Optics Communications 369 (2016) 7–11

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Invited Paper

Amplified light storage with high fidelity based on electromagnetically induced transparency in rubidium atomic vapor

Wei Zhou [a], Gang Wang [a,b], Guoyu Tang [a], Yan Xue [a,c,*]

[a] Key Laboratory of Coherent Light and Atomic and Molecular Spectroscopy of Educational Ministry, College of Physics, Jilin University, Changchun 130012, PR China
[b] College of Electronic Science and Engineering, Jilin University, Changchun 130012, PR China
[c] College of Chemistry, Jilin University, Changchun 130012, PR China

ARTICLE INFO

Article history:
Received 19 October 2015
Received in revised form
21 January 2016
Accepted 27 January 2016
Available online 19 February 2016

Keywords:
Electromagnetically induced transparency
Four-wave mixing
Light storage

ABSTRACT

By using slow and stored light based on electromagnetically induced transparency (EIT), we theoretically realize the storage of optical pulses with enhanced efficiency and high fidelity in ensembles of warm atoms in ^{85}Rb vapor cells. The enhancement of storage efficiency is achieved by introducing a pump field beyond three-level configuration to form a N-type scheme, which simultaneously inhibits the undesirable four-wave mixing effect while preserves its fidelity. It is shown that the typical storage efficiency can be improved from 29% to 53% with the application of pump field. Furthermore, we demonstrate that this efficiency decreases with storage time and increases over unity with optical depth.

1. Introduction

Quantum memory [1–4] is essential for quantum information processing, including quantum communication [5,6] and quantum computation [7]. Quantum memory with high storage efficiency and storage fidelity and long coherence time are the keys to successful operation of long-distance quantum communication and quantum information processing. Several storage devices based on different mechanisms, such as EIT [8,9] and time–space reversing method [10], have been proposed and experimentally demonstrated.

With time–space reversing method, Yu's group report a 78% storage efficiency and the classical fidelity of recalled pulse is better than 90% in a cold atomic medium [10]. And with the phase measurement his group have achieved the classical fidelity of 0.94 from the EIT-based quantum memory, and the fidelity is nearly independent of the storage time [11]. According to Nikolai Lauk's work due to scattering, the fidelity of four-wave mixing EIT is still worse than that for standard EIT unless the fidelity is below $1/\sqrt{2}$ [13]. In hot rubidium atoms, the maximum efficiency for EIT-based storage is limited to 43% because of FWM process [12]. Therefore for an EIT quantum memory, it is always preferential to avoid FWM [13].

In this paper for the fidelity and storage efficiency in the three-level atomic scheme, we firstly calculate them with Doppler effect and then without Doppler effect. And we find that without the Doppler effect, storage efficiency significantly increases and fidelity remains high. In the practical application quantum memory needs high storage efficiency and high fidelity in hot atoms. We need to find a way to improve storage efficiency. We propose an N-type scheme to suppress FWM effect and then improve the storage efficiency by introducing a pump field beyond three-level Lambda-type configuration. In our proposed scheme, we add a pump field beyond the typical three-level Lambda-type configuration. The pump field provide a Raman gain for the probe pulse so as to compensate the probe loss before it is stored in the medium and the delay time for slow light is also decreased and even slow light for the probe pulse could be converted to fast light by the action of the added pump field. Thus the waveform distort of the probe pulse is reduced and its fidelity during the storage process could be maintained The numerical results show that the storage efficiency is significantly improved while its fidelity keeps a rather high level. The optical depth *OD* and storage time τ affect the storage efficiency. Previous theory predicts that the storage efficiency of EIT-based memory could increase significantly at a high optical depth [14]. And the longer storage time results in exponential reduction of the recover signal pulse energy due to spin wave decoherence during storage [9]. So with the increase of storage time the efficiency decreases gradually. In this paper, we calculated the fidelity and storage efficiency as a function of

---

* Corresponding author at: Key Laboratory of Coherent Light and Atomic and Molecular Spectroscopy of Educational Ministry, College of Physics, Jilin University, Changchun 130012, PR China.
E-mail address: xy4610@jlu.edu.cn (Y. Xue).

http://dx.doi.org/10.1016/j.optcom.2016.01.079
0030-4018/© 2016 Elsevier B.V. All rights reserved.

storage time and optical depth, respectively. We find that the storage efficiency increases over unity with optical depth and decreases with storage time.

