# Quantum Information Processing in Rare Earth Ion Doped Insulators

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A thesis
submitted for the degree
of
Doctor of Philosophy
of the
Australian National University

*The Australian National University*
*April 2003*

## Statement of authorship

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text.

Jevon Longdell
November 29, 2003

For Poppa.

# Acknowledgements

Firstly I would like to thank my primary supervisor Matt Sellars. I have very good reason to be grateful for his talent, his continual and intense interest in this work, and for his friendship and support throughout.

Secondly I'd like to thank Neil Manson who in his role as my supervisor and the head of our group provided substantial support and wise advice.

This PhD is a very different one to that which I started in the Applied Maths department. I have to thank my original supervisor Stephen Hyde for the enjoyment that only comes from working alongside a talented and passionate individual. I also must thank Stephen for his understanding when I decided to change tack and his friendship then and now.

I am grateful to all the members of the Applied Maths department for the fantastic environment that Applied Maths provides. I would especially like to thank Mathias Boström and Barry Ninham for the work we did together.

I'd like to also thank the technical staff of the Laser Physics Centre, Ian McRae, John Bottega, Craig Macleod, Mike Pennington and Anita Smith, both for their skills and their willingness to use them in the aid of this project.

To all of the students I have shared an office or a lab with, Gerd, Elliot, Joanne, Darryl, Elena, Annabel, thank you for providing such an enjoyable and productive working environment.

I have had a rich life during my stay in Canberra, for this I must thank all my friends, be they my fellow students at the RSPhysSE, fellow outdoors freaks from the ANUMC, or people I have met along the way. I must make special mention of Glen who took on the job of my running coach without being asked, 4:02:12, I couldn't have done it without you.

I have to thank my family, I didn't get to see enough of any of you in the last three years, but you never felt far away.

I am unable to sufficently repay my to proof readers, Katherine Lilly and Susie Longdell, for the many hours of service they willingly provided.

Finally I thank you Kat, for being the only thing that really matters.

*Jevon Longdell*
*April 2003*

# Abstract

A great deal of theoretical activity has resulted from blending the fields of computer science and quantum mechanics. Out of this work has come the concept of a quantum computer, which promises to solve problems currently intractable for classical computers. This promise has, in turn, generated a large amount of effort directed toward investigating quantum computing experimentally.

Quantum computing is difficult because fragile quantum superposition states of the computer's register must be protected from the environment. This is made more difficult by the need to manipulate and measure these states.

This thesis describes work that was carried out both to investigate and to demonstrate the utility of rare earth ion dopants for quantum computation. Dopants in solids are seen by many as a potential means of achieving scalable quantum computing. Rare earth ion dopants are an obvious choice for investigating such quantum computation. Long coherence times for both optical and nuclear spin transitions have been observed as well as optical manipulation of the spin states. The advantage that the scheme developed here has over nearly all of its competitors is that no complex nano-fabrication is required. The advantages of avoiding nano-fabrication are two fold. Firstly, coherence times are likely to be adversely effected by the "damage" to the crystal structure that this manufacture represents. Secondly, the nano-fabrication presents a very serious difficulty in itself.

Because of these advantages it was possible to perform two-qubit operations between independent qubits. This is the first time that such operations have been performed and presents a milestone in quantum computation using dopants in solids. It is only the second time two-qubit operations have been demonstrated in a solid.

The experiments performed in this thesis were in two main areas: The first was the characterisation of hyperfine interactions in rare earth ion dopants; the second, simple demonstrations directly related to quantum computation.

The first experiments that were carried out were to characterise the hyper-

fine interactions in $Pr^{3+}:Y_2SiO_5$. The characterisation was the first carried out for the dopants in a site of such low symmetry. The resulting information about oscillator strengths and transition frequencies should prove indispensable when using such a system for quantum computation. It has already enabled an increase in the coherence times of nuclear spin transitions by two orders of magnitudes.

The experiments directly related to the demonstration of quantum computation were all carried out using ensembles. The presence of a significant distribution of resonant frequencies, or inhomogeneous broadening, meant that many different sub-ensembles could be addressed, based on their resonant frequencies. Furthermore, the properties of the sub-ensembles could be engineered by optically pumping unwanted members to different hyperfine states away from resonance with the laser.

A previously demonstrated technique for realising ensembles that could be used as single qubits was investigated and improved. Also, experiments were carried out to demonstrate the resulting ensembles' utility as qubits. Further to this, ions from one of the ensembles were selected out, based on their interaction with the ions of another. Elementary two qubit operations were then demonstrated using these ensembles.

# Contents

# Outline

The thesis begins with two introductory chapters, describing relevant details from the fields of quantum computation and rare earth spectroscopy respectively.

The first experiments carried out in the course of this work were to characterise the hyperfine structure in praseodymium doped yttrium orthosilicate ($Pr^{3+}$:$Y_2SiO_5$). This characterisation was the first to be successful in a site with such low symmetry. These and an attempt to gain similar information for europium dopants in the same host are described in Chapter 3.

It was initially envisioned that the characterisation of the $Pr^{3+}$:$Y_2SiO_5$ system would be used to improve the demonstrations of slow and stopped light in the material. However, the first time these results were used was in a technique to extend this material's coherence times for hyperfine transitions by over two orders of magnitude. This represented a very significant result for rare earth quantum computing because it is these transitions that would be used for the long term storage of quantum information.

In Chapter 4 a review is made, with the emphasis on rare earth ion dopants, of the mechanisms that cause interactions between optical centres in solids. Following this, the previously published schemes for achieving quantum computation in such materials are evaluated. The general plan for quantum computation pursued in this thesis is then presented. This plan consists of two areas of endeavour. The first is the demonstration, using ensembles, of quantum logic operations for a small number of qubits. As part of this, a practical method that was developed for achieving two qubit operations is presented. The second area of endeavour is the study of methods for scaling to a large number of qubits. Various possibilities for scaling are discussed.

Chapter 5 describes the experimental work that was directly aimed at carrying out quantum computing operations. Ensembles that can act as qubits (anti-holes) have been demonstrated previously. Here the improvements made are discussed. Also, the utility of the resulting ensembles as qubits was demonstrated using single qubit quantum state tomography experiments.

Following this, various experiments with two of these anti-holes were carried out. These were used to both characterise the strength of the interaction between the ions and demonstrate its suitability for multi-qubit operations.

This was followed by the application of some of the techniques described theoretically in Chapter 4. Using these techniques, a phase shift in the state of one qubit, that was conditional on the state of another qubit, was demonstrated. This represents the most elementary two qubit operation. Various simple ways in which the experiment could be improved to significantly increase the fidelity of the operation are discussed.

The thesis finishes with a summary of the results achieved. The future for quantum computing that is based on optical centres, and rare earth ion dopants in particular, is discussed.