Inertial Navigation using Atom Interferometry

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A dissertation submitted for . . .

Abstract

This thesis describes work I did during my PhD…

Declaration

This dissertation is the result of my own work…

Jimmy Stammers

Acknowledgements

Some people worth thanking…

Preface

This thesis describes my research on various aspects of…

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Chapter 1

Introduction

- atom interferometry experiments for precision measurements of inertial forces
- inertial navigation suffers from long-term bias drift
- recent experiments have demonstrated measuring acceleration in environments of interest to navigation

Chapter 2

Theory

- Describe general principles of light-matter interaction
- Specific cases for laser cooling (doppler/sub-doppler) and Raman transitions
- Lead into atom interferometry
- Perhaps split this into two shorter chapters

2.1 Overview

2.2 Light-Matter Interactions

2.3 Laser Cooling of Rubidium-87

2.4 Raman Transitions in Rubidium-87

2.5 Light Pulse Atom Interferometry

Chapter 3

Experimental Setup

This chapter provides a description of the hardware that makes up the experiment. Over the course of the project, the complexity of the experiment necessarily increased. The setup is presented in a bottom-up approach, starting from the most fundamental components, to provide a clear overview of the system.

To-Do:

- Figures describing each of the lasers
- Describe 3D and 2D MOT setups
- Imaging systems
- Microwave synthesisers
- Raman Assembly
- MOT light distribution

3.1 Chapter Overview

The first two sections describe the two commercial laser systems used in this experiment. The μQuans laser system which generates the light used for cooling and repump in the 2D and 3D Magneto-optical Traps (MOTs), referred to as the MOT light. The design and operation of this laser is given in Section 3.3. A secondary laser system, built by MSquared, is used to generate light to drive Raman transitions between two hyperfine ground states in Rubidium-87 (^{87}Rb)[1], otherwise referred to as Raman light. This is described in Section 3.4.This is followed by a description of the vacuum chamber in Section 3.2 which contains both the 2D Magneto-optical Trap (MOT) (Section 3.2.1) and the 3D MOT (Section 3.2.2).

3.2 Vacuum Chamber

3.2.1 The 2D MOT

3.2.2 The 3D MOT

3.2.3 Imaging Systems

CCD Camera

Photodiode

3.3 The μQuans Laser System

To-Do:

- Laser Schematic
- Plots of lock signals
- DDS Serial communication
- Power output, stability
- Refs for other experiments using Muquans systems

All the MOT light in this experiment was generated by the μQuans laser [**?**]. μQuans is a French laser company that is a spin-off from the Institut d'Optique and Observatoire de Paris. Consequently, their technology has been developed over a long history of performing experiments into atom interferometry using Rubidium. A schematic of

[1] The μQuans laser also has a pair of lasers designed for driving Raman transitions, but these are not used in this experiment. Section 3.4 gives an explanation for this.

this laser system is shown in Figure 3.1. The μQuans laser is comprised of four 1560nm **ECDLs!**s (**ECDLs!**s) which are frequency-doubled to produce light at wavelengths close to 780nm. The telecommunications industry, which relies heavily on light in the 1530-1565nm wavelength band for optical communications, has motivated a rapid development in low-noise, robust lasers which are much more stable outside of laboratory conditions than their 780nm counterparts. The requirement for long-term stability of a laser system is one which many applications of quantum mechanics to technology will greatly benefit from by removing a need for frequent maintainence.

3.3.1 Absolute Frequency Reference

The purpose of the master laser is to provide an absolute frequency reference so that the MOT light and Raman light can be controlled by comparing the frequency difference of the slave lasers to this. The master laser is locked to the 3,4 crossover in ^{85}Rb, so that the

3.3.2 Generating MOT light

3.3.3 Raman light

3.3.4 Real-time Frequency Control

3.4 The M-Squared Laser System

To-Do:

