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Coherent Operations in a Microfabricated Ion Trap

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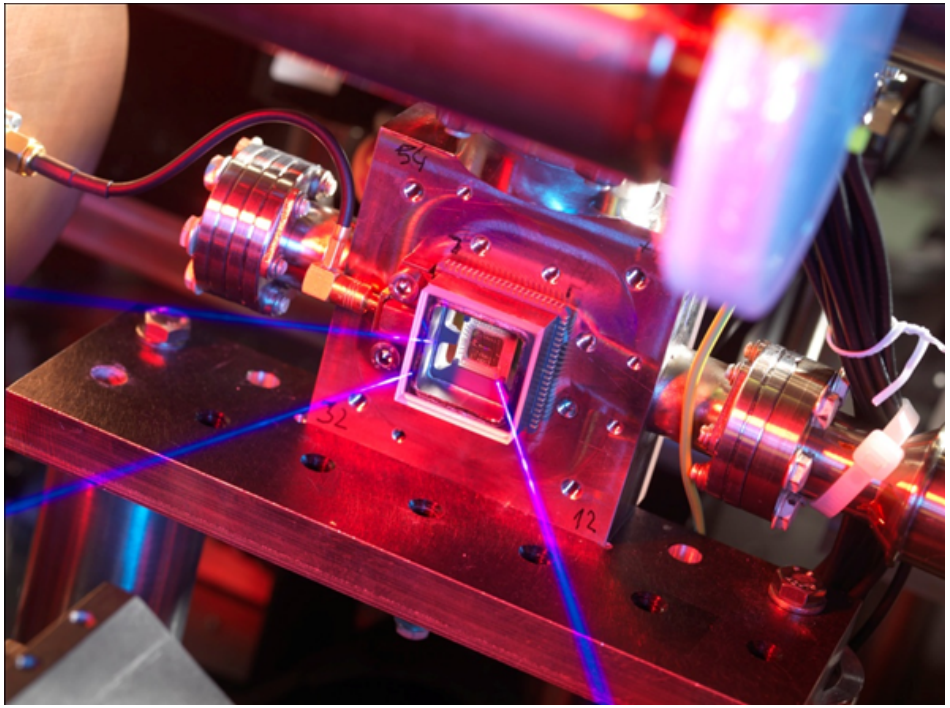
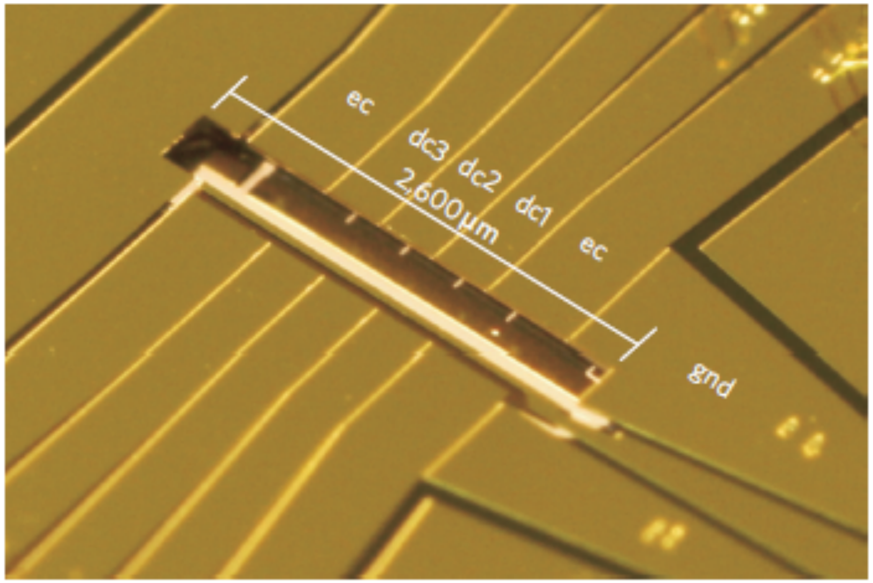
University of Strathclyde Glasgow

EPSRC
Engineering and Physical Sciences Research Council

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





Introduction

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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

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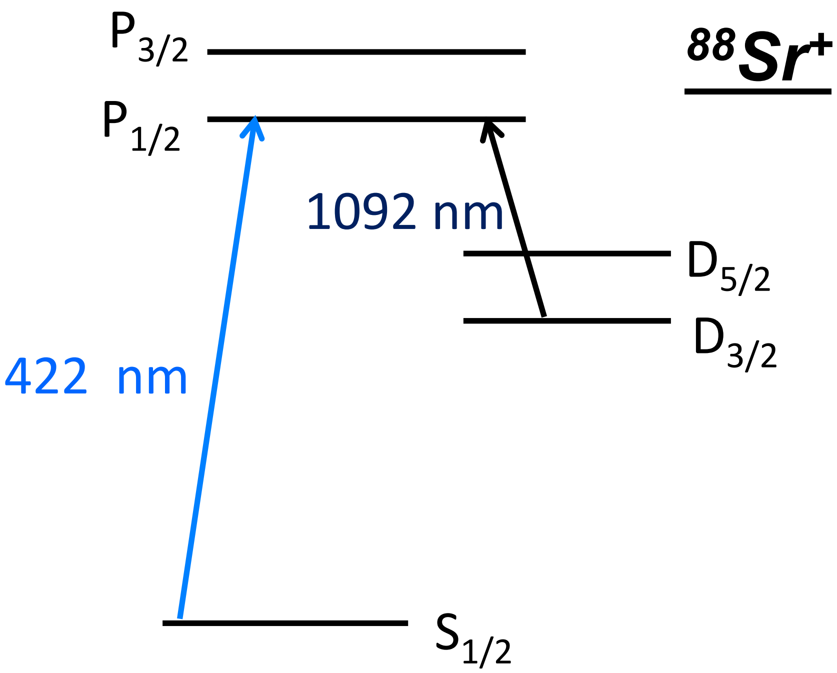
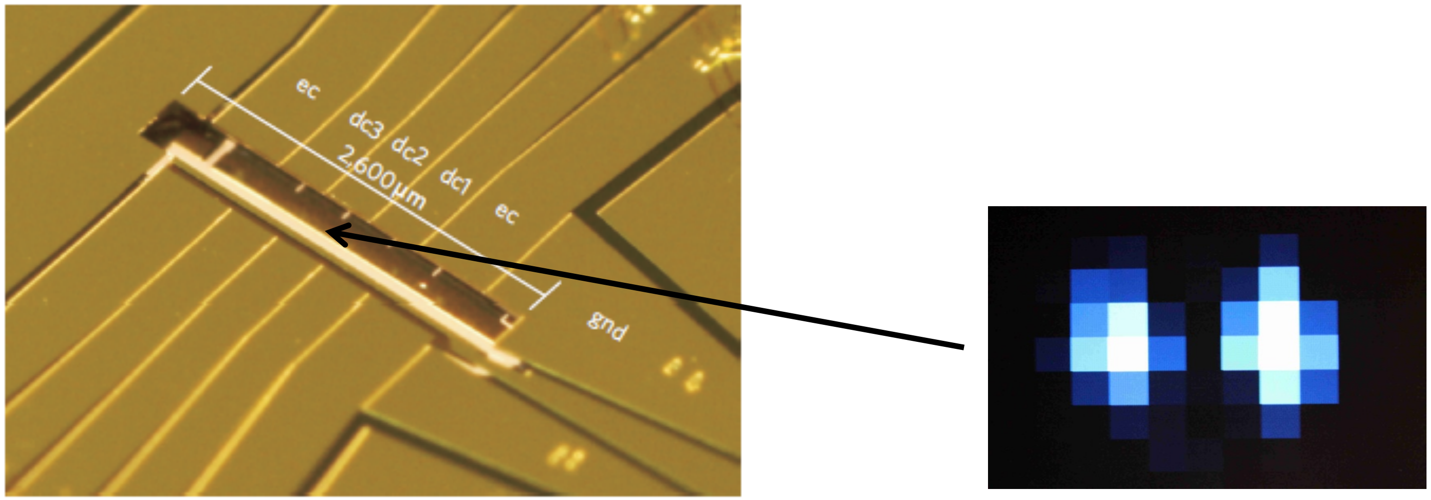
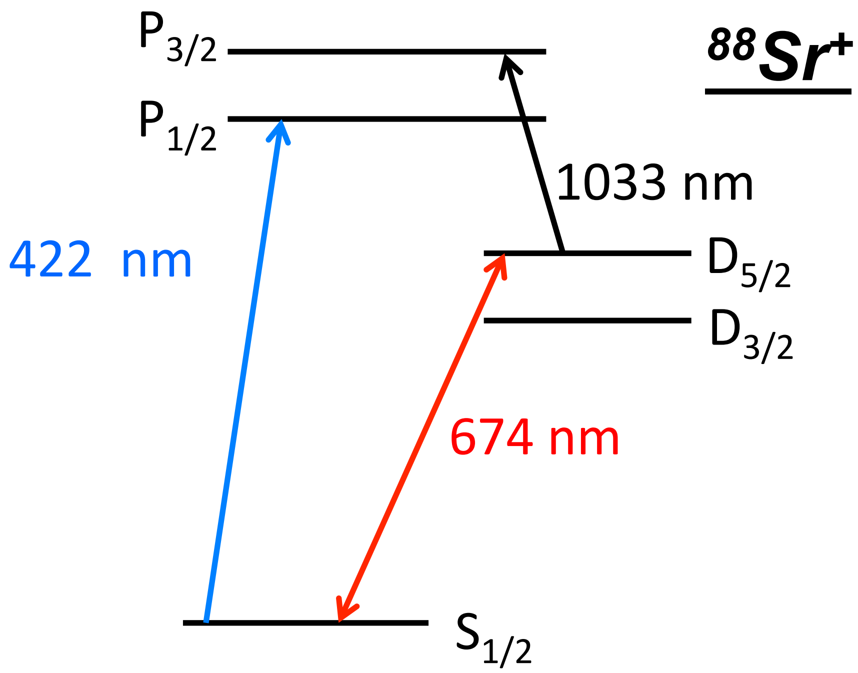


422 nm: Laser cooling/state detection

1033 nm: Repumper to enable closed cooling cycle



Experimental System



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

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- Quantum computers and optical atomic clocks require coherent control

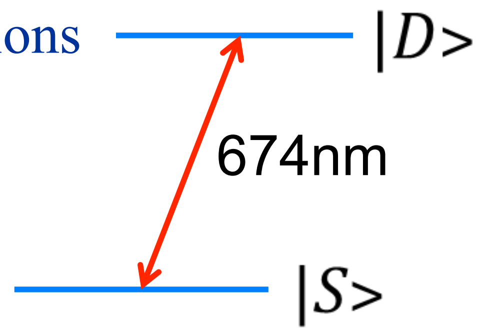
  → confinement in the Lamb-Dicke regime….