2. Typical three-level light storage based on EIT

In this section, we review the theoretical work on the three-level Λ-type ^{85}Rb atoms condition. The three-level Λ-type cold ^{85}Rb atoms as shown in Fig. 1(a). The excited state $|3>$ is coupled to the ground state $|1>$ and $|2>$ by the probe field Ω_p and coupling field Ω_c, to form a standard three-level Λ-type energy scheme. The signal field is mapped on the spin coherence by adiabatically switching off the control field and later, after some storage time, is retrieved by switching on the control field. Under the rotating-wave and electric-dipole approximation, the Hamiltonian describing the atomic response to the light fields can be expressed as:

$$H = \begin{pmatrix} 0 & 0 & -\Omega_p^* \\ 0 & 0 & -\Omega_c^* \\ -\Omega_p & -\Omega_c & 0 \end{pmatrix} \tag{1}$$

where, $\Omega_c = \mu_{23}E_c/2\hbar$ and $\Omega_p = \mu_{13}E_p/2\hbar$ are the Rabi frequencies of the coupling field and probe field, where E_c and E_p represent the corresponding slowly varying envelopes. μ_{ij} is the dipole matrix elements of the respective transitions from $|i>$ to $|j>$. The optical Bloch equation for the atomic density-matrix operator are given by

$$\begin{aligned}
\frac{\partial}{\partial t}\rho_{21} &= \left(\rho_{23}\Omega_p - \rho_{31}\Omega_c^*\right) \\
\frac{\partial}{\partial t}\rho_{22} &= \Gamma_{32}\rho_{33} - i\left(\rho_{23}\Omega_c - \rho_{32}\Omega_c^*\right) \\
\frac{\partial}{\partial t}\rho_{31} &= \frac{1}{2}\left(-\Gamma_{31} - \Gamma_{32}\right)\rho_{31} - i\left(-\rho_{21}\Omega_c - \rho_{11}\Omega_p + \rho_{33}\Omega_p\right) \\
\frac{\partial}{\partial t}\rho_{32} &= \frac{1}{2}\left(-\Gamma_{31} - \Gamma_{32}\right)\rho_{32} - i\left(-\rho_{22}\Omega_c + \rho_{33}\Omega_c - \rho_{12}\Omega_p\right) \\
\frac{\partial}{\partial t}\rho_{33} &= -\Gamma_{31}\rho_{33} - \Gamma_{32}\rho_{33} - i\left(-\rho_{23}\Omega_c - \rho_{13}\Omega_p + \rho_{32}\Omega_c^* + \rho_{31}\Omega_p^*\right)
\end{aligned} \tag{2}$$

where γij are the decoherence rates from $|i>$ to $|j>$. The light propagation of the weak probe is described by the Maxwell equation

$$\frac{1}{c}\frac{\partial}{\partial t}\Omega_p + \frac{\partial}{\partial z}\Omega_p = i\rho_{31}\frac{OD\cdot\Gamma}{4L} \tag{3}$$

where OD and L are the optical depth and the length of the medium. The spontaneous decay rate Γ of the excited state $|3>$ is 5.75 MHz. To make the theoretical predictions, the space–time evolution of weak pulses passing through the Rb cell can be accessed by numerically solving the Maxwell equation of the light pulse and optical Bloch equation of the atomic density-matrix operator.

The storage efficiency is defined as the ratio of the retrieved pulse energy to that of the input and

$$\eta = \int |E_{out}(t)|^2 dt / \int |E_{in}(t)|^2 dt \tag{4}$$

the fidelity is defined as the convolution of the input and output electric fields [10].

$$f = \left| \int E_{in}^*(t - t_d)E_{out}(tdt) \right|^2 / [\ \int |E_{in}(t)|^2 dt \int |E_{out}(t)|^2 d] \tag{5}$$

In Eqs. (4) and (5) E_{in} and E_{out} are the electric fields of input pulse and output pulse and t_d is the delay time. When $OD = 55\Gamma$, $\Omega_p = 0.001\Gamma$, $\Omega_c = 0.35\Gamma$ and the storage time τ is 15 μs we numerically solve the Maxwell equation of the light pulse and optical Bloch equation. Using the numerical result we plot the change of probe pulse over time as shown in Fig. 1(b). And according the numerical result and Eqs. (4) and (5) we calculate the storage efficiency and the fidelity is 94.7% and 99.3%. We adjust the parameters to the practical situation; i. e., $OD = 150\Gamma$, $\Omega_c = 1.1\Gamma$, the efficiency 99.3% and fidelity 97.5% as shown in Fig. 1(c) is similar to the results reported by Yu's group [10].

