Conversion of Coherent Light in Electromagnetically Induced Transparency (EIT) based optical memory via Four-Level Scheme

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Abstract: Coherent optical memories based on electromagnetically induced transparency (EIT) offer a convenient way to convert the frequency or polarization of optical pulses by storing in one channel and retrieving in another channel. We report an experimental study on the efficiency variation after such coherent light conversion using cold atomic ensembles. Miss-match in transition dipole moments between the two channels may result in different delay-bandwidth products and cause an efficiency change in the retrieved pulses. Besides, the population distribution among the Zeeman degenerate manifolds in the involved energy levels may introduce nonadiabatic energy loss in the retrieved pulses due to incompatibility between the ground-state coherence and the ratio of the probe and control Clebsch-Gordan coefficients. Our work provides essential knowledge and insight for the efficiency change in memory-based light conversion.

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1. Introduction

Storage and retrieval of light pulses in atomic ensembles using the effect of electromagnetically induced transparency (EIT) in a Λ-type three-level system have been intensively studied due to its vast applications as quantum memory in quantum information processing [1]. By controlling the intensity or direction of the control field during the retrieval process, the temporal width or propagating direction of the retrieved probe pulses can be manipulated [2–4]. With a four-level double-Λ system, the polarization or wavelength of the retrieved probe pulses can be changed by turning on a different control field driving another transition during retrieval process [4–7]. This can be served as frequency converter or multiplexer to interface different quantum systems in the quantum network. Furthermore, by turning on both control fields during retrieval, the stored atomic coherence could be simultaneously released into two separate photonic channels with the amplitude ratio controlled by the intensity ratio of the two control fields [4, 5, 8, 9]. This can be served as frequency-domain tunable beam splitter [3, 10] or two-color quantum memory [11].

For the double-Λ system in real atoms, the transition dipole moments and thus the optical depths for the stored and retrieved probe channel are usually different. The difference in delay-bandwidth products for the stored and retrieval probe channels may lead to different retrieval efficiency. Furthermore, the involved energy levels may contain degenerate Zeeman sub-levels. As have been pointed out in Refs. [5, 6, 12], this can lead to a nonadiabatic energy loss in the retrieved pulses due to the incompatibility between the stored ground-state coherence and the ratio of the probe and control Clebsch-Gordan coefficients. In the steady-state regime, an analytic relation of the energy ratio for the retrieved pulse in the second channel to that of the first channel is derived which is related to Zeeman population distribution and the ratio of the Clebsch-Gordon coefficient for the control and probe transitions [12]. In a recent theoretical study, we have
2. Optical Converter via EIT-based Memory

Our experiment is based on a cesium magneto-optical trap (MOT) with optically dense cold atomic media. Details of the MOT and experimental setup can be referred to Refs. [14,15]. The relevant energy levels and laser excitations are plotted in Fig.1a. For the storage channel, the writing control field and probe field drive the $|F = 4\rangle \rightarrow |F' = 4\rangle$ and $|F = 3\rangle \rightarrow |F' = 4\rangle$ transition of cesium $D_1$ line with $\sigma^-$ polarizations, respectively. For the retrieval channel, reading control field and conversion field drive the same transitions but with $\sigma^+$ polarizations (main figure in Fig.1a). We compare these conversion behaviors with those of opposite driving sequence, i.e., storing with $\sigma^+$ transition and retrieving with $\sigma^-$ transition (sub-figure in Fig.1a). In such an experiment, we manipulate the polarization of the retrieved light but not its frequency. Although it is also possible to manipulate the frequency of the retrieved pulses by choosing another control transition during retrieval process, such a choice allows us to concentrate our study on the relative efficiency change of the retrieved pulses without bothering by the systematic effects during detection of the retrieved pulses with different frequencies. On the other hand, in the process of conversion, multiple degenerate Zeeman sub-levels might be involved and complicate the converting dynamics, and these phenomena do influence conversion efficiency significantly [5,6,12]. To realize light conversion via atomic system into application, however, such a loss is one of unavoidable issues. Thus, we include seven Zeeman sub-levels of atomic
energy levels \((m = -3 \sim m = 3)\) in our following discussion (Fig.1a).

