Coherent Operations in a Microfabricated Ion Trap

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Introduction

- Trap strings of individual atomic ions using a combination of static and oscillating electric fields
- Applications in quantum information and quantum metrology
- Ion trap constructed from a monolithic semiconductor chip
- Laser pulses interact with electronic levels of ion
Motivation: Accurate and agile control of laser fields required in ion trapping, neutral atom manipulation, quantum simulation, atom interferometry and CQED based single photon generation

Aim: Develop highly agile laser source with accurate control over optical parameters

Outline:
- Introduction to experiment and coherent control
- Requirements in terms of phase, amplitude and frequency agility
- Laser setup and full characterisation
Experimental System

$422 \text{ nm}: \text{ Laser cooling/state detection}$

$1033 \text{ nm}: \text{ Repumper to enable closed cooling cycle}$
Experimental System

\[
\begin{align*}
\text{P}_{3/2} & \quad \rightarrow \quad \text{P}_{1/2} \\
\quad & \quad \rightarrow \quad 1033 \text{ nm} \\
\quad & \quad \rightarrow \quad \text{D}_{5/2} \\
\quad & \quad \rightarrow \quad \text{D}_{3/2} \\
\quad & \quad \rightarrow \quad \text{S}_{1/2}
\end{align*}
\]

88Sr+:

- 674 nm: Qubit transition laser/ resolved sideband cooling
- 1033 nm: Clearout /quencher

Laser cooling

422 nm
1092 nm

State manipulation pulse sequence
674 nm

Measure: S or D?
Fluorescence at 422 nm
Coherent Control of Qubit State

- Quantum computers and optical atomic clocks require coherent control
  → confinement in the Lamb-Dicke regime….

\[ \eta = \frac{2\pi}{\lambda} \cos \theta \sqrt{\frac{\hbar}{2M\omega}} \] \[ \eta^2 \sqrt{2n} + 1 \ll 1 \]

…and laser with long coherence time (i.e. narrow linewidth)

- Need to be able to create arbitrary superpositions

\[ |\psi\rangle = c_1 |S\rangle + c_2 |D\rangle \]

For full control over final state, need accurate and fast switching of optical **phase** $\phi$, **amplitude** $E$ and **frequency** $\nu$.

*J Thom et al, Optics Express, 21, 18712 (2013)*
Ramsey Pulse Sequence

\[ \tau \Omega = \pi/2 \quad \varphi = 0^\circ \]

\[ T_{\text{Precession}} = 4\tau \]

\[ \tau \Omega = \pi/2 \quad \varphi = 0^\circ \]

\[ \delta \nu \rightarrow \text{Detuning} \]

\[ \Omega \rightarrow \text{Rabi frequency} \]

\[ \delta \nu / \Omega = 2 \]

\[ \delta \nu \times T_{\text{Precession}} = 4\pi \]
**Ramsey Pulse Sequence**

- **Detuning**: $\delta\nu \rightarrow$ Detuning
- **Rabi frequency**: $\Omega \rightarrow$ Rabi frequency
- $\delta\nu / \Omega = 2$
- $\delta\nu \times T_{\text{Precession}} = 4\pi$

**Diagram:**
- Time axis with two $\tau$ intervals, $T_{\text{Precession}} = 4\tau$
- Amplitude axis with $\tau \Omega = \pi/2$, $\varphi = 0^\circ$
- Quantum states $|0\rangle$ and $|1\rangle$
- $\pi/2$ Pulse
Ramsey Pulse Sequence

\[ \delta \nu \rightarrow \text{Detuning} \]
\[ \Omega \rightarrow \text{Rabi frequency} \]
\[ \delta \nu / \Omega = 2 \]
\[ \delta \nu \times T_{\text{Precession}} = 4\pi \]
Errors in phase, amplitude and detuning all lead to errors in final position of Bloch vector → *Decreased gate fidelities*

- Realistic sequences extend to ~ 30 pulses (e.g. teleportation)
  → require accurate and agile switching of parameters
Coherent excitation spectrum of a single ion in the microfabricated trap

- Quantum logic operations require sideband operations
- High power required to drive sidebands due to reduced coupling strength

$\eta = 0.033$

$\rightarrow$ Shape optical pulses in amplitude to minimise off resonant excitation
$\rightarrow$ Minimise decoherence, maximise fidelity
**Bichromatic Operation for Entangling Gate**

