Towards High Performance Finite Temperature Atomic Raman Quantum Memory: Analytical and Numerical Techniques

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A practical and reliable quantum memory (QM) is important for use in various quantum technologies, particularly for secure quantum communication. While there are schemes which use cascade configurations such as off-resonant cascaded configuration, the most commonly explored three-level configuration for QM is the lambda configuration. QM schemes such as electromagnetically induced transparency (EIT) [1, 2] and far-off resonance Raman memory (FORRM) [3], and also the three-level versions of controlled reversible inhomogeneous broadening (CRIB) [4, 5], gradient-echo memory (GEM) [6–8] and atomic frequency comb (AFC) [9, 10] use the lambda configuration, where one transition from a ground to an excited state is coupled with a weak quantum signal, and the other with a control laser field.

In a previous work [11], we found a more general theory and analytical solution than that presented by Raymer [12] for *stimulated Raman scattering (SRS)*. Our solution is valid for both near resonance and far-off resonance, and also includes the AC Stark effect as well as the background susceptibility which was neglected by [12]. However, the solution did not include inhomogeneous broadening, and population dynamics, which are essential for QM schemes such as CRIB, GEM and AFC.

In this work we include population dynamics, and the inhomogeneous broadening. We focus mainly on implementations in gases where the dominant inhomogeneous broadening is due to Doppler broadening. We include a microwave control coupling the ground states, which has not been explored before, and also consider the effects of having the signal and control co-propagating and counter-propagating. We further discuss the potential benefits of using standing waves and a train of pulses for the control field on QM performance.

1 Methodology

The complete set of 9 c-number variables in Bloch equations coupled to Maxwell equations are solved numerically with the Crank-Nicolson method. The propagation in one dimension is included by solving the set of equations for each step in space. This gives exact numerical solutions for any time dependent probe and control pulses. We then include the Doppler broadening, we solve the set of $9 \times N_u$, where N_u is the number of velocity points, and then average it over the Maxwell distribution in the propagation equation. We study the effects of temperature and inhomogenous broadening on the application of a sequence of control pulses in the AFC scheme.

For full quantum approach, we solve the complete set of 11 operators (9 atomic + 2 fields) in linearized Heisenberg-Langevin-Maxwell equations are solved numerically with the Crank-Nicolson method $\frac{d}{dt}Z = MZ$ where $Z = \{\hat{p}_{ij}\}, \hat{E}, \hat{E}^{\dagger}$ and it includes the space-discretized field operator equation for the quantum fields

The self-consistent solutions may be written similar to Refs [13] and [11] with boundary and initial conditions, and the noise operators. An improvement can be achieved by inserting the numerical results of the density matrix elements into the generalized analytical solution for SRS [11] with memory kernels attached to the initial and boundary conditions of the fields and ground state coherence.

We are thus able to compute the performance parameters of the simulated QM (such as efficiency, fidelity, and lifetime) for various different conditions with all physical effects included. We are also able to manipulate the density matrix elements (populations and coherences) for different velocities, testing *different atomic preparation schemes* such as in Refs. [14], and study their advantages and disadvantages for a QM. Using the numerical tool that we develop we are able to determine the optimal conditions for a quantum memory.

We further explore the use of **microwave** control field to increase the lifetime of the quantum memory. The effects of **co-propagating and counter-propagating** control fields on the signal field within the medium is also explored.

2 Main Results

We have developed new methods to control the populations in a three level lambda configuration and their velocity distributions, including a microwave control coupling the ground states. The performance of the quantum memory is simulated, parameters optimized for high efficiency and fidelity with a long lifetime for the implementation of a robust QM for long distance quantum communication. We have improved and refined previous ideas for QMs. The results presented here will enable the realisation of a practical working quantum memory.

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