measurements, these micromirrors could be useful for cavity QED experiments using $^{87}\text{Rb}$ which has a natural linewidth of $\gamma = 6.067$ MHz for the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ transition. Figure A.2 shows the calculated values for a single atom cooperativity, $C_1$, as a function of the cavity length. The expected cooperativity varies from 99 for the longest cavities (L=123 µm) to 204 for the shortest (L=19 µm) indicating that these cavities should exhibit a clear response to the presence of a single atom in the cavity.
Appendix A. Ultrasmooth microfabricated mirrors for quantum information

Figure A.3: Calculated single atom cooperativity
Figure A.4: A SEM image of two Si mirrors. The picture below shows the radius of curvature of the micro mirror.
References


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