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Sensor State Protection in Λ-type Atomic Ensemble Quantum Memories

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Abstract: We simulate Λ-type quantum memory in atomic ensembles with the addition of a high-lying sensor state in the continuous dynamical decoupling regime. We find order-of-magnitudes memory lifetime enhancement and explore the dressing-field parameter space.

The ability to store and retrieve single photons in an on-demand fashion is critical for enabling many quantum technologies, and maximizing the duration for which photons can be stored without loss of efficiency is integral to this process. We demonstrate through numerical simulation that the coupling of a sensor state, which effectively has an opposite sensitivity from the storage state to the source of dephasing [1], to a Λ-type atomic ensemble quantum memory through continuous dynamical decoupling allows for enhanced storage times. Simulating a Λ-type atomic ensemble quantum memory in hot atomic barium vapor [2] through a 4-level expansion of the Maxwell-Bloch equations, we obtain over a hundredfold increase in the memory lifetime. The incorporation of a sensor state for correcting inhomogeneous decay has been demonstrated previously in a FLAME-type atomic ensemble quantum memory in hot rubidium vapor using continuous wave dressing fields [1]. This implementation requires the sensor state to have a large s, so it is not applicable to all systems. Continuous dynamical decoupling and the spin echo technique have been shown to reduce dephasing in solid-state spin qubits [3] and inhomogeneous broadening from motional dephasing in a Λ-type atomic ensemble quantum memory in cold rubidium vapor [4], respectively. Our simulations apply a similar dynamical decoupling mechanism using a quasi-CW dressing field in a Λ-type atomic ensemble quantum memory in a hot atomic vapor. The results show the potential for significant reductions in dephasing from inhomogeneous broadening. Advantages of our implementation over continuous protection are that a sensor state with any s could be used since s simply influences the shape of the dressing field, and less power is required for any given s. Additionally, we conduct a deeper analysis of the effect on lifetime from off-resonant continuous protection vs. resonant dynamical decoupling by sweeping over the CW dressing field Rabi frequency and detuning for different s.

We begin with a Λ-type level structure coupled to a high-lying sensor state, as shown in Fig. 1(a)-(b). Initially, atoms begin in the ground ($|1\rangle$) state, and a weak signal and strong control field are tuned off-resonance from the $|1\rangle \to |2\rangle$ and $|2\rangle \to |3\rangle$ transitions, respectively, to transfer population to the storage ($|3\rangle$) state. To this existing framework, we now couple the sensor ($|4\rangle$) state to the storage state through the use of a dressing field acting on the $|3\rangle \to |4\rangle$ transition.

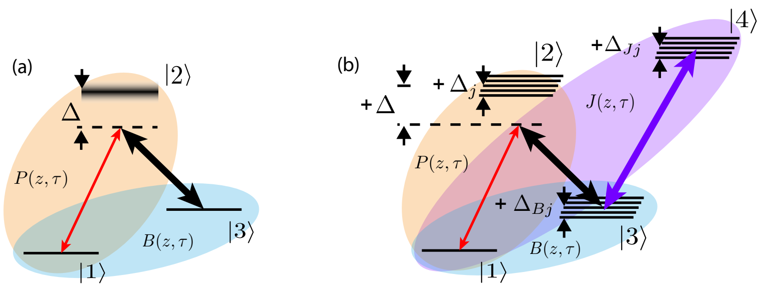

Fig. 1. The red arrow on the $|1\rangle \to |2\rangle$ transition depicts the signal field $A(z,\tau)$, and the black arrow on the $|2\rangle \to |3\rangle$ transition depicts the control field. The orange and blue ellipses depict the atomic polarization $P(z,\tau)$ and spin wave $B(z,\tau)$, respectively. (a) Typical Λ-type atomic structure with signal and control both tuned Δ away from resonance. (b) Modified Λ-type atomic structure with inhomogeneous broadening formed by coupling a high-lying sensor state to the storage state. The purple arrow on the $|3\rangle \to |4\rangle$ transition depicts the dressing field and the purple ellipse depicts the sensor field $J(z,\tau)$.