3. Theoretical Background

In our experiment, to quantitatively compare efficiencies of conversion pulses with those of unconverted pulses (stored light), we focus our discussion on relative conversion efficiency, \(\xi^R\), which is defined as the ratio of conversion pulse to that of stored light. Note that in our definitions, stored light means both storing and retrieving process share the same transition channels, and conversion light means they undergo different transition channels. Based on Maxwell-Bloch equations and considering Zeeman internal manifold, one can show that [13]-

\[
\xi^R = \xi_1 \xi_2,
\]

\[
\xi_1(\eta) = \frac{\zeta_p(\eta)}{\zeta_c(\eta)}, \quad \xi_2 = \frac{\sum p_j R^p_j R^c_j}{\sum p_j R^{p^2}_j \sum p_j R^{c^2}_j},
\]

where \(\zeta_p, \zeta_c\) are retrieval broadening factors of probe and conversion channels, respectively. Those factors are given by

\[
\zeta_p(\eta) = \left[ 1 + \frac{16\ln2(1-\kappa/\eta)^2 \sum p_j R^p_j R^{d^2}_j / (a_{p,j}^2 a_{p})}{\beta^2_w(L_c) / (\sum p_j R^p_j)^2} \right]^{1/2},
\]

\[
\zeta_c(\eta) = \left[ 1 + \frac{16\ln2(1-\kappa/\eta)^2 \sum p_j R^c_j R^{d^2}_j / (a_{c,j}^2 a_{c})}{\beta^2_w(L_c) / (\sum p_j R^c_j)^2} \right]^{1/2},
\]

and

\[
R^p_j = \frac{a_{p,j}}{a_{w,j}}, \quad R^c_j = \frac{a_{c,j}}{a_{r,j}}, \quad \eta \equiv \frac{T_d}{T_p}, \quad \kappa \equiv \frac{T_w}{T_d},
\]

\[
\beta_w \equiv [1 + 16\ln2 \frac{\eta(\eta-\kappa)}{D_c}]^{1/2}, \quad \beta_r \equiv [1 + 16\ln2 \frac{\eta(\eta-\kappa)}{D_c}]^{1/2},
\]

All subscripts \(j\) denote \(j^{th}\) Zeeman sub-level, and \(p_j\) denotes normalized population in \(j^{th}\) state; \(a_{(p,c,r,w)}\) denote Clebsch-Gordon coefficients for probe, conversion, reading control, and writing control fields. \(a_{p,c}\) are probe and conversion field’s normalized optical depth, which is the one without multiplied by Clebsch-Gordon coefficients for specific channels. i.e, real optical depth \(D_{p,c} = \sum a_{(p,c)} a_{p,c}^2\), \(T_d\) denotes time delay of slow light and can be expressed as \(D_p \Gamma / \Omega_n^2\), where \(D_p\) means probe field’s optical depth, \(\Omega_n\) denotes writing control’s Rabi frequency, and \(\Gamma\) denotes natural linewidth; \(T_w\) denotes period of time that writing control beam is switched on; \(T_p\) denotes temporal full width at half maximum (FWHM) of the probe input pulse.

In Eq.1, the relative conversion efficiency is determined by the product of two factors, finite bandwidth factor (\(\xi_1\)) and ground-state coherence mismatch factor (\(\xi_2\)) [13]. \(\xi_2\), ranging from zero to unity, stands for nonadiabatic energy loss when conversion occurs. It is less than unity when population is distributed among several Zeeman states and \(R^p_j / R^c_j\) mismatches on any of them [12]. The other term, \(\xi_1\), is in charge of finite bandwidth effect. This effect results from the difference of delay-bandwidth products of storing and retrieval channels [13], and it can be understood below. Since bigger transition dipole moment favors pulse’s efficiency for given \(\eta\) [15], we can view it as low-loss channel [15], while small transition dipole moment corresponds to high-loss channel. Thus, different transition dipole moments between the storing and retrieval channels causes different energy loss, and \(\xi_1\) is responsible for this factor. Specifically, \(\xi_1 > 1\) \((\xi_1 < 1)\) when converted from small (big) to big (small) transition dipole moment, meaning
We demonstrate our raw data in Fig.2. In all these measurements, we switch on optical pumping weak writing control beam. Firstly, (PM fiber). The control beam passes through an electro-optic modulator, which allows us to The schematic setup of the experiment is summarized in Fig.1b. The probe beam is temporally , and these two effects compete against each other. In the strong writing control regime (small case, finite bandwidth effect tells that since now it converts from small into big optical depth. Yet, ξ1 should be less than one in the σ+ → σ− conversion, leading to even smaller ηD. In the reverse case, finite bandwidth effect tells that ξ1 should be larger than one in the σ− → σ+ conversion, since now it converts from small into big optical depth. Yet, ξ2 drags conversion efficiency down .

