Atomic quantum memories for light

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Abstract. We consider the coherent stimulated Raman process developing in an optically dense and disordered atomic medium in application to the quantum memory scheme. Our theoretical model predicts that the hyperfine interaction in the excited state of alkali atoms can positively affect on the quantum memory efficiency. Based on the concept of the coherent information transfer we analyze and compare the memory requirements for storage of single photon and macroscopic multi-photon light pulses.

Keywords. Quantum memory, Autler-Townes structure with hyperfine interaction, ultracold atomic ensembles, coherent information

Introduction

Many implementations of quantum information processing, quantum computing or secure communication need quantum memories for light. Various physical systems are intensively studied as candidates for efficient light storage and retrieval. Among those are the alkali atomic gases at room temperature Refs.[1]-[5] and ultracold atomic ensembles Refs.[6]-[8], which have been successfully used for demonstrating the quantum memory effect. Theoretical investigations of the memory properties of atomic systems driven by a strong control field propose reliable storage and retrieval of the quantum light in optically thick and ultracold gases Refs.[9]-[12], and the predicted parameters and conditions are experimentally feasible. In the present report we discuss the role of the hyperfine interaction in alkali atoms and follow how it modifies the stimulated Raman process applied to the quantum memory. We show that the multilevel hyperfine structure of alkali atoms in their excited states cannot be ignored and it is very important for the correct description of the scattering process.

Having a quantum memory channel with certain efficiency it is important to overcome a classical benchmark justifying that the memory is indeed quantum. The fidelity of storage and retrieval is usually exploited to find such a benchmark. The fidelity based benchmark has only been established for a limited number of the quantum states and reveals to be different for each state, see Refs.[13]-[15],[10]. In the present report we

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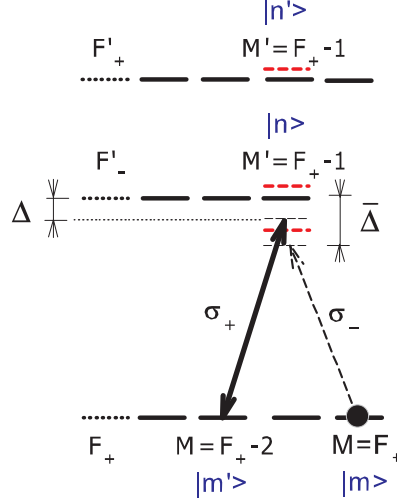
Figure 1. Schematic diagram showing the energy structure and the excitation channels considered in D_1 line of alkali atom. The atoms populate the upper hyperfine sublevel of their ground state with maximal spin projection $F_+ = I + 1/2, M = F_+$. The system is "dressed" by a strong mode of the control field in right-handed (σ_+) polarization with frequency detuning Δ and probed by a weak mode in left-handed (σ_-) polarization. The probe mode with frequency detuning $\bar{\Delta}$ scans the quasi-energy structure of the Autler-Townes resonances. Locations of these resonances are shown by red dashed bar lines.

explore the benchmark based on the properties of the coherent information originally proposed by Nielsen and Schumacher in Ref.[16]. This measure gives a convenient criterion if the memory channel preserves the quantum correlations, which is intrinsically independent on the quantum state nature. We apply it for evaluating the memory quality for different quantum states of light.

1. Quantum memory in a multilevel atomic system

In this section we consider storage of a signal pulse in an ensemble of atoms dressed by interaction with the off-resonant control field in the excitation geometry shown in figure 1. In contrast with the widely used approach of a single Λ-scheme we keep in our consideration both the interaction with the control field and the hyperfine interaction in the exited state of the alkali atom. As we show the interaction of the probe light with the medium, which is determined by the dielectric susceptibility, is strongly modified by the presence of the hyperfine interaction. We demonstrate that the storage and retrieval of coherent signal light pulse with the rectangular temporal profile can be optimized by relevant detuning of the control mode.