In our simulations, we model the dynamics of an N-type system through Maxwell-Bloch equations. In terms of optical depth d, two-photon detuning from the excited state Δ, control field Rabi frequency Ω, dressing field Rabi frequency Ω_d, signal field A, polarization P, spin wave B, and sensor field $J \propto \sum_{\beta(\mathbf{r})} \tilde{\sigma}_{14}^{j(\beta)} e^{i\Delta_{Jj}\tau}$, these equations are

$$\partial_z A(z,\tau) = -\sqrt{d}\sum_j \sqrt{p_j} P_j(z,\tau) \quad (1)$$

$$\partial_\tau P_j(z,\tau) = -\gamma P_j(z,\tau) + i(\Delta+\Delta_j)P_j(z,\tau) + \sqrt{d}\sqrt{p_j}A(z,\tau) - i\Omega(\tau)B_j(z,\tau) \quad (2)$$

$$\partial_\tau B_j(z,\tau) = -\gamma_B B_j(z,\tau) + i\Delta_{Bj}B_j(z,\tau) - i\Omega^*(\tau)P_j(z,\tau) - i\Omega_d^*(\tau)J_j(z,\tau) \quad (3)$$

$$\partial_\tau J_j(z,\tau) = -\gamma_J J_j(z,\tau) + i\Delta_{Jj}J_j(z,\tau) - i\Omega_d(\tau)B_j(z,\tau) \quad (4)$$

where we have separated the system into inhomogeneously distributed frequency classes j, and Δ_j, Δ_{Bj}, and Δ_{Jj} represent the frequency shifts due to this broadening as seen in Fig. 1(b). To induce continuous dynamical decoupling between the storage and sensor states, we require a dressing field in the form of sequential π-pulses whose durations vary by $1/s$. In terms of γ_{Bi} and γ_{Ji}, the rate of decay of the inhomogeneously broadened storage and sensor states, respectively, $s = \gamma_{Ji}/\gamma_{Bi}$ is the sensitivity of the sensor state to the source of inhomogeneous decay. Thus, we find the optimal quasi-CW dressing field is described by

$$\Omega_d(\tau) = \frac{f\pi/\ln s}{s/(s-1) - f(\tau+\Delta\tau_d)}, \quad (5)$$

where f is a factor that scales the duration of the first π-pulse and $\Delta\tau_d$ controls its group delay. After optimizing f and $\Delta\tau_d$ for each retrieval delay individually, we find that the lifetime of our barium quantum memory (initially 0.515(6) ns) could be enhanced by a factor of over 100 using this quasi-CW field to couple to a sensor state with $s = 10$, as seen in Fig. 2(a). In Fig. 2(b), we show preliminary simulation results of the lifetime enhancement obtained using a CW dressing field for the continuous protection and dynamical decoupling protocols for $s = 10$.

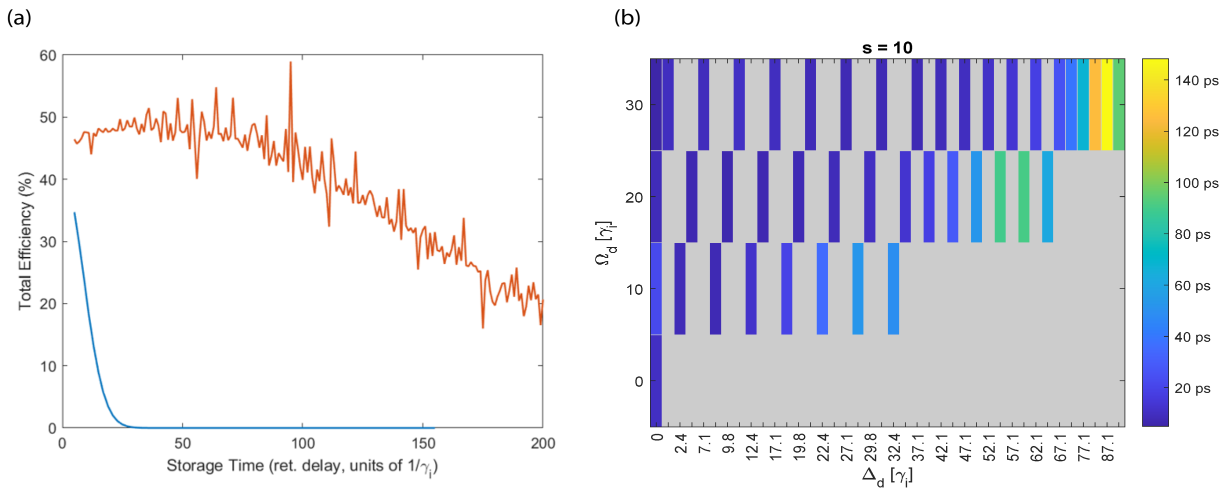

Fig. 2. (a) The blue line shows the lifetime of the memory without a sensor state incorporated, while the orange shows the case with a sensor state and dressing field for $s = 10$, where f and $\Delta\tau_d$ have been optimized for each individual retrieval delay. (b) The color map shows lifetimes obtained for various combinations of dressing field Rabi frequency and detuning across the parameter space for $s = 10$. The data at (0,0) is the lifetime obtained with no protection, and the grey areas are where data has yet to be simulated.

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