4. Experimental Setup

The schematic setup of the experiment is summarized in Fig.1b. The probe beam is temporally shaped into the Gaussian pulse before sent into atomic module via polarization-maintaining fiber (PM fiber). The control beam passes through an electro-optic modulator, which allows us to fast change its polarization within ~ 10 ns after the storage and before the retrieval process. It then couples with the probe beam through a beam splitter before entering into the cold atomic clouds. The probe beam is focused to an intensity e−2 diameter of ~100 μm around the atomic clouds while the control beam is collimated with a diameter of ~ 1 mm. After coming out of the MOT cell, the control beam is blocked by a window with a black dot while the probe beam passes through it. The probe beam then passes through three irises and an etalon filter before coupled into a fiber and detected by a photomultiplier tube (Hamamatsu R636-10). To control ground-state coherence mismatch factor (ξ2), which is sensitive to population distribution in Zeeman sub-levels, we shoot additional optical pumping beam in our cooling cycles (D2, |F = 3⟩ → |F′ = 2⟩ with σ+ transition), pumping atomic state toward right side (m = 3) of Zeeman sub-levels before EIT measurements. Without optical pumping, population is equally distributed among seven Zeeman sub-levels, while it is mainly prepared in |F = 3, m = 3⟩ sub-state when optical pumping is fully switched on for 20 μs, and both of them are confirmed via microwave measurements [15]. By turning on and off this beam, we are able to create different Zeeman sub-states distribution, making this population-induced loss controllable.

5. Experimental Observations

We demonstrate our raw data in Fig.2. In all these measurements, we switch on optical pumping (20 μs) to pump atoms towards |F = 3, m = 3⟩ [15], and we choose pulse’s full width at half maximum (FWHM), denoted as Tp, to be 200 ns. Fig.2a and Fig.2b shows slow and stored light. In order to reach optimized retrieval efficiency, we adjust control beam power to let time delay (Td) ≈ 540 ns [15]. Fig.2a and Fig.2b are measurements without conversion, and they correspond to σ+ and σ− channels, respectively. Under the case that atoms are mainly located in the |F = 3, m = 3⟩, since transition dipole moment in σ+ transition is larger than that of σ− transition, the optical depth corresponding σ+ channel is also larger. Based on EIT performance for pulse storage, higher optical depth favors higher efficiencies, and it explains why both efficiencies in slow light (67 %) and stored light (66 %) in σ+ transition (big optical depth) are larger than those (49 %, 45 %) in σ− transition (small optical depth).