- Schematic
- Raman PLL phase-noise
- Laser Control
- DCS module

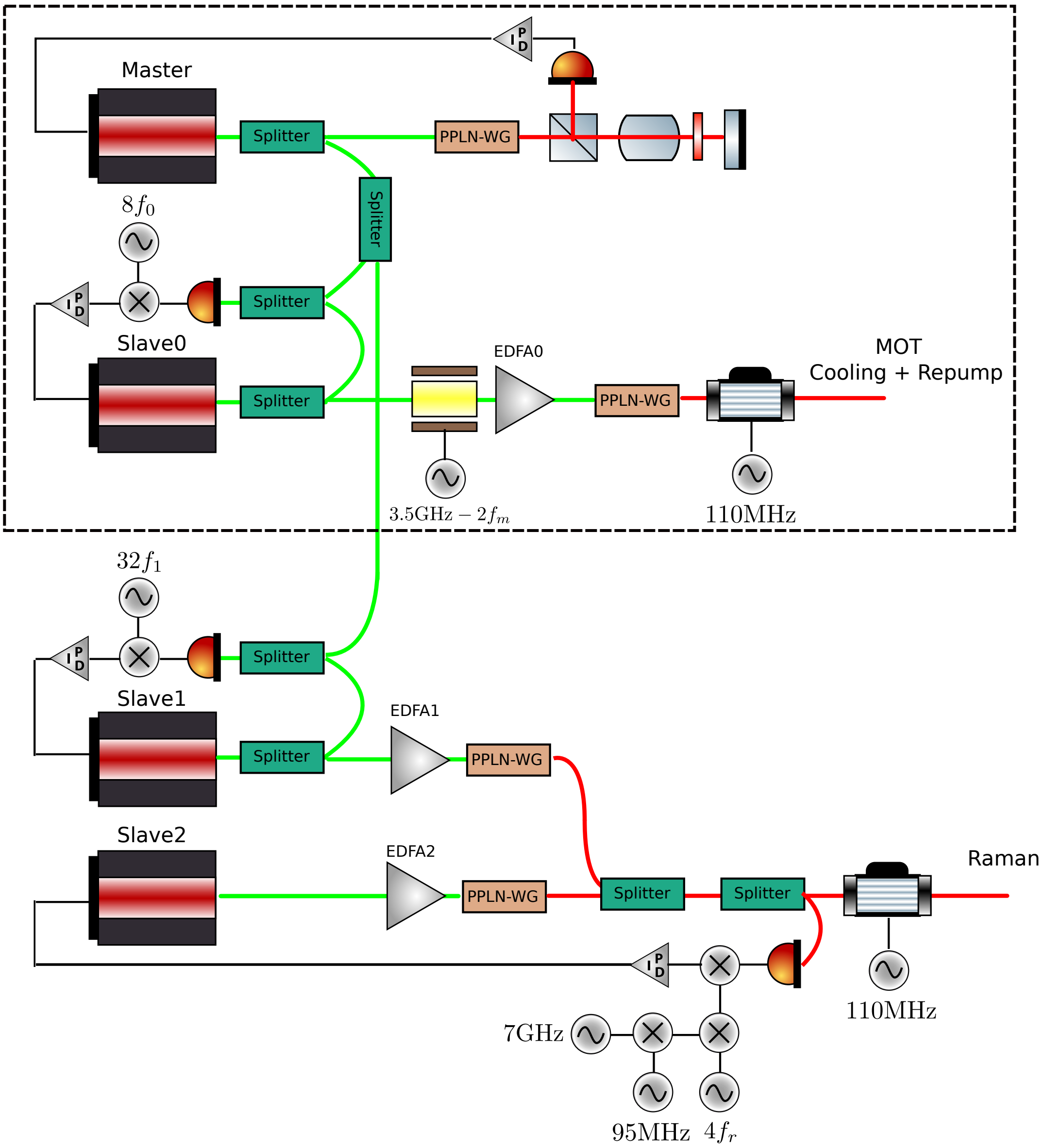

Figure 3.1: Schematic of the μQuans laser system. Each output laser is derived from a 1560nm ECDL (shown in green) which is amplified using an EDFA and then frequency-doubled to 780nm using a PPLN crystal. A master laser is locked to the 3,4 crossover in ^{85}Rb and the output lasers are offset-locked to their corresponding frequencies. The dashed region indicates the components used for generating light for the MOTs, which was the only function of this laser for this experiment.

3.4.1 Raman Light

3.5 Raman Optical System

3.5.1 Vacuum design

3.5.2 Raman Beam Collimator

3.5.3 Retro-reflection Assembly

3.6 MOT Light Distribution

3.6.1 Optical Fibre Network

3.6.2 Power Control

3.7 Microwave Field Generation

3.7.1 Setup

3.7.2 Wind-Freak Microwave Synthesiser

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Chapter 4

Computer Interface

4.1 Overview

- New MOTMaster software to control experiment
- Control system diagram
- Interfacing with muquans/msquared lasers
- Acquiring data from experiment — axelsuite

4.2 MOTMaster

4.2.1 Hardware Abstraction

4.2.2 Voltage Pattern Generation

4.2.3 Timed Serial Communication

4.2.4 Analogue Voltage Acquisition

4.2.5 Interfacing with External Software

4.3 External Laser Control

4.3.1 Muquans Interface

4.3.2 M-Squared Interface

Browser-based Control

Remote JSON Protocol

4.4 Processing Experimental Data

- Describe real-time processing and visualisation of data

4.4.1 Image Processing

4.4.2 Photodiode Voltages

4.4.3 MEMS Accelerometer

Acronyms

CCM Centre for Cold Matter

^{87}Rb Rubidium-87

^{85}Rb Rubidium-85

MOT Magneto-optical Trap

AOM Acousto-optic Modulator

EOM Electro-optic Modulator

PM Polarisation-Maintaining

QWP Quarter-wave Plate

HWP Half-wave Plate

MFD Mode Field Diameter

PPLN Periodically Poled Lithium Niobate

PLL Phase-Locked Loop

FPGA Field-Programmable Gate Array

EDFA Erbium-Doped Fibre Amplifier

ECDL External-Cavity Diode Laser

TTL Transistor-transistor Logic Circuit

NI National Instruments

DAQ Data Acquisition

ADC Analogue-to-Digital Converter

DAC Digital-to-Analogue Converter

HAL Hardware Abstraction Layer

SPI Serial Programming Interface

DDS Direct Digital Synthesiser

PBS Polarising beam-splitter

DRO Dielectric Resonator Oscillator

CCM Centre for Cold Matter

^{87}Rb Rubidium-87

^{85}Rb Rubidium-85

MOT Magneto-optical Trap

AOM Acousto-optic Modulator

EOM Electro-optic Modulator

PM Polarisation-Maintaining

QWP Quarter-wave Plate

HWP Half-wave Plate

MFD Mode Field Diameter

PPLN Periodically Poled Lithium Niobate

PLL Phase-Locked Loop

FPGA Field-Programmable Gate Array

EDFA Erbium-Doped Fibre Amplifier

ECDL External-Cavity Diode Laser

TTL Transistor-transistor Logic Circuit

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