### 1.1. Autler-Townes effect in the D_1-line of alkali atom

Let us consider D_1-line of alkali atoms, which is typical for experiments on quantum memories. As shown in figure 1 all the atoms populate the Zeeman sublevel with the maximal projection of the total angular momentum in the ground state $F_+ = I + 1/2, M = F_+$ (where I is atomic nuclear spin). This state we denote as $|m\rangle$. Atomic response
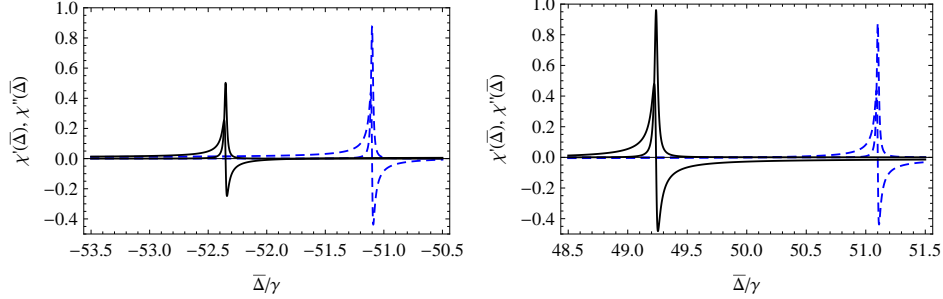
Figure 2. The absorption and dispersion parts of the sample dielectric susceptibility induced by the control mode tuned by $\Delta = -50\gamma$ (left panel) and $\Delta = 50\gamma$ (right panel) from the atomic transition $|m'\rangle \rightarrow |n\rangle$, see figure 1, for the Rabi frequency $\Omega_c = 15\gamma$. The susceptibility components are scaled by $n_0(\lambda/2\pi)^3$ (n_0 is the density of atoms and λ is the transition wavelength). Black solid curves relate to the exact calculations for the AT-triplet and the blue dotted curves indicate the dependencies plotted in the Λ-scheme approximation.

for the left-hand circular polarized (σ_-) probe mode is controlled by the presence of the right-hand circular polarized (σ_+) strong field. The energy levels of the atom ($|n\rangle$: $F'_- = I - 1/2$, $M' = F_+ - 1$ and $|n'\rangle$: $F'_+ = I + 1/2$, $M' = F_+ - 1$) and the field mode, which is occupied by the strong control field, transform to the quasi-energy resonance structure in accordance with the Autler-Townes (AT) effect, see Refs.[17,18]. For the off-resonant control field two of the AT-resonances will be located near the unperturbed atomic exited levels and one of the resonances will be located near the frequency of the control field $\bar{\Delta} \sim \Delta$. The latter resonance plays a crucial role for slowing down and storing the signal light pulse. In comparison with widely used theoretical models including only one exited state, see Refs.[9,14], our model shows that both the exited states contribute to the AT resonance structure and thus should be equally taken into consideration, see Refs.[19,20].

To demonstrate the importance of the hyperfine interaction in the upper state and explain why it cannot be assumed as infinitely strong in figure 2 we present the spectral dependencies of the sample susceptibility $\chi(\bar{\Delta}) = \chi'(\bar{\Delta}) + i\chi''(\bar{\Delta})$ for the probe mode, which were calculated for the control field tuned to either red (left panel) or blue (right panel) wings of the optical hyperfine transition $|m'\rangle \rightarrow |n\rangle$, see figure 1. The Rabi-frequency Ω_c is defined by the relevant matrix element for this transition. The calculations were done for D_1-line of ^{133}Cs atom, which has the hyperfine splitting approximately equal to 256γ, where γ is the atomic natural decay rate. The considered detunings $\Delta = \mp 50\gamma$ are relatively small in comparison with the hyperfine splitting. However from the plotted dependencies one can observe a significant deviation with predictions of the three-level model, which presumes an infinitely strong hyperfine interaction. The calculations based on three-level approximation with ignoring the exited state $|n'\rangle$ are indicated by dashed curves. Our calculations show that because of the hyperfine interaction the AT-resonance can be either smaller (red wing) or bigger (blue wing) than predictions of the three level model, when its amplitude does not depend on frequency detuning at all. It is important that the enhancement of the AT-resonance takes place only for the control mode tuned between the upper state hyperfine sublevels. This effect has practical impact on the quantum memory since dispersion part of this resonance is responsible for the delay and storage of the signal pulse in the atomic system.
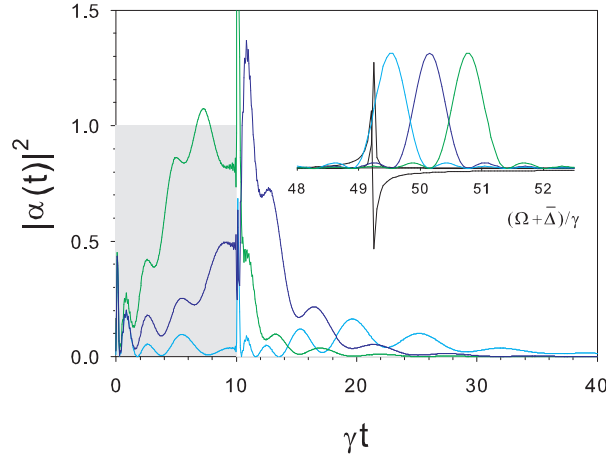
Figure 3. Time dependence of the probe pulses, with initially identical rectangular profiles of duration $T = 10\gamma^{-1}$ (shadowed box) and with different carrier frequencies, after they have passed the optically thick sample with optical depth $n_0(\lambda/2\pi)^2 L = 50$. Inset shows the spectral locations of the pulses with respect to the AT resonance. The central pulse has an optimal carrier frequency to adjust the compromised balance between transparency and delay. The carrier frequencies of two satellites are shifted by $\pm 2\pi/T$ from the central pulse frequency.