In the following, we present our data on light conversion. We store via σ+ channel (σ− channel) and convert it out via σ− channel (σ+ channel), corresponding to Fig.2c, Fig.2e (Fig.2d, Fig.2f). Both Fig.2c and Fig.2d use strong writing control beam, and Fig.2e and Fig.2f use weak writing control beam. Firstly, ξ1 should be less than one in the σ+ → σ− conversion, since it converts from big optical depth channel into small one. Combined with ξ2, ξD must be smaller than unity based on Eq.1, which agrees with both Fig.2c and Fig.2e. In Fig.2e, when choosing weaker writing control and thus larger η (η ≡ Td/Tp = DpΓ/(TpΩ2 )), ξ1 decreases further because of stronger finite bandwidth effect, leading to even smaller ξD. In the reverse case, finite bandwidth effect tells that ξ1 should be larger than one in the σ− → σ+ conversion, since now it converts from small into big optical depth. Yet, ξ2 drags conversion efficiency down , and these two effects compete against each other. In the strong writing control regime (small
Figure 2. (a,b) Red: input; Green: slow light; Blue: stored light; (c,d,e,f) Red: input; Green: stored light; Blue: conversion light. In all six subplots, Thin-solid and thick-solid curve represent experimental data and fitting curve, respectively. (a): $\sigma^+\rightarrow\sigma^-$, $\Omega_w = 4.03\Gamma$; (b): $\sigma^+\rightarrow\sigma^-$, $\Omega_w = 1.97\Gamma$; (c): $\sigma^+\rightarrow\sigma^-$, $\Omega_w = 3.11\Gamma$, $\xi^R_{c} = 17.4\%$; (d): $\sigma^+\rightarrow\sigma^-$, $\Omega_w = 1.51\Gamma$, $\xi^R_{c} = 93.8\%$; (e): $\sigma^+\rightarrow\sigma^-$, $\Omega_w = 2.11\Gamma$, $\xi^R_{c} = 15.4\%$; (f): $\sigma^+\rightarrow\sigma^-$, $\Omega_w = 0.93\Gamma$, $\xi^R_{c} = 150.5\%$. The high frequency noises appearing in (c,d,e,f) at roughly 1.8 $\mu$s comes from electronic noises due to switching on high voltage power supply for our electro-optics modulator.

$\eta$), where finite bandwidth effect isn’t obvious, $\xi^R_{c}$ is mainly affected by ground-state coherence mismatch factor ($\xi_2$) and thus smaller than unity, corresponding to Fig.2d. In the weak writing control regime (large $\eta$), finite bandwidth effect dominates, making $\xi_1$ even larger. Therefore, in Fig 2f, even in the presence of ground-state coherence mismatch, $\xi^R_{c}$ is still larger than unity. Under this condition, efficiency of conversion light is even larger than that without conversion, and this bizarre phenomenon has been discussed in [13].

It should be noted that both pulse heights and temporal widths of retrieval signal can be manipulated by different choices of reading control beam’s Rabi frequency ($\Omega_r$), while their efficiencies remain unaffected [2]. In our work, we want to focus on conversion efficiency instead of manipulating pulse shape, and therefore we all use strong reading control beam ($\sigma^+\rightarrow\sigma^-\rightarrow\sigma^+$) to retrieve signal out. On one hand, such a choice doesn’t change retrieval efficiency, and strong control beam also shortens pulse temporal widths and increases pulse heights, making signals more clear. To further confirm this does not affect retrieval efficiency, we also conduct measurements on stored light efficiencies with different $\Omega_r$, as shown in Fig.3. Retrieval efficiencies remain unaffected among different reading controls, and therefore we all use strong reading control beams for retrieving out signals in all conversion measurements.

To give a more comprehensive picture, we conduct series of measurements of $\xi^R_{c}$ with different $\eta$ in different population distributions of Zeeman substates. Since the change of $\xi^R_{c}$ with different $\eta$ is more obvious in $\sigma^-\rightarrow\sigma^+$ conversion, we first experimentally focus on this conversion. We measure $\xi^R_{c}$ with different time delay ($T_d$) by using different $\Omega_w$ ($T_d = T_p \Gamma / \Omega_w^2$), and we remain the same $T_p = 200$ ns for all below measurements. In addition, these series of measurements
Figure 3. (a,c), (b,c) correspond to stored light via $\sigma^+$, $\sigma^-$ channels, respectively. (a, b) demonstrate some of raw data, and (c, d) show all stored light efficiency. As shown in (c,d), different choice of reading control Rabi frequency doesn’t change retrieval efficiency. In (a), Retrieval $\Omega_c$: 2.0231, 2.8996, 6.0866\Gamma; In (b), Retrieval $\Omega_c$: 4.6844, 5.5025, 6.7392\Gamma

include both pulses and continuous wave (CW) input and also cases when optical pumping is on and off (Fig.4 a), which corresponds to different Zeeman internal distributions [15].

