Optimization of Broadband $\Lambda$-type Quantum Memory Using Gaussian Pulses

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Abstract: We optimize the efficiency of broadband $\Lambda$-type quantum memories under the restriction of Gaussian-shape optical fields. We demonstrate an experimentally-simple path to enhancing memory efficiency over a wide range of broadband memory parameters.

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1. Introduction

Optical quantum memory—the ability to store single-photon states and retrieve them on-demand—is a critical resource for emerging quantum technologies and photonic quantum information protocols [1]. Optimizing quantum memory efficiency and bandwidth are both important and outstanding tasks. In this work we consider $\Lambda$-type atomic quantum memories with the level structure shown in Fig. 1(a). We restrict our analysis to include only optical fields with Gaussian temporal envelope [i.e., the signal field, $A_{\text{in}}(\tau)$, and control field, $\Omega(\tau)$, are Gaussians]. This restriction is motivated by experimental considerations; whereas quantum memory optimization techniques that rely on non-Gaussian control field shaping greatly enhance quantum memory efficiency, they incur significant cost in terms of experimental complexity, especially in the broadband regime. Herein we aim to optimize quantum memory performance without incurring this cost.

In the interaction we consider, the weak signal field [$A(z, \tau)$], resonant or near-resonant with the $|1\rangle \rightarrow |2\rangle$ transition, is sent into an ensemble of atoms and creates an atomic polarization [$P(z, \tau)$], which is transferred to a so-called spin wave [$B(z, \tau)$] with the application of a strong, undepleted control field [$\Omega(\tau)$]. In one dimension, the equations of motion that describe this storage process in space ($z$) and time ($\tau$, in the co-moving frame) are the normalized Maxwell-Bloch equations [2, 3]:

\[
\partial_z A(z, \tau) = -\sqrt{d}P(z, \tau)
\]

\[
\partial_\tau P(z, \tau) = -\gamma P(z, \tau) + \sqrt{d}A(z, \tau) - i\frac{\Omega(\tau)}{2}B(z, \tau)
\]

\[
\partial_\tau B(z, \tau) = -\gamma_0 B(z, \tau) - i\frac{\Omega^*(\tau)}{2}P(z, \tau),
\]

where $d$ is the resonant optical depth of the ensemble, $\gamma = (\gamma - i\Delta)/\gamma$ is the complex detuning for polarization decay rate $\gamma = \Gamma/2$ and two-photon detuning $\Delta$, and $\gamma_0$ is the spin-wave decay rate in units of $\gamma$, which we neglect for long-lived spin-wave states. We consider ‘backward retrieval’ of the signal field, such that the atomic dynamics during retrieval are the time reverse of those during the storage process; to this end we take the numeric integration of (1)-(3) during the storage process to be representative of the quantum memory process as a whole, and the total memory efficiency $\eta_{\text{tot}} = \eta^2$, for storage efficiency $\eta$.

2. Methods

We calculate the storage efficiency $\eta = \int_0^1 dz |B(z, \tau \rightarrow \infty)|^2 / \int_{-\infty}^\infty d\tau |A_{\text{in}}(\tau)|^2$, for Gaussian control fields parameterized by the field pulse area $\theta$, delay with respect to the signal $\Delta \tau_{\text{int}}$, and duration $\tau_{\text{FWHM}}$. We optimize over these control field parameters using a Nelder-Mead simplex method, which rapidly identifies the global efficiency maxima, as verified by deterministic searches. We define $\tau = 0$ at the maximum of the signal field. We normalize the efficiencies calculated via the method above by the protocol-independent efficiency bound for a fixed optical depth, $\eta_{\text{opt}}$, described in Refs. [2, 3].

3. Results

Our optimization procedure connects three physically-distinct quantum memory protocols through continuous transformation of the memory parameters and optimization of the control field parameters, and further provides
an experimentally-simple route to optimization of storage efficiencies in the regions of the memory parameter space that are not optimal for any of the three protocols individually, and optimal storage requires a mixture of protocol type.

Reference [4] demonstrated that the Atuler-Townes-Splitting (ATS) storage protocol and the Electromagnetically-Induced-Transparency (EIT) protocol can be connected through continuous transformation of the control field Rabi frequency for fixed memory parameters, under the condition of a constant control field. Here we distinguish between the memory parameters $d$ and $\tau_{\text{FWHM}}$, which represent the physical characteristics of a particular quantum memory for a chosen signal bandwidth ($\tau_{\text{FWHM}}$), and the control field parameters $\theta$, $\Delta \tau_{\text{ctrl}}$, and $\tau_{\text{FWHM}}$, which fully define any Gaussian control field. In this formalism, Ref. [4] derived a connection between ATS and EIT storage for fixed memory parameters by varying the intensity of a control field that is constant in time. In this work, we consider the distinct condition of Gaussian-shape control fields, and we show that again ATS and EIT memory behavior can be connected, however we consider the transformation as a function of the memory parameters, where optimization of the control field parameters at each point ensures optimal or near-optimal storage efficiency. Further, we show the two protocols can be connected to the ‘absorb-then-transfer’ protocol of e.g. Ref. [5] through the same continuous transformation.

Figure 1(b) shows the storage efficiencies we achieve through the Gaussian optimization process, which saturate the optimal bound over the entire memory parameter space we investigate, except when $d / \tau_{\text{FWHM}} > 1$ [Fig. 1(c)], where we see the expected decay of the storage efficiency [3]. In the region $d / \tau_{\text{FWHM}} = 1$ to 3, we find optimized control fields that correspond to the ‘absorb-then-transfer’ protocol, where in Fig 1(e)-(g) we show pulses of area approximately equal to $\pi$ that and arrive after linear absorption of the signal has taken place ($\Delta \tau_{\text{ctrl}} > 0$), and are shorter than the signal fields they store ($\tau_{\text{FWHM}} < \tau_{\text{FWHM}}$). For adiabaticities $d / \tau_{\text{FWHM}} = 3$ to 8 we observe ATS storage, with $\theta = 2\pi$, $\Delta \tau_{\text{ctrl}} = 0$, and $\tau_{\text{FWHM}} \approx \tau_{\text{FWHM}}$. And for character ratios $\tilde{C}$ defined in Ref. [4] satisfying $\tilde{C} \leq 0.1$ [Fig. 1(d)] we observe control fields with the signature of EIT storage, with relatively large pulse areas, $\Delta \tau_{\text{ctrl}} < 0$, and $\tau_{\text{FWHM}} > \tau_{\text{FWHM}}$. In the regions between optimal memory parameters for each protocol we observe optimal storage efficiencies that correspond to storage protocols of mixed type.

We have also extended this analysis to near-resonant interaction of the optical fields with the $\Lambda$-type level system, where $\Delta / \gamma \sim 1$ to 10, so as to investigate any connection with the off-resonant Raman protocol [2]. With increasing $\Delta$ we observe the expected increase in necessary control field power (expressed through $\theta$) in order to maintain optimal storage efficiency for fixed memory parameters.

References

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