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

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

- Need to be able to create arbitrary superpositions

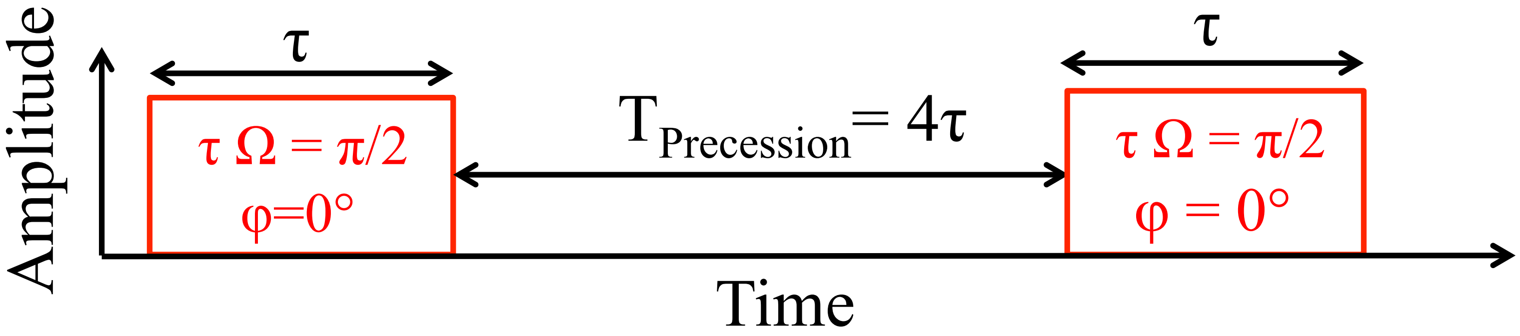
$$|\psi\rangle = c_1\,|S\rangle + c_2\,|D\rangle$$

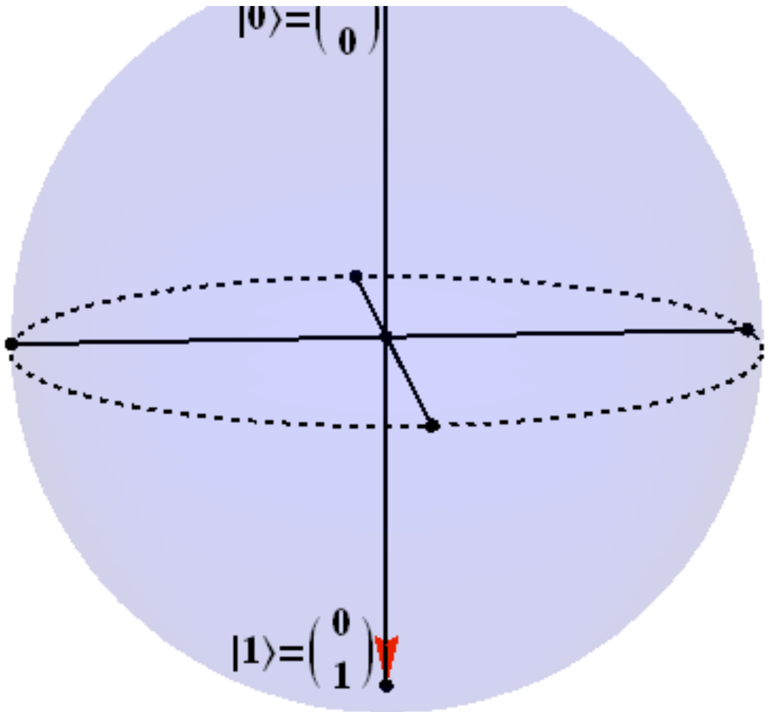


For full control over final state , need accurate and fast switching of optical **phase φ**, **amplitude E** and **frequency υ.**

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

Ramsey Pulse Sequence





π/2 Pulse

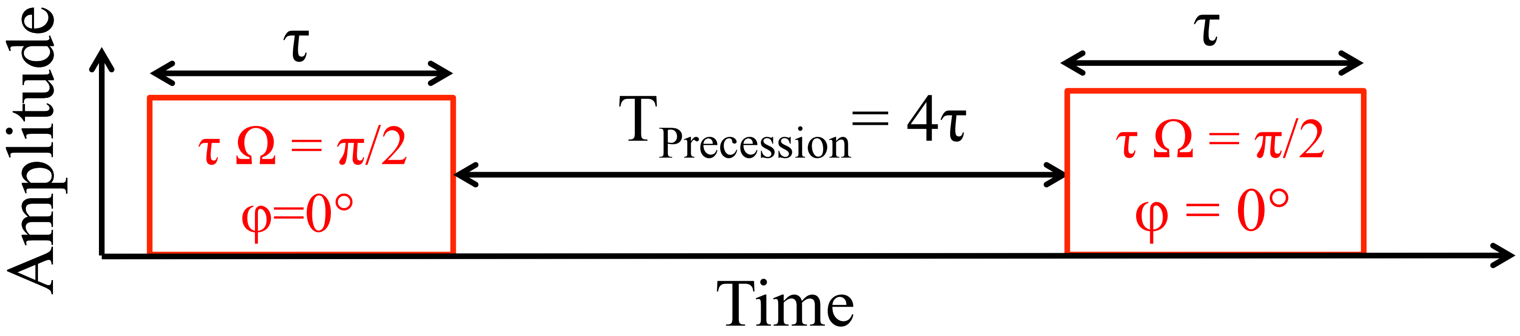
$\delta\upsilon \rightarrow$ Detuning

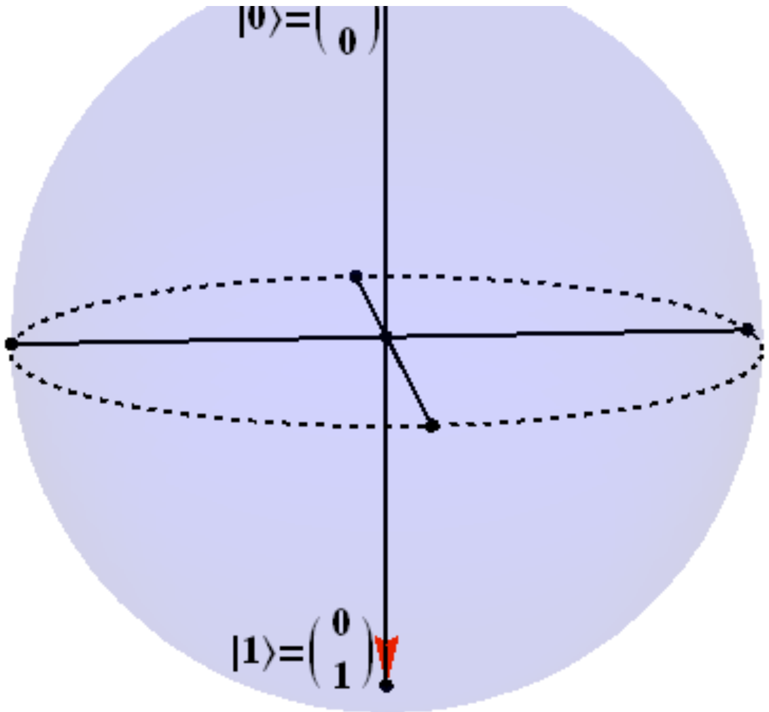
$\Omega \rightarrow$ Rabi frequency

$\delta\upsilon/\Omega=2$

$\delta\upsilon\times T_{Precession} = 4\pi$

Ramsey Pulse Sequence





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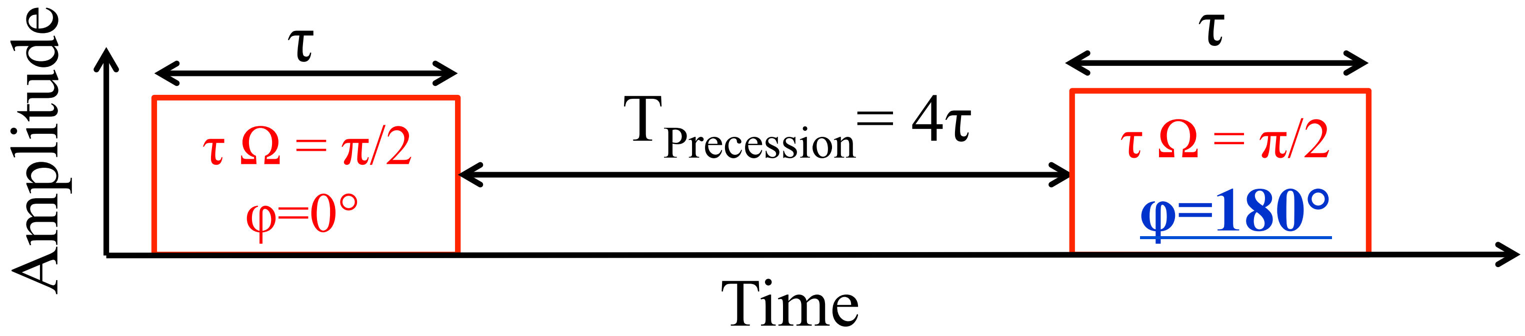