- We aim to create entanglement in our system between two or more ions → Key resource in quantum computing and quantum metrology
- Mølmer-Sørensen gate - Used to create entangled states with 99.3% fidelity (Innsbruck 2008)

### Table: Excitation Probability

<table>
<thead>
<tr>
<th>Laser Frequency</th>
<th>Excitation Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier</td>
<td>Red Sideband</td>
</tr>
<tr>
<td></td>
<td>Blue Sideband</td>
</tr>
<tr>
<td>(\omega_{Red})</td>
<td>(\omega_{Blue})</td>
</tr>
</tbody>
</table>

\(\omega_{Blue} - \omega_{Red} \approx 4\text{MHz}\)

\(\rightarrow\) Require bichromatic operation

![Diagram of bichromatic operation for entangling gate](image)
Agile Slave Laser System: Optics

- Injection lock to master laser → Narrow linewidth for long coherence times
- Three AOM passes and second fibre → high extinction $\approx 5 \times 10^{11}$ to maintain qubit coherence between pulses
Direct Digital Synthesis (DDS) source provides agility in phase, amplitude and frequency via AOM1

AOM2 produces single frequency or bichromatic operation
Agile Slave Laser System: Test Setup

- Test measurement setup allows routine measurement of system properties
- Phase steps are detected via beat note with the master
Phase Control

- Accurate phase control is a requirement in some quantum logic gates and in interrogation schemes for atomic clocks.
- Transfer phase agility of DDS to laser light through acousto-optic modulation.
- Detect via beat note between AOM shifted and master light.

- $\pi$ phase shift
- Fits either side to calculate phase shift value.
Phase Control

- Measure the phase change over the full range of values from $0 < \delta\phi < 2\pi$.

![Graph showing the relationship between programmed and measured phase steps with a gradient of 1.00086(2)]
Phase Control - Fine Resolution

- Measure the phase change over a narrow range

- Gradient $= 1.000(5)$
Amplitude Control

- Need amplitude control $E(t)$ for fine control over ion state
- However AOM response to applied RF field is non-linear
- Account for this non-linearity using automated calibration routine
Amplitude Control

- Need amplitude control $E(t)$ for fine control over ion state
- However AOM response to applied RF field is non-linear
- Account for this non-linearity using automated calibration routine
After calibration, can generate Blackman pulses of duration $2T$ with the form:

$$E(t) = \begin{cases} 
E_0 \left[ 0.42 - 0.5 \cos \left( \frac{t}{T} \right) \cos 2\pi \frac{t}{T} \right] & \text{for } 0 \leq t \leq T \\
0 & \text{elsewhere}
\end{cases}$$
Operation over six orders of magnitude in duration

Short Pulses – Quantum Computing

Long Pulses – Atomic Clocks
Power Spectrum of Optical Pulses

- Calculated the Fourier spectrum of measured pulse shapes
- Measured Blackman pulse of 500 µs duration
Power Spectrum of Optical Pulses

- Calculated the Fourier spectrum of measured pulse shapes
  - Measured Blackman pulse of 500 µs duration
  - Measured square pulse of the same integrated power
Power Spectrum of Optical Pulses

- Calculated the Fourier spectrum of measured pulse shapes
  - Measured Blackman pulse of 500 µs duration
  - Measured square pulse of the same integrated power
  - Theoretical Blackman pulse of 500 µs duration
**Bichromatic Operation**

- Light field that interacts with two sidebands of center of mass mode of two ions.

- Use single pass AOM to create light field with two optical frequencies separated by 4 MHz.
- 30 ns rise time
**Microfabricated Ion Trap**

- **3-D electrode geometry** produces deep trapping potential.
- **Unity aspect ratio** design for highly efficient trap.
- **Monolithic** production process using conventional semiconductor fabrication techniques.

Fabrication: P. See et al, JMEMS, 10.1109/JMEMS.2013.2262573 (2013)
Summary

- Developed agile laser system –  
  *J Thom et al, Optics Express, 21, 18712 (2013)*

- Characterised full phase, amplitude and frequency agility

- Arbitrary pulses over six orders of magnitude in duration

Outlook

Coherent spectroscopy on ions:

- Demonstrate laser agility on ions

- Characterisation of decoherence of superpositions during ion transport

- Full implementation and characterisation of entangling gate