Storage and Manipulation of Optical Information Using Gradient Echo Memory in Warm Vapours and Cold Ensembles

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This thesis is dedicated to my beautiful Mel,
who makes the world a better place simply by being in it.

Declaration

This thesis is an account of research undertaken between February 2009 and February 2013 at The Department of Quantum Science, Research School of Physics & Engineering, The Australian National University (ANU), Canberra, Australia. The author was a visitor at Laboratoire Kastler Brossel (LKB), Université Pierre et Marie Curie, Paris, France, from October 2011 to December 2011, and the work performed at the LKB is reported in Chapter 11.

The majority of the research presented here was supervised by Prof. Ping Koy Lam (ANU), Dr. Ben Buchler (ANU), and Dr. Thomas Symul (ANU). Part of the work recorded in Chapter 11 was supervised by Dr. Julien Laurat (LKB) and Prof. Elisabeth Giacobino (LKB). 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.

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Acknowledgements

"So Long, and Thanks for all the [Physics]." - Book Four in *The Hitchhiker's Guide to the Galaxy* Trilogy, Douglas Adams, 1984, wilfully mis-quoted.

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Abstract

Quantum memories for light lie at the heart of long-distance provably-secure communication [1], while containing the potential to help break current encryption methods [2], and allow better measurement of quantities than ever before [3]. Demand for a functioning quantum memory is therefore at a premium. Unfortunately, the same properties of light that make it such an effective carrier of quantum information make it difficult to store. Furthermore, by the laws of quantum mechanics, storage must be achieved without measurement to preserve the quantum state.

A quantum memory needs to have an efficiency approaching unity without adding noise to the state, and storage times from milliseconds to seconds. Ideally it would also have a high bandwidth and be able to store many pieces of information simultaneously. Many different techniques are currently being developed and much experimental progress has been made over the past few years, with: efficiencies approaching 90% [4]; storage times of over seconds [5]; bandwidths of gigahertz [6, 7]; and over 1000 pieces of information stored at one time [8]. These results were, however, achieved using different memory schemes in different storage media. The challenge now is to reproduce these results with one memory.

This thesis focuses on extending the gradient echo memory (GEM) scheme, which shows great promise due to the high efficiencies achieved (87%) [4]. GEM has also been used to demonstrate temporal compression and stretching of pulses, as well as a capacity to arbitrarily resequence stored information [9] and the interference of initially time-separated pulses [10].

Firstly, we demonstrate the noiseless nature of GEM storage in a warm vapour cell to prove that the output from the memory is the best-possible copy of the input allowed by quantum mechanics. We show GEM's ability to coherently and precisely spectrally-manipulate stored information by having fine control over the memory's frequency gradient, with potential applications for dynamic conditioning of information inside quantum networks [11]. We demonstrate cross-phase modulation of a stored light pulse with an additional optical field, a process with applications in quantum computing [12]. We also carry out storage of different spatial modes and arbitrary images, demonstrating the potential for orders of magnitude improvement in storage capacity.

We then switch from warm vapour cells to cold atomic ensembles to improve the storage time of GEM, seeing a maximum coherence time of 350 μs (seven times that of the warm vapour system) and achieving efficiencies of up to 80%, on a par with the highest efficiency achieved with a cold atomic ensemble [13]. In the process we developed an ultra-dense cold atomic cloud with potential applications in a range of quantum optics experiments. Cold atoms, and the small volumes they occupy, also allowed us to develop an alternative to using magnetic field gradients for our alkali-atom memories in the form of a light-field gradient. This holds promise for extremely fast gradient switching and fine control over the gradient.

We also present a digital locking code with application in a range of quantum optics experiments.

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