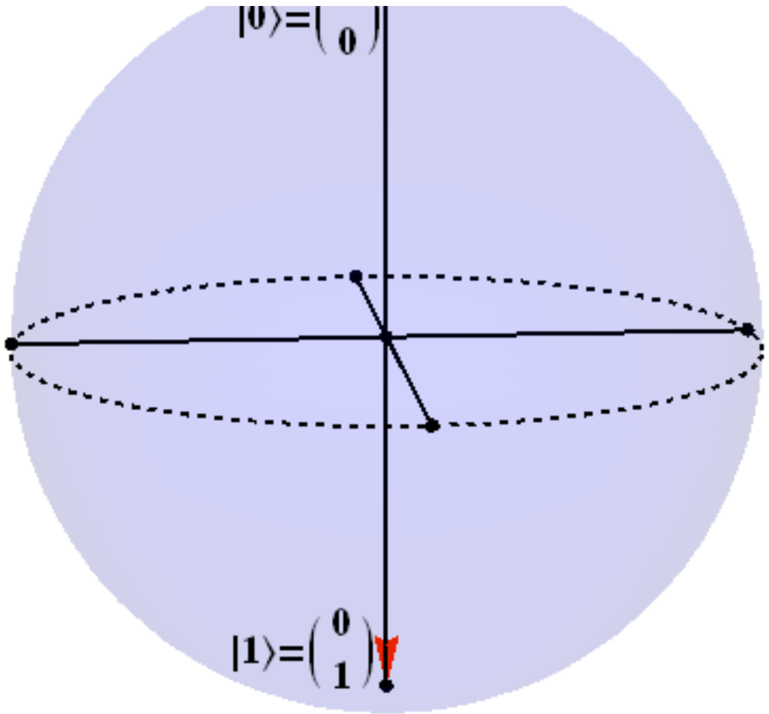

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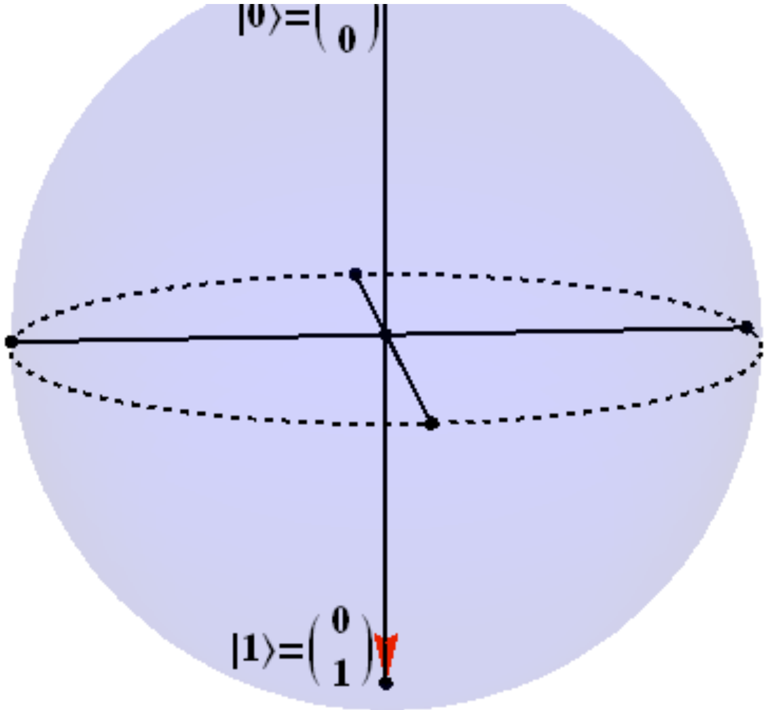
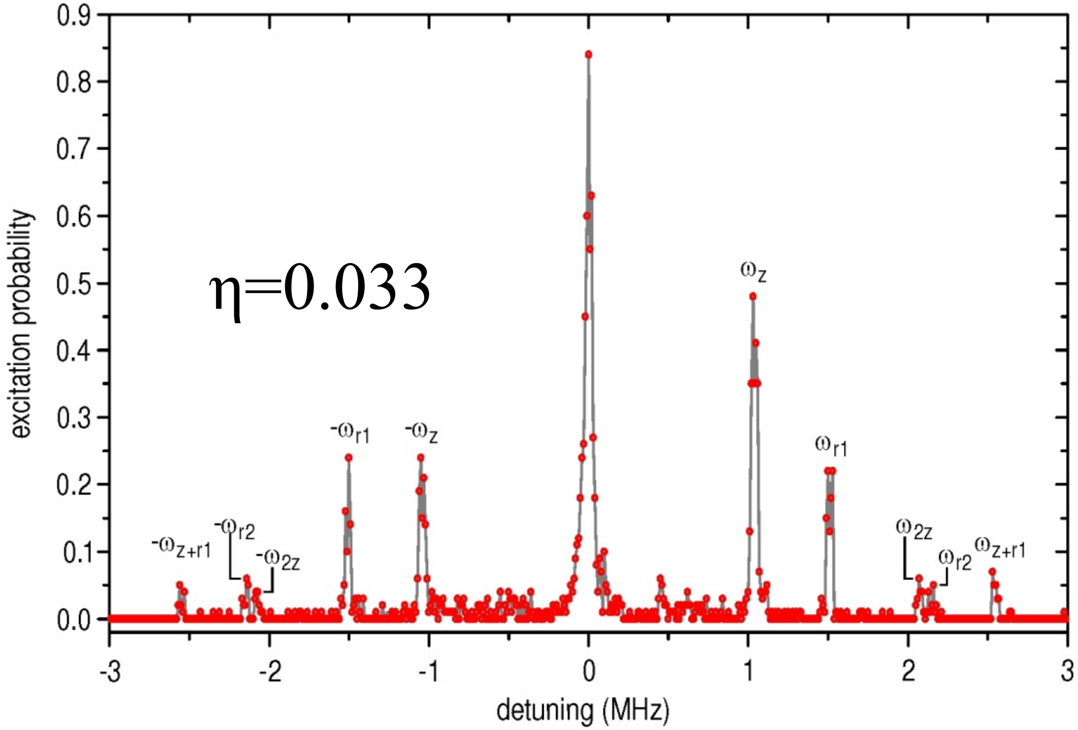


π/2 Pulse

- 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

Optical Spectrum of Trapped Ion

- 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

→Shape optical pulses in amplitude to minimise off resonant excitation

→ Minimise decoherence, maximise fidelity

Bichromatic Operation for Entangling Gate

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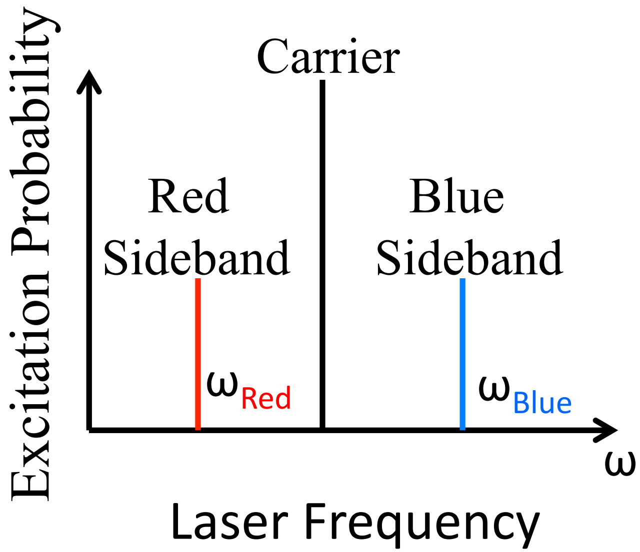
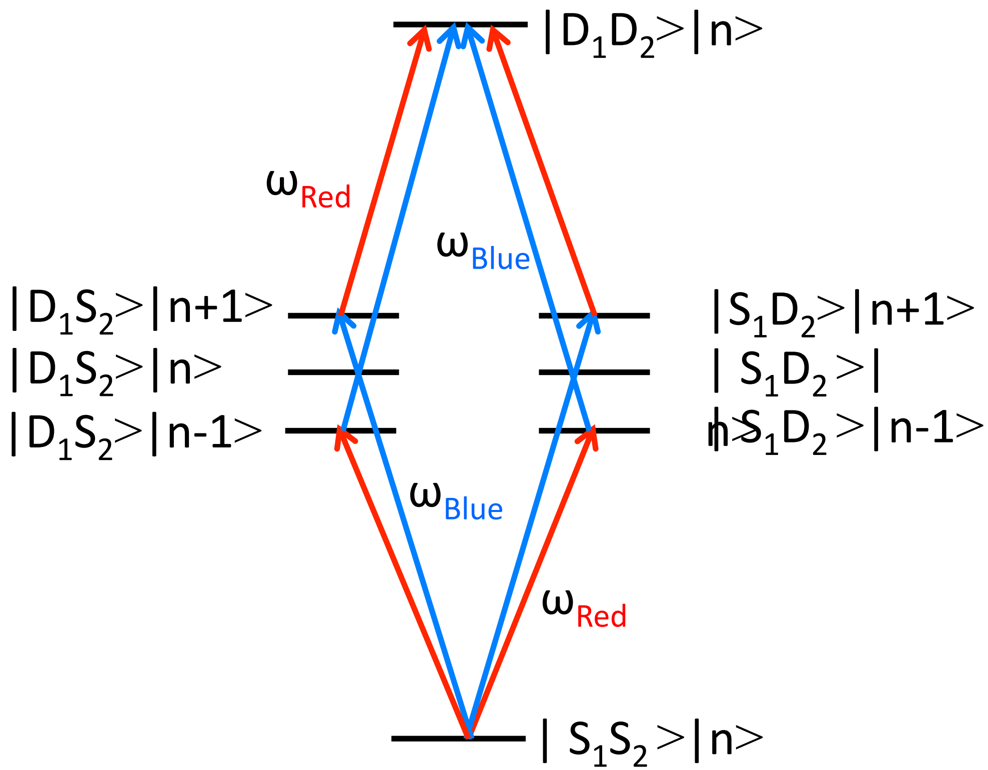
- We aim to create entanglement in our system between two or more ions → Key resource in quantum computing and quantum metrology
- Mølmer-Sørensen gate -Used to create entangled states with 99.3% fidelity (Innsbruck 2008)