The result of storage efficiency and fidelity in cold atoms meet the practical requirements. But in the practical applications the quantum memory need to consider storage efficiency and fidelity in hot atoms condition. Using the same parameters, the fidelity and storage efficiency are 92.6% and 29% respectively in hot atoms with Doppler effects as shown in Fig. 2(b). The low efficiency for EIT-based light storage is due to FWM process in a Doppler broadened absorption spectrum. Previously mentioned the storage efficiency of 43% is reported by Nathaniel B. Phillips is bigger than 29% the same considering FWM effect due to they use the optimal input signal pulse shape for any given control field beyond an idealized three-level system of ^{87}Rb. Compare with ^{85}Rb atom the ^{87}Rb atom have larger detuning between the two ground states, the FWM can be diminished to the point of have negligible contribution to the signal field at comparable optical depths [15]. The ^{85}Rb's energy level is shown in Fig. 2(a).

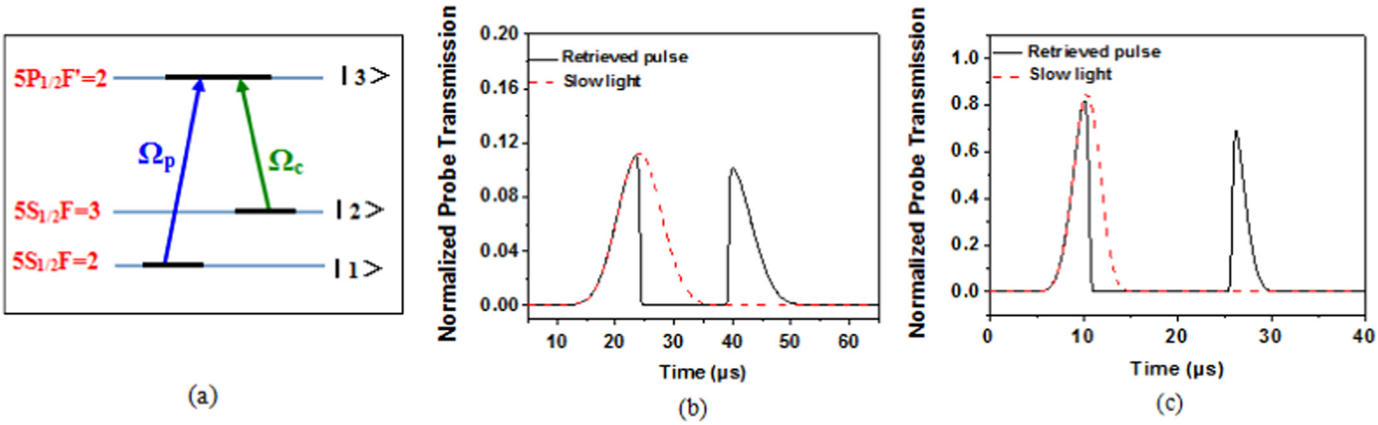

Fig. 1. (a) Diagrams of the energy levels of three-level cold atoms (b) Typical plots theoretical prediction store and retrieve pulses in three-level cold atoms where $OD = 55\Gamma$, $\Omega_p = 0.001\Gamma$, $\Omega_c = 0.35\Gamma$ and the storage time τ is 15 μs. Red dash curve is the slow light and the black solid curve is storage and retrieved pulse in this scheme. (c) Theoretical prediction stored and retrieved pulses in three-level cold atoms where $OD = 150\Gamma$, $\Omega_p = 0.001\Gamma$, $\Omega_c = 1.1\Gamma$ and the storage time τ is 15 μs. Red dash curve is the slow light and the black solid curve is storage and retrieved pulse in this scheme. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)