Firstly, let us focus on pulse case in Fig.4a. As discussed in the previous paragraph, large $T_d$, corresponding to large $\eta (\eta T_d = T_d)$ and thus stronger finite bandwidth effect, favors $\xi_1$ and therefore increases $\xi^R_c$ in the $\sigma^- \rightarrow \sigma^+$ conversion. Fig.4a captures this behavior. When optical pumping is switched on, $\xi^R_c$ rises with $T_d$ significantly. When optical pumping is off, however, the curve goes flat and much less sensitive to different $T_d$, and it can be explained below. Finite bandwidth effect, which is in charge of $\eta$-dependence of $\xi^R_c$, occurs when converted between channels with different transition dipole moments. Therefore, we can expect this effect becomes stronger when bigger contrast exists between probe and conversion field’s transition dipole moments. Due to properties of Clebsch-Gordan coefficients, when populated toward $|F = 3, m = 3\rangle$, transition dipole moment becomes larger (smaller) in $\sigma^+$ ($\sigma^-$) channel. This big contrast leads to enhanced finite bandwidth effect and huger $\xi^R_c$ change with different $\eta$. When optical pumping is off, atomic population is equally distributed among different substates, and thus transition dipole moments of $\sigma^- \rightarrow \sigma^+$ and $\sigma^+ \rightarrow \sigma^-$ are the same, causing this contrast and thus finite bandwidth effect to disappear. Then, $\xi^R_c$ is only determined by $\xi_2$, which is not $\eta$-dependence. This explains why $\xi^R_c$ barely changes when optical pumping is off. The solid line is fitting curve based on Eq.1, and the fitted populations agree with those of microwave measurements [15].

To generalize our discussion, we also consider CW as probe input in Fig.4a [15]. Since CW doesn’t possess finite bandwidth and thus is free from finite bandwidth effect, $\xi^R_c$ is only determined by $\xi_2$ [12], and this factor doesn’t change with different $T_d$. In Fig.4a, $\xi^R_c$ remains almost flat when both optical pumping on and off, which is consistent with above arguments. Also, $\xi^R_c$ is smaller when optical pumping is off. This is because when population is distributed broadly (optical pumping is off), non-adiabatic energy loss increases [12, 13], meaning $\xi_2$ becomes smaller and thus leading to smaller $\xi^R_c$.

We next conduct the corresponding experiments of $\sigma^+ \rightarrow \sigma^-$ conversion (Fig.4b). Here, opposite to the precious case, the light is converted from large to small transition dipole moments,
Figure 4. We perform our measurements of $\xi^R_{c}$ in (a)(b). (a): $\sigma^- \rightarrow \sigma^+$, (b): $\sigma^+ \rightarrow \sigma^-$. Solid curves are fitted by Eq.1. The fitting population (%) from m=3 to -3 is ((a), op: on) = (52.1136, 28.9520, 17.3712, 0.0000, 1.5632, 0, 0); ((a), op: off) = (24.9115, 24.9120, 18.8084, 6.2281, 6.2280, 6.2280); ((b), op: on) = (55.2132, 23.6270, 15.5299, 0.1733, 0.2209, 7.7065); ((b), op: off) = (19.7280, 16.4399, 10.0300, 9.1398, 6.6211, 16.8700, 21.1712).

meaning that the finite bandwidth effect results in the decrease of $\xi^R_{c}$ when time delay increases. We capture this trend in our experiment when optical pumping is on, and this behavior also becomes insensitive to $\eta$ when optical pumping is off, as mentioned before.

In our work, we utilize cold atomic system to implement EIT-based coherent light conversion on polarization space. We experimentally study the behavior of relative conversion efficiencies ($\xi^R_{c}$) and extend our discussion into both pulse and continuous wave (CW) input. We conclude that two factors, finite bandwidth effect and ground-state coherence mismatch, are in charge of variation of conversion efficiencies. Series of measurements of $\xi^R_{c}$ provide comprehensive experimental results on four-level conversion system, and it also quantitatively shows good agreements with theoretically discussions [13]. All in all, we provide essential knowledge for realizing memory-based optical converter via atomic system, and we also present physics insights about such conversion behavior.
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