$$\omega_{Blue} - \omega_{Red} \approx 4\text{MHz}$$

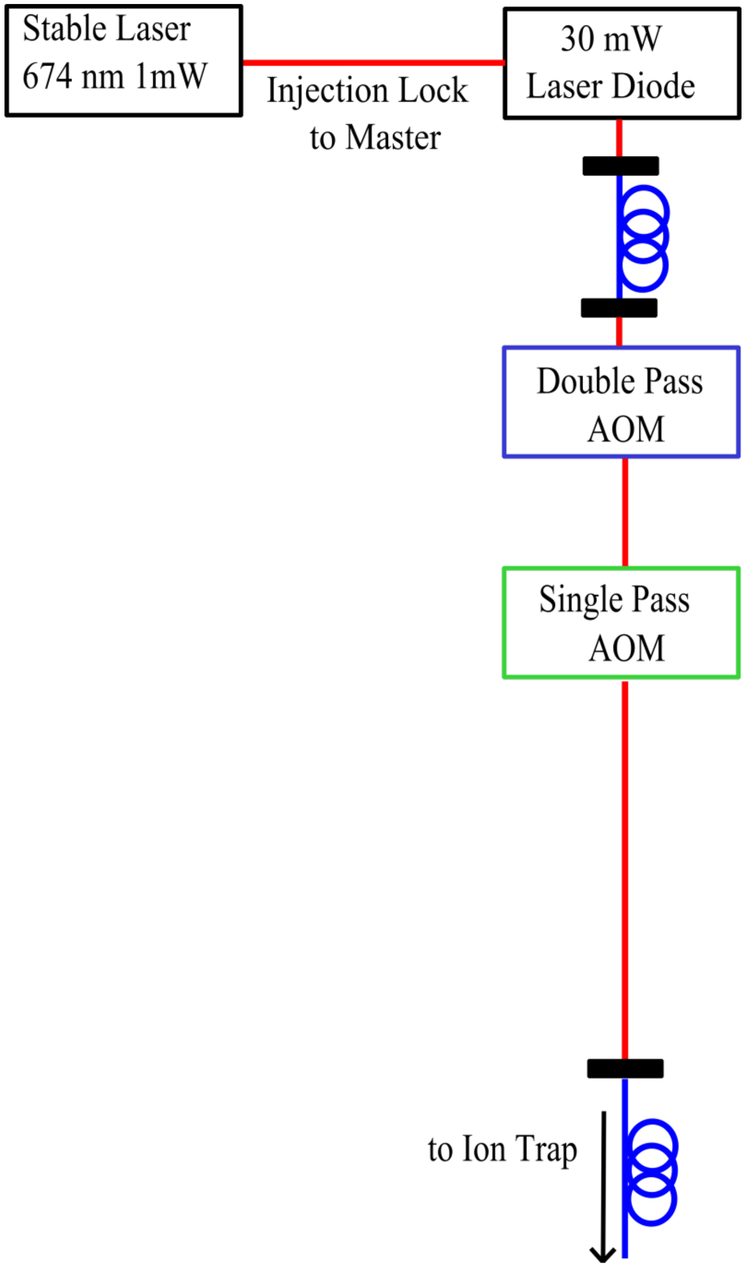
→Require bichromatic operation



Agile Slave Laser System: Optics

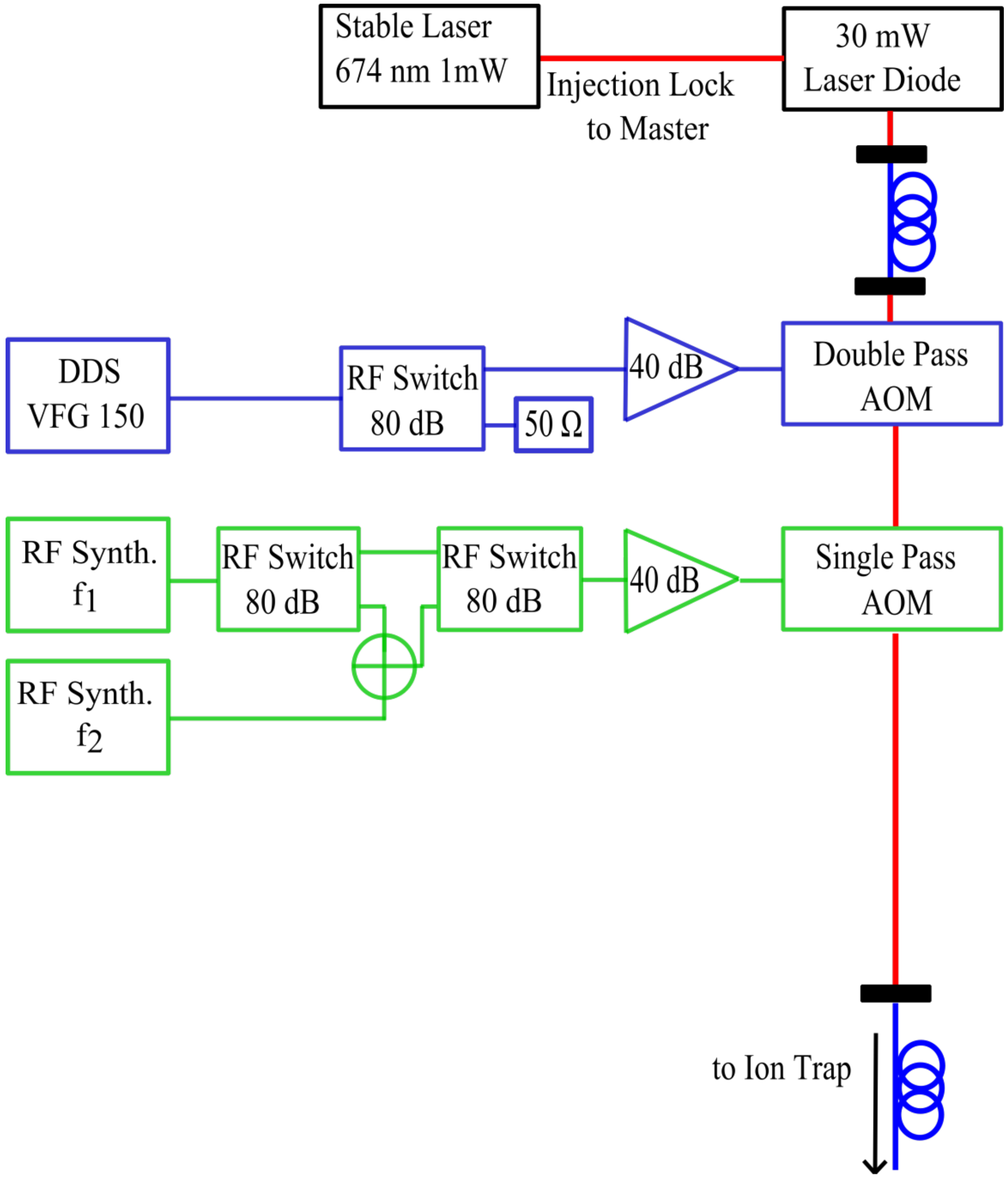
- Injection lock to master laser
  → Narrow linewidth for long coherence times

- Three AOM passes and second fibre
  → high extinction ≈ 5 x10^{11} to maintain qubit coherence between pulses



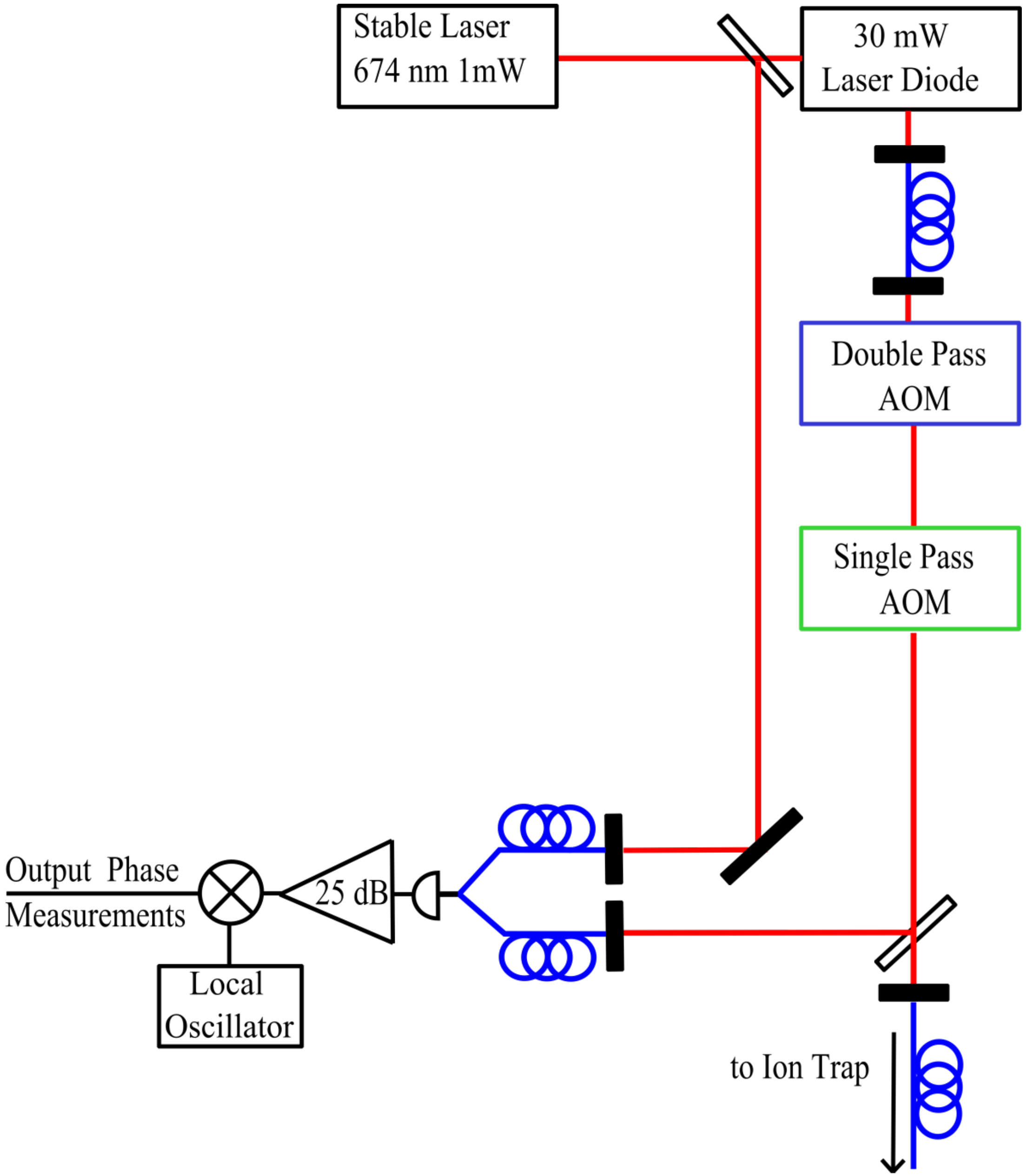
Agile Slave Laser System: RF control

- Direct Digital Synthesis (DDS) source provides agility in phase, amplitude and frequency via AOM1
- AOM2 produces single frequency or bichromatic operation



