Control and engineering of optical nonlinearities in multi-level quantum systems

By

Johann-Heinrich Christiaan Schönfeldt

A thesis submitted to Macquarie University
for the degree of
Doctor of Philosophy
Department of Physics and Astronomy
October 2011

MACQUARIE
UNIVERSITY
FACULTY OF SCIENCE

Typeset in $\LaTeX\,2_\varepsilon$.

Except where acknowledged in the customary manner, the material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree in any university.

The contribution by the author to this research lies in the models used for Chapter 2, Chapter 5 and Chapter 6, the results presented in these Chapters, and in the background research required to fit models to physical systems.

Johann-Heinrich Christiaan Schönfeldt

Acknowledgements

I would like to acknowledge the hard work and extreme patience of my supervisors Prof. Jason Twamley and Assoc. Prof. Stojan Rebić, thank you very much, it has been a wonderful priveledge working with you. Thank you Leigh Gibbens for looking after us all and keeping administrative tasks at bay where possible. Thank you also to the rest of the staff in the quantum group for creating a friendly and interesting group of high academic standard.

Furthermore it would be remiss of me to neglect thanking Prof. Alexei Gilchrist and Prof. Gavin Brennen for the coffee they provided that fuelled much of this work. Music sustained my sanity and focused my concentration: Mogwai; Godspeed You! Black Emperor; Silver Mt. Zion; Modest Mouse and Nine Inch Nails to name but a few of the bands that I am thankful to for their magic.

Great friendships were forged amongst the students in the quantum group and I would like to thank each and everyone for creating a great work environment and for all the extracurricular activities we engaged in. Thanks dudes! A big thanks to all my friends for all the good times and support. I also thank Proph. Fwiffo for his revelations.

A thank you also to my family. In particular my brother Andreas, for being my brother and all the good music he introduced me to and all the great tunes he and Martinique makes. Keep it up. A great big thank you to my parents who have supported me financially and otherwise throughout the many years of study I have undertaken, for this I am eternally grateful.

Last, but certainly not least, I thank the love of my life, Elna for *everything*.

List of Publications

- J-H. Schönfeldt, J. Twamley and S. Rebić, *Optimized control of Stark-shift-chirped rapid adiabatic passage in a Λ-type three-level system*, Phys. Rev. A **80**(4), 043401 (2009).

Abstract

We investigate methods related to achieving interaction between photonic qubits. The first general approach to achieve this is to transfer photonic qubits to solid state systems, where the qubit interactions can then take place. The other approach is to enhance the strength of the photon-photon interaction.

We first robustly study methods related to the first approach: in particular we focus on how to convert the photonic quantised excitation into an atomic excitation. The Stark-shift-chirped rapid adiabatic passage (SCRAP) technique in a three level Λ-type system is a coherent population transfer (CPT) technique similar to Stimulated Raman Adiabatic Passage (STIRAP) ,which in itself is closely related to electro-magnetically induced transparency (EIT). SCRAP has been shown to perform CPT with a high fidelity for a range of different detunings making SCRAP far more robust when there is large inhomogeneous broadenings present in the ensemble. We make use of optimum control techniques in order to optimise the standard SCRAP pulses so as to minimise the decrease in fidelity brought on by inhomogeneous broadenings of the transitions. Our result is that we can improve the average fidelity of population transfer over a wide range of detunings for both the ground to excited state detuning and the ground to target state detuning (two-photon detuning).

Finally we consider the enhancement of photon-photon interactions and the implementation of an optical quantum controlled not (CNOT) gate via a cavity-QED setup. We explore the Nitrogen-vacancy centre in diamond as a suitable four-level tripod system in which to generate the cross-Kerr nonlinearity required to facilitate the strong interaction between the two fields (control and target) held in a cavity. We show that with an ultra-high quality factor cavity, and only a single NV centre strongly coupled to the trapped light, a sufficiently large interaction can be generated between the two fields to obtain a conditional phase shift (CPS) in excess of the required π for the successful implementation of a CNOT gate. We also show that it is possible to use this system to create an entangled state of two macroscopically distinguishable states, that is a Schrödinger cat state, by using two weak coherent fields as input and making a measurement on the second field.

Contents

List of Figures

List of Acronyms

The following list is neither exhaustive nor exclusive, but may be helpful.

CNOT Controlled Not

CPHASE Controlled Phase

C-sign Controlled Sign Flip

CPS Conditional Phase Shift

CPT Coherent Population Transfer

CVD Chemical Vapour Deposition

EIT Electromagnetically Induced Transparency

KLM Knill, Laflamme and Milburn [1]

NV Nitrogen Vacancy

Q-factor Quality-factor

QED Quantum Electrodynamics

QPG Quantum Phase Gate

QND Quantum Nondemolition

SCRAP Stark-shift Chirped Rapid Adiabatic Passage

STIRAP Stimulated Raman Adiabatic Passage

WGM Whispering Gallery Mode

XPM Cross-Phase Modulation

ZPL Zero-Phonon Line