1.2. Pulse storage and retrieval efficiency

The advantage given by the enhancement of the dispersion properties of the medium when the control field is tuned between the hyperfine states can be used to provide longer delay of the signal pulse. The AT resonance shown in the right panel of figure 2 implements the delay of the signal pulse, which spectral extension is essentially broader than the width of the absorption part of this resonance. This allows to minimize the losses caused by the incoherent scattering of the signal light to other directions out of the coherent control mode. For optimal compromise between transparency and delay the carrier frequency of the probe pulse and its duration should be properly adjusted in respect to the AT resonance location and width and to the optical depth of the sample.

In figure 3 we show how three different signal pulses originally having identical rectangular temporal profile but different carrier frequencies would propagate the optically thick (for resonance radiation) sample. In inset we show the spectral shape and position of the pulses as well as the location of the AT resonance induced by the control field. The plotted dependencies show how the original profiles of the signal pulses, given in dimensionless units by $\alpha_{\mathrm{in}}(t) = \theta(t) - \theta(t - T)$, were T is the pulse duration, are modified after they have passed the optically thick medium. For the round of calculations presented in figure 3 we set optical depth as $n_0(\lambda/2\pi)^2 L \sim 50$. Our choice is motivated by the existing experimental limits accomplished for ultracold atomic systems confined with either magneto optic or quasistatic atomic traps.

The best compromise between transparency and delay of the probe is found for the central carrier frequency among the presented in the inset of figure 3. It is shifted from the induced resonance to minimize the absorption but still overlap with the steep dispersion of the medium which provides the pulse delay. For the pulse more overlapping

the AT resonance (left spectrum) the delay is longer but the pulse is mostly incoherently scattered. While shifting the carrier frequency far away from the induced resonance (right spectrum) allows to preserve the pulse shape as well as its integral intensity but gives a quite short delay. That part of the signal pulse which emerges the sample after the back front of the incoming pulse enters the sample at time T could be stored by switching off the control field after time T. By switching the control field on the stored signal pulse can be recovered with the same shape as the part of dependence shown in figure 3, which follows after time T. As was earlier verified in Ref.[11] for off-resonant stimulated Raman scattering the transient processes, associated with switching on/off the control mode, only weakly interfere with the transport of the signal pulse.

Detail optimization of the incoming pulse profile and use of the backward retrieval scheme based on time reversion arguments could be further applied to increase the memory efficiency. The strategic ideas of such optimization procedure in example of three-level system have been discussed in Ref. [9]. Here we just point out that the output profile of the retrieved pulse, which is not rectangular any longer, determines the optimal mode profile of the local oscillator field in the case of its homodyne detection, i. e. if the quantum memory is considered in terms of continuous variables. In the next section we briefly discuss the basic criteria for the memory to be quantum and the required efficiency for the storage of different quantum states.

2. Figure of merit for the quantum memory channel

Quality of the quantum memory is normally estimated via comparison with the best possible classical strategy to memorize and reproduce the quantum state by optimal measuring and reconstructing the state based on the measurement results. The optimal classical protocol gives the lower bound for the *fidelity* of the quantum memory. Estimation of the classical fidelity for the different quantum states requires different type of measurements, see Refs.[13,10,15]. As we shall point out here it is possible to avoid the problem with classical fidelity benchmark and define easier criterion of the memory quality for various of the quantum states. For this goal we shall consider the stored light subsystem Q as a part of compound system, which is correlated i. e. entangled with the remaining reference subsystem R. Such a situation seems typical for any quantum network. Then in accordance with the general theory for noisy quantum information channel developed by Schumacher and Nielsen in Ref. [16] we can define the *coherent information* transmitted through the memory channel. This parameter supposes to be positive only if the quantum correlations between the retrieved light pulse and the reference subsystem are preserved. In this case the memory could be qualified as quantum since any possible measurement attacks would destroy the existing quantum correlations.

In accordance with definition of Ref.[16] the coherent information transferred through the channel is given by the difference between the von Neumann entropies of the retrieved subsystem Q' and the entire system RQ' in the output of the channel

$$I_e = S_{Q'} - S_{RQ'} \tag{1}$$

In input of the channel this quantity is equal to the entropy of the signal light S_Q. If the channel losses were caused by interaction with environment, originally existed in a

vacuum state, then in accordance with the Schmidt decomposition rule the subtracted term $S_{RQ'}$ would be equal to the entropy transferred to environment $S_{E'} = S_{RQ'}$.