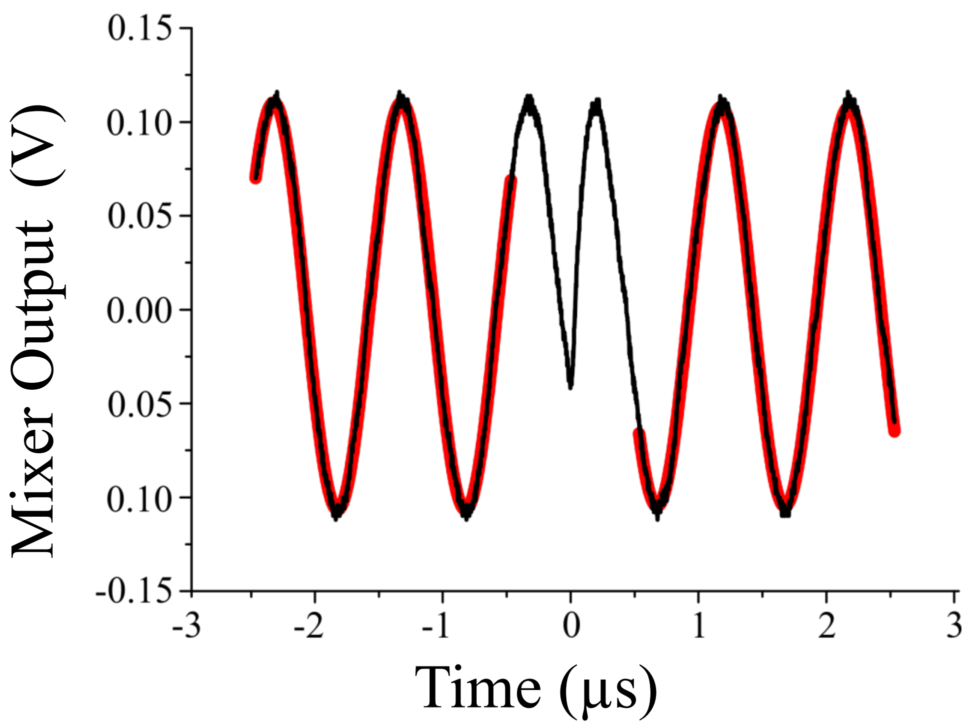
Agile Slave Laser System: Test Setup

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



Phase Control

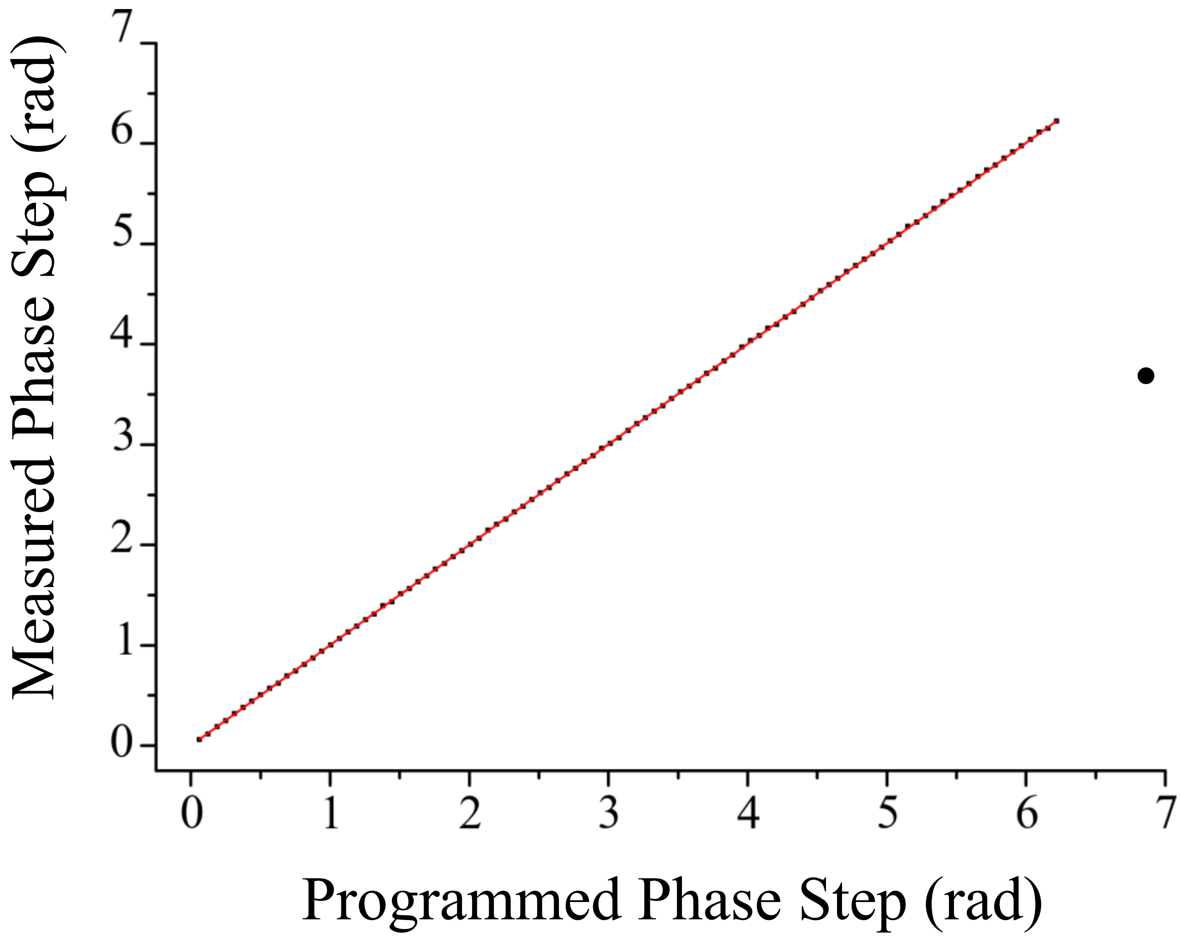
- Accurate phase control is a requirement in some quantum logic gates and in interrogation schemes for atomic clocks
- Transfer phase agility of DDS to laser light through acousto-optic modulation
- Detect via beat note between AOM shifted and master light



- π phase shift
- Fits either side to calculate phase shift value

Phase Control

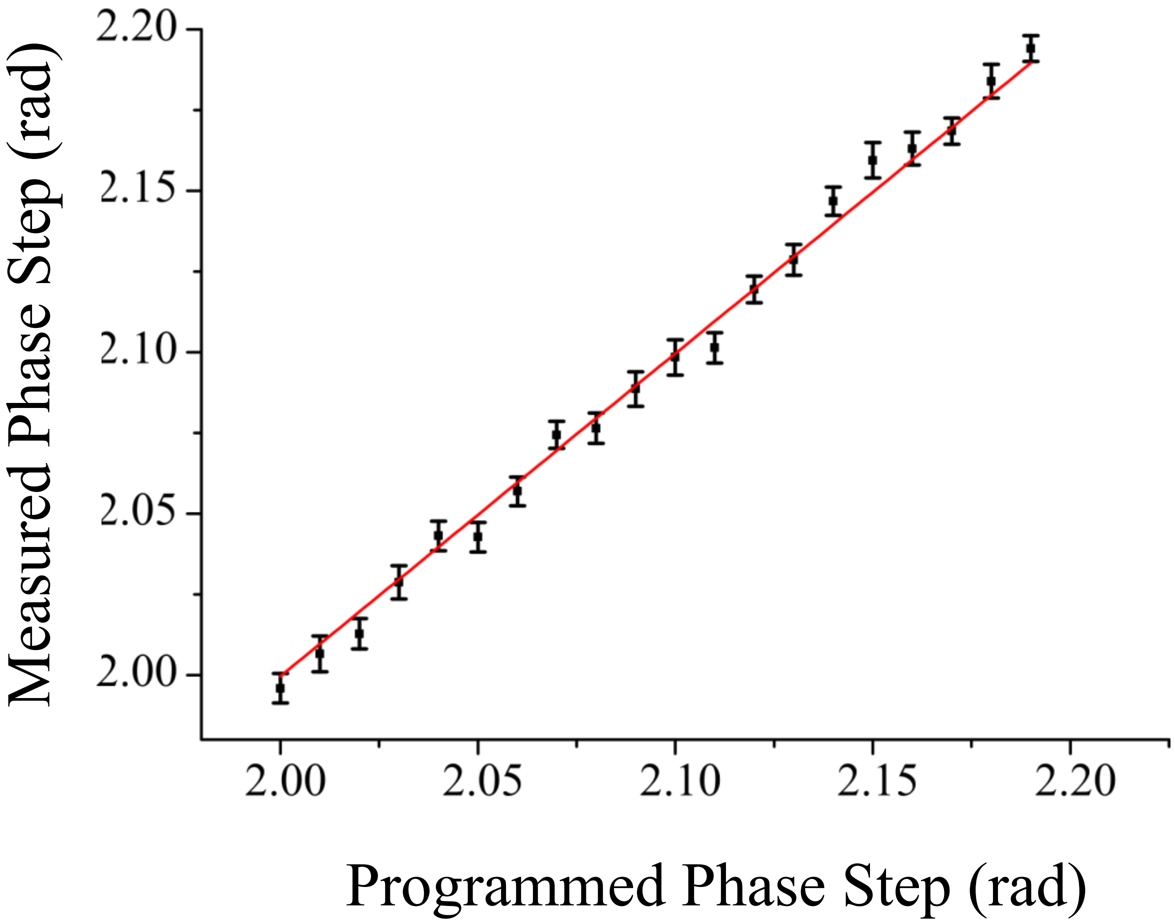
- Measure the phase change over the full range of values from $0 < \delta\varphi < 2\pi$.



- Gradient =1.00086(2)

Phase Control - Fine Resolution

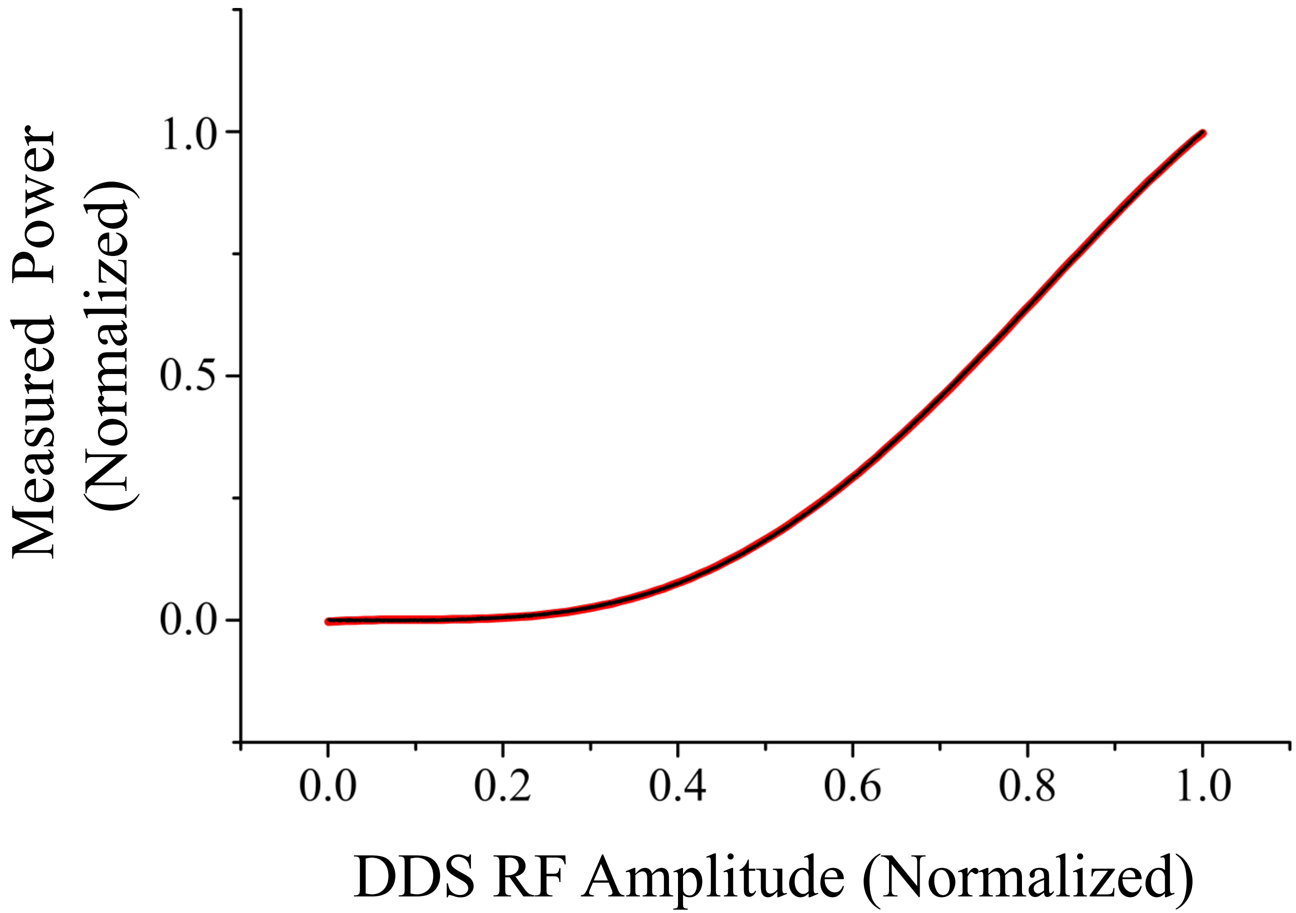
- Measure the phase change over a narrow range



- 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



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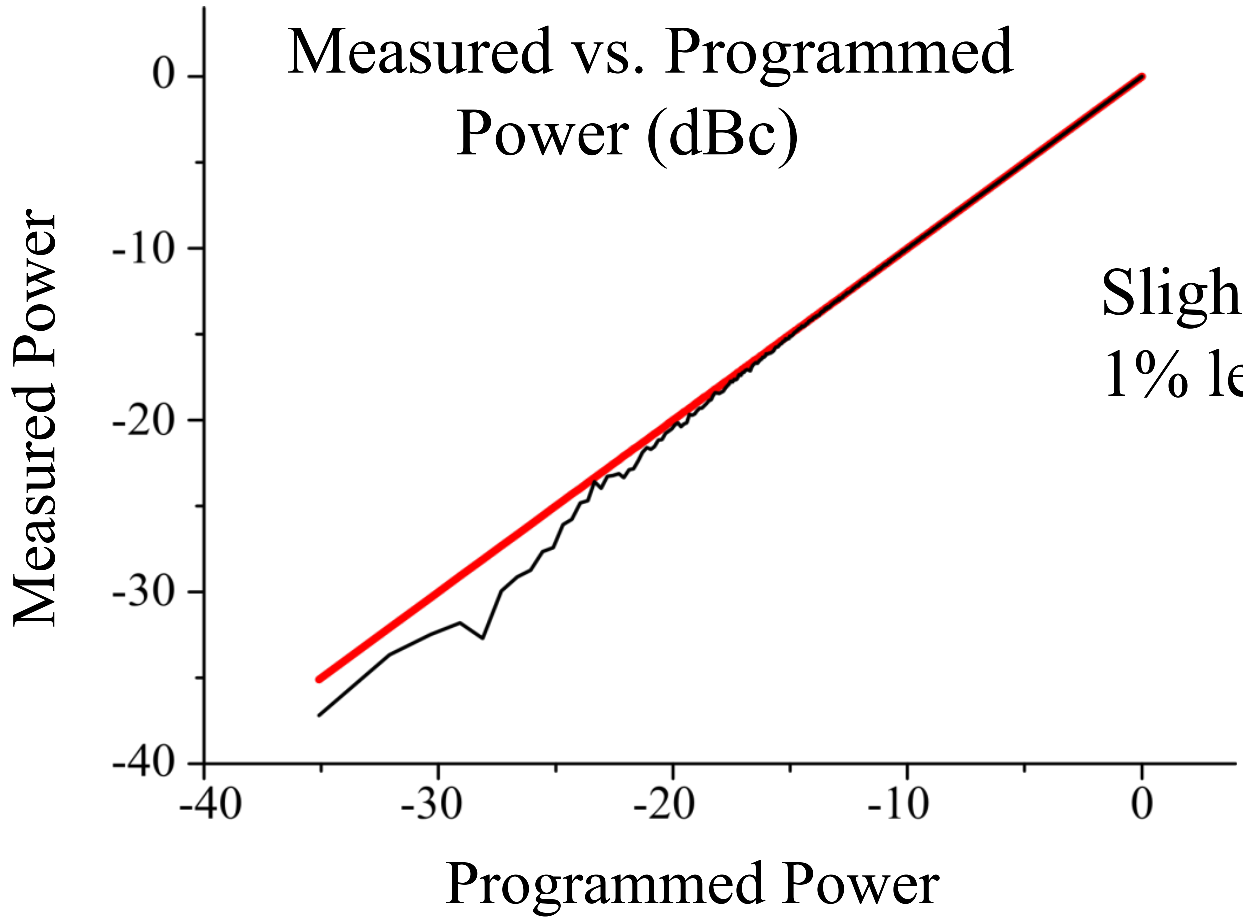