As an illustrating example let us consider first the memory channel when RQ-system performs a pair of two polarization entangled photons, one of which can be either stored and retrieved without changes or lost because of incoherent scattering. With the verification scheme the presence of the retrieved photon could be controlled in experiment and the experiment can be repeated by a number of attempts till the single photon will appear in the output. Such a conditional memory protocol is directly applicable to the quantum repeater scheme aiming the qubit teleportation. The imperfection of the conditional protocol is mainly determined by the thermal noise, which in our situation can be induced by a random Raman photon spontaneously scattered into the signal mode, and by low efficiency of the memory channel. Let us define by η the total memory efficiency including the spontaneous scattering and verification losses and by μ the probability to extract in output the random thermal photon. Then in the limit when $\mu \ll \eta < 1$ the coherent information passed through the channel is given by

$$I_e \sim 1 - \frac{3\mu(1-\eta)}{4\eta} \log_2 \left[\frac{4e\eta}{\mu(1-\eta)} \right] \tag{2}$$

This quantity is positive and even approaches its maximal possible value under the formulated conditions, which indicates that even at low level of the quantum memory efficiency the quantum correlations can be preserved if the excess noise is relatively small.

As a second illustrating example let us consider another typical situation when the object Q and reference R subsystems are two initially identical entangled macroscopic light beams. Such an EPR-type entangled state may be produced either by combining two single-mode squeezed states at a beam splitter or directly via a nonlinear two-mode squeezing interaction. For the sake of convenience we prefer to discuss the former preparation scheme and parameterize the state by its original level of squeezing $s \geq 1$ given by enhancement of the square variance for the anti-squeezed quadrature at the input of beam splitter. Then the average number of photons per mode for each beam at the output of the beam splitter, which enters to the memory channel is given by

$$\bar{n}(s) = -\frac{1}{2} + \frac{1}{4} \left(s + \frac{1}{s} \right) \tag{3}$$

The von Neumann entropy of each beam, which reproduces the original volume of the coherent information transmitted through the channel, is given by

$$S(\bar{n}) = [\bar{n} + 1] \ln [\bar{n} + 1] - \bar{n} \ln [\bar{n}] \tag{4}$$

Assuming that the environment was originally in a vacuum state and has absorbed $(1-\eta)$ part of the beam, in the output of the channel the coherent information reduces to

$$I_e = S(\eta\bar{n}) - S((1-\eta)\bar{n}) \tag{5}$$

and it can be positive only if the level of losses expressed by efficiency η is smaller than 50%. In figure 4 we show the dependence of $I_e = I_e(\eta)$ for different intensities of the input light beam i.e. for different level of original squeezing s, see Eq.(3). These de-
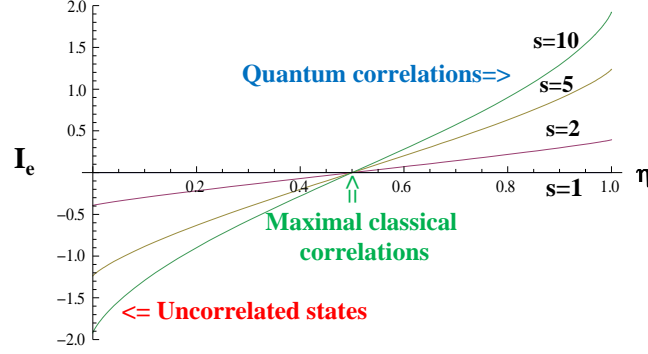
Figure 4. Coherent information representing the level of correlations between two entangled light beams one of which has passed the memory channel with efficiency η. The initial level of entanglement is given by the squeezing parameter s, see text.

pendencies show that higher efficiency is required for storage of better correlated light beams. Comparing the estimate (5) with the conditional discrete variable analog (2) one can recognize that the unconditional continuous variable scheme poses stronger requirements to the efficiency of the quantum memory and thus to the quantum information processing in general.

3. Conclusion

In this paper the quantum memory protocol via stimulated Raman process in D_1-line of alkali atom has been discussed in context of optimal choice of the control mode and signal pulse parameters. The Raman process has been considered beyond the widely used Λ-scheme approximation with paying attention to the hyperfine interaction in the upper state. We have pointed out that for the effective Raman-type storage of the signal pulse it is better to tune the control field between the upper state hyperfine sublevels. The parameters of the signal pulse, such as its carrier frequency and pulse duration, should be properly adjusted in accordance with the Autler-Townes resonance structure created by the control field.

In our estimate of the quality of the quantum memory channel we have followed the criterium based on the volume of coherent information passed through the channel. We have linked the coherent information with efficiency of the memory channel and showed that the unconditional protocol requires higher efficiency than it is in the case of conditionally verified single photon storage.

Acknowledgements

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