Slight deviation at 1% level

Amplitude Shaped Pulse Generation

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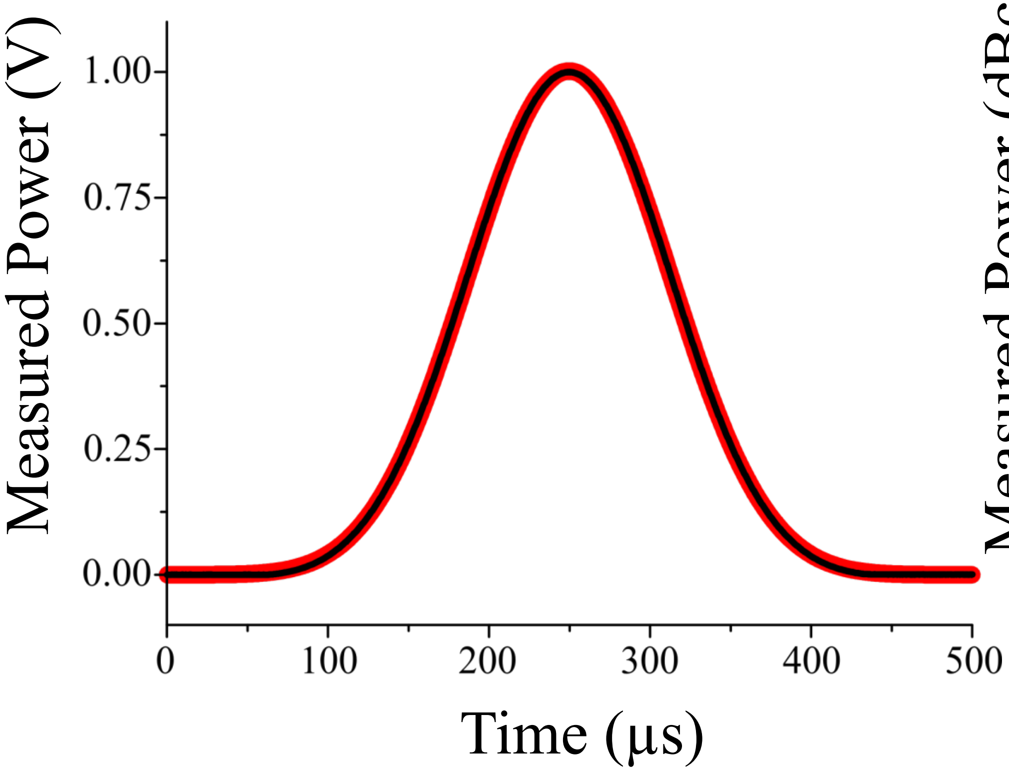
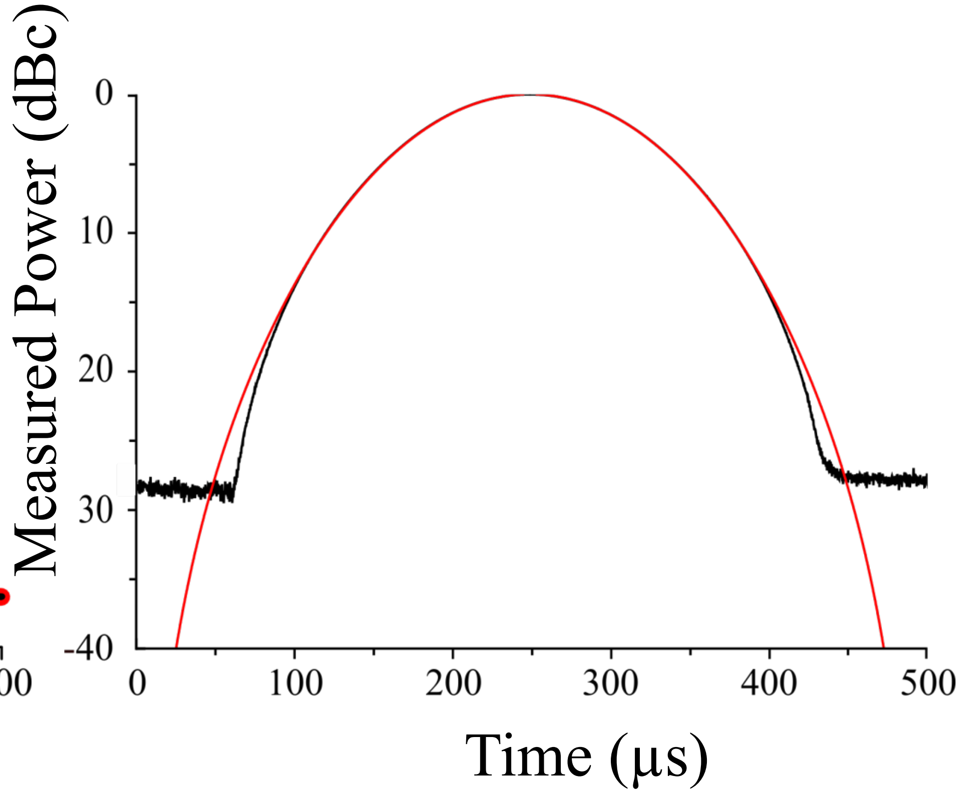
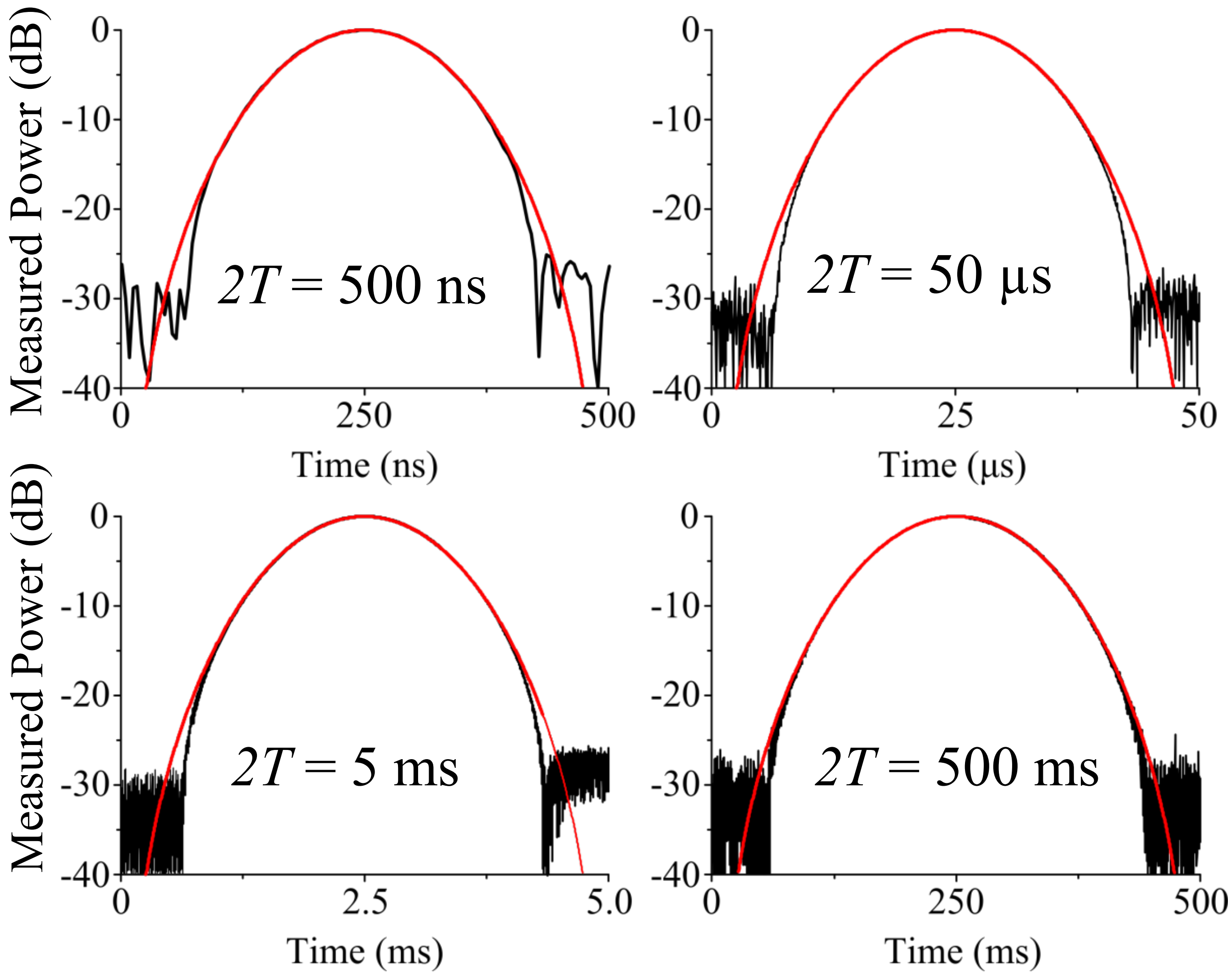
- After calibration, can generate Blackman pulses of duration $2T$ with the form the form

$$E(t) = \begin{cases} E_0\left[0.42 - 0.5\cos(\pi t/T) + 0.08\cos(2\pi t/T)\right] & \text{for } 0 \le t \le 2T \\ 0 & \text{elsewhere} \end{cases}$$





Operation over six orders of magnitude in duration

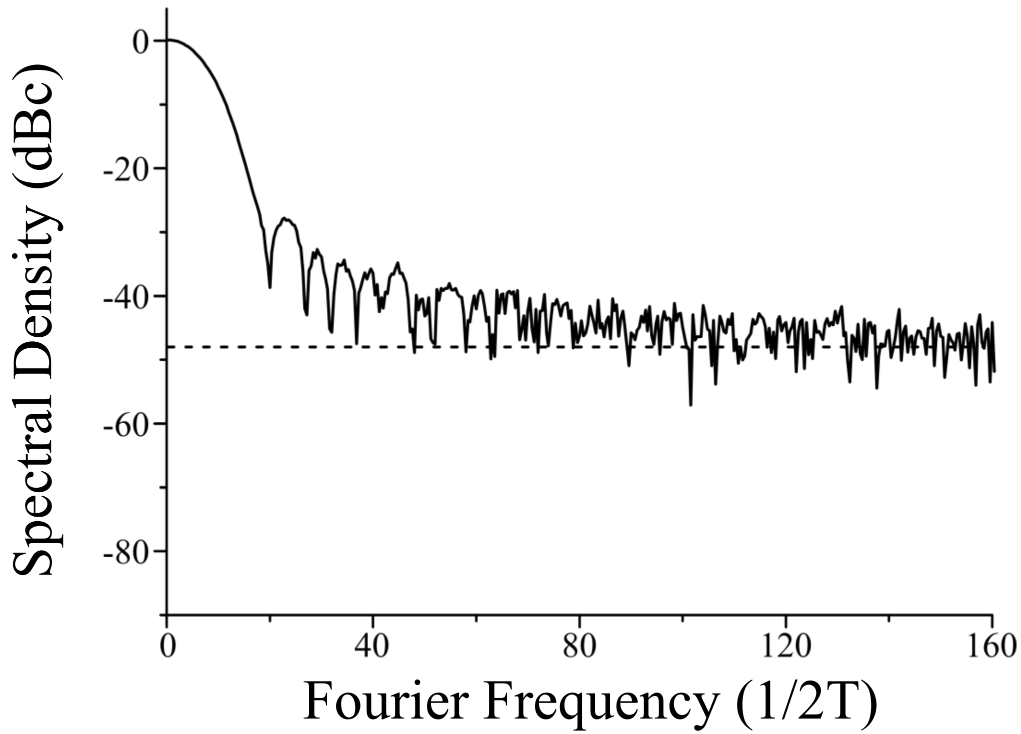


Short Pulses – Quantum Computing

Long Pulses – Atomic Clocks

Power Spectrum of Optical Pulses

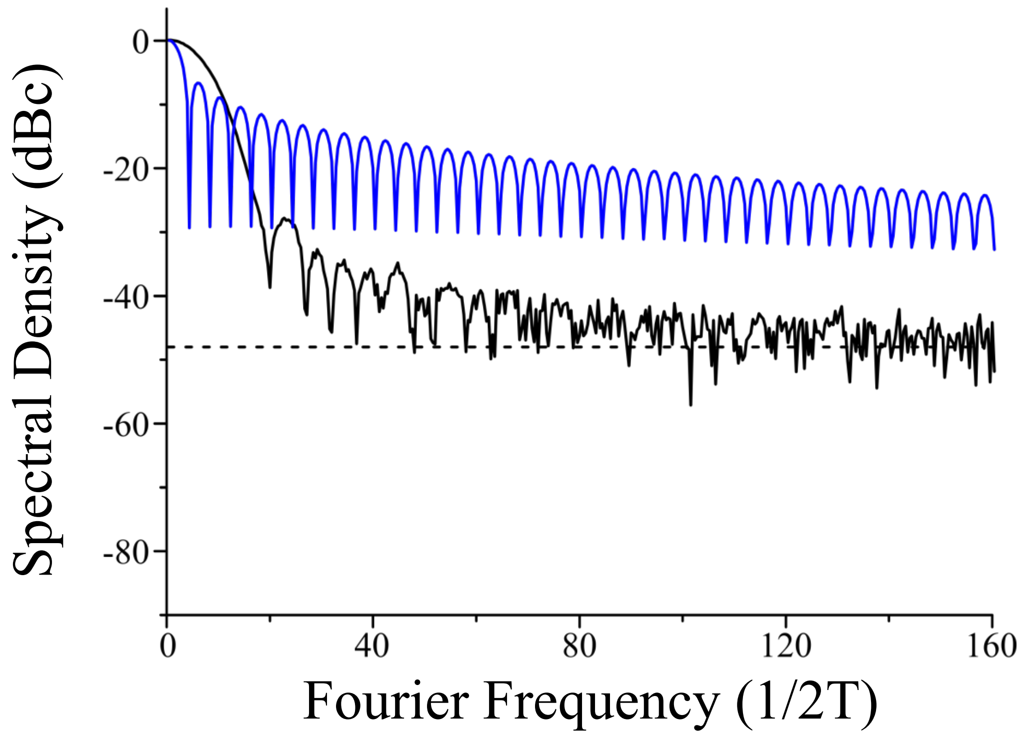
- Calculated the Fourier spectrum of measured pulse shapes



- Measured Blackman pulse of 500 μs duration

Power Spectrum of Optical Pulses

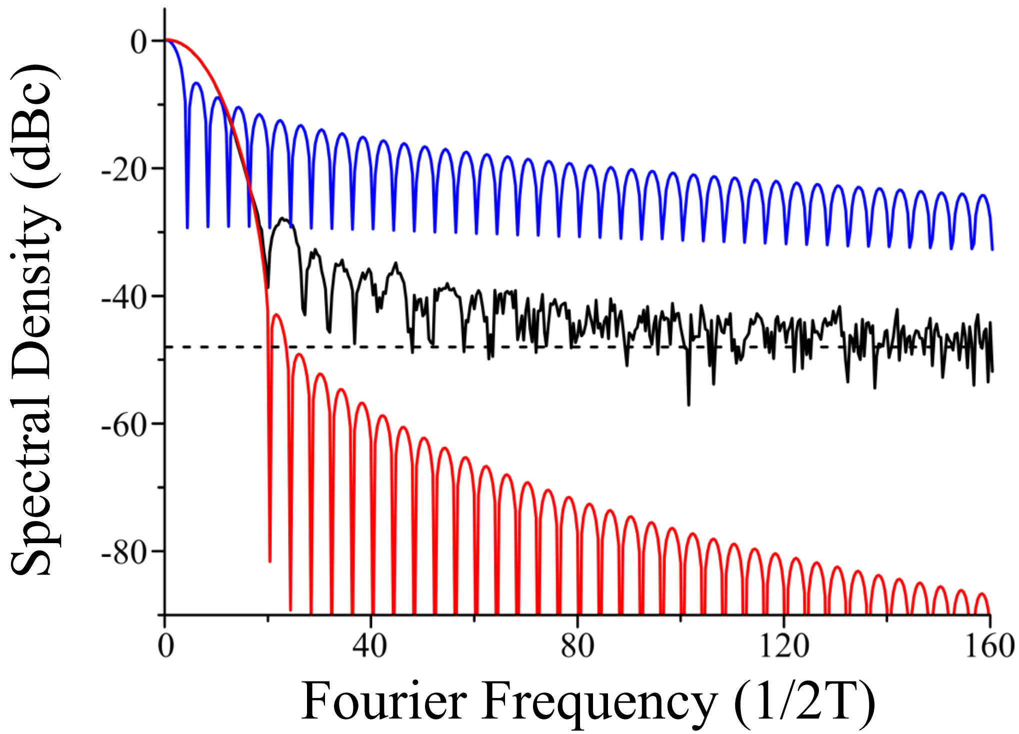
- Calculated the Fourier spectrum of measured pulse shapes



- Measured Blackman pulse of 500 μs duration
- Measured square pulse of the same integrated power

Power Spectrum of Optical Pulses

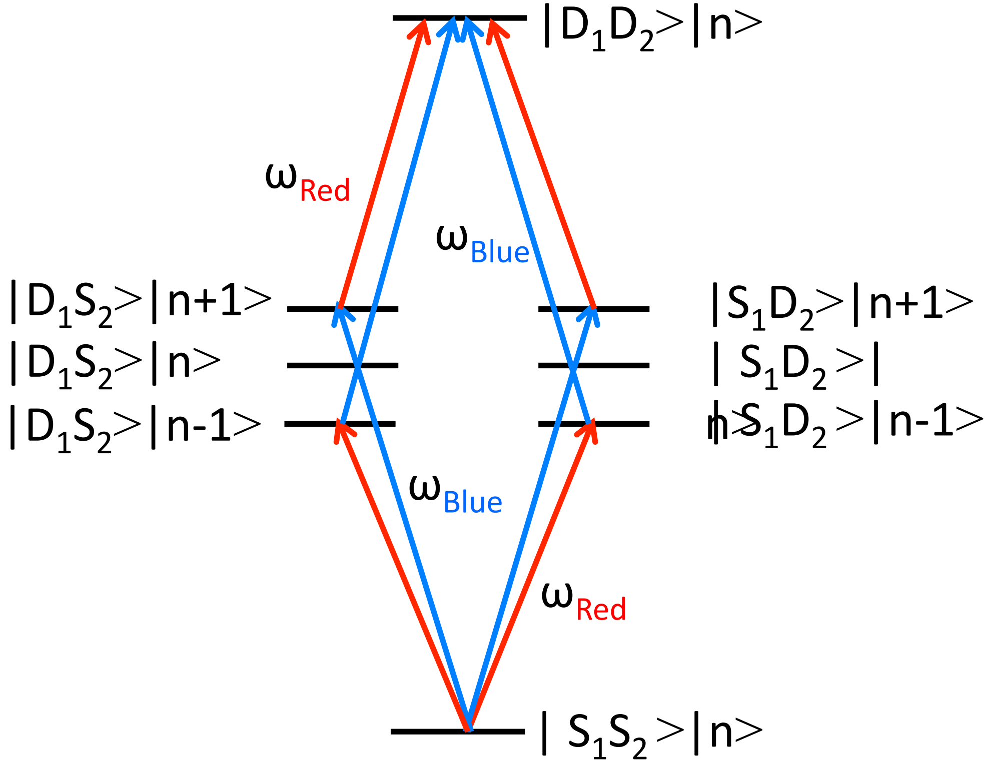
- Calculated the Fourier spectrum of measured pulse shapes

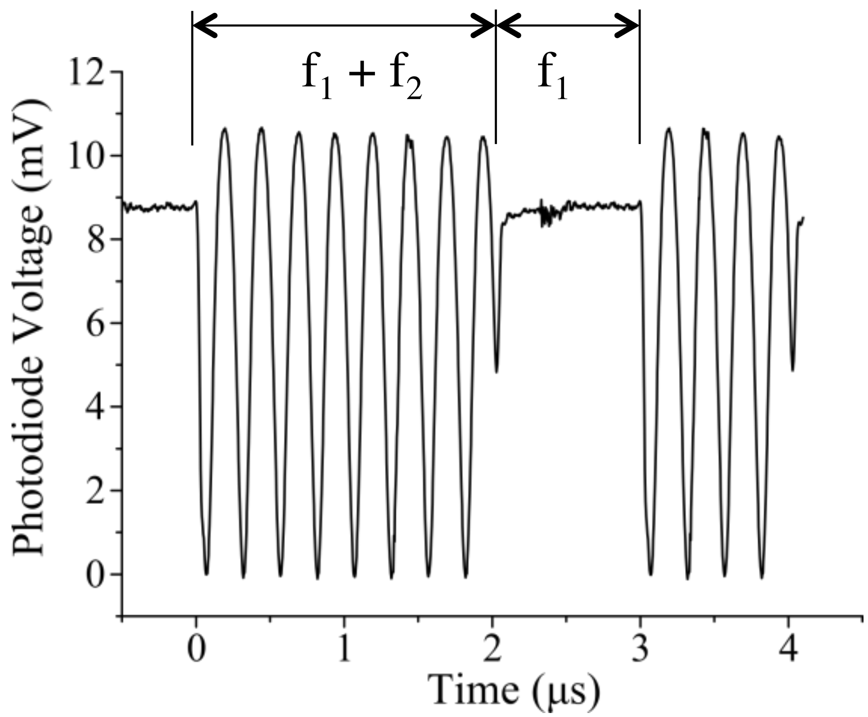


- Measured Blackman pulse of 500 μs duration
- Measured square pulse of the same integrated power
- Theoretical Blackman pulse of 500 μs duration

Bichromatic Operation

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

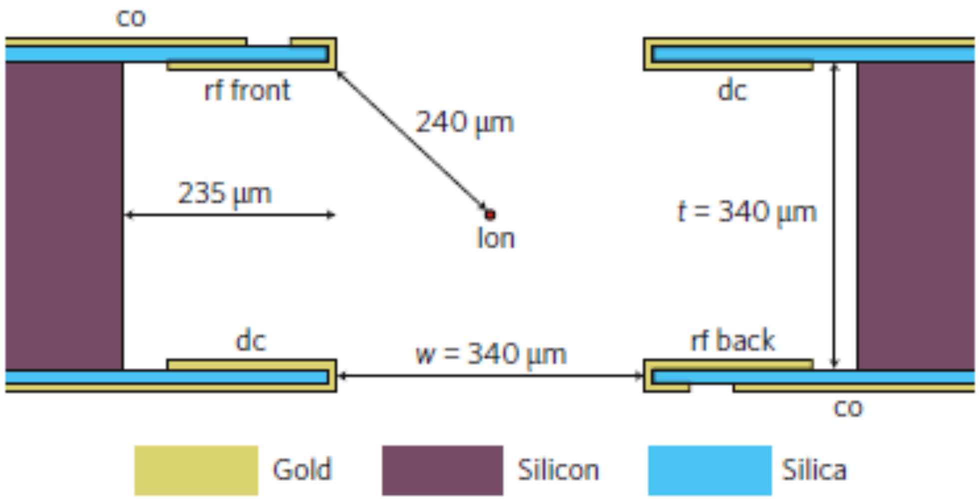


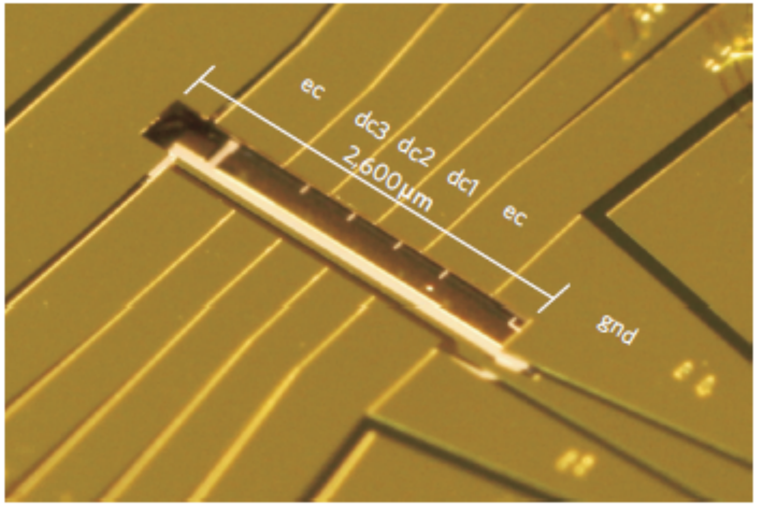


- Use single pass AOM to create light field with two optical frequencies separated by 4 MHz
- 30 ns rise time

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





Demonstration: G. Wilpers et al, Nature Nanotechnology, **7**(9), 572 (2012)
UHV Packaging: G. Wilpers et al, Applied Physics B, **111**(1), 21 (2013)
Fabrication: P. See et al, JMEMS, 10.1109/JMEMS.2013.2262573 (2013)

Summary

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- 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