Optics Communications 343 (2015) 183–187

Contents lists available at ScienceDirect

Optics Communications

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

Phase control of stationary light pulses due to a weak microwave coupling

Yan Zhang [a], Yi-Mou Liu [b], Hong Yang [c], Gang-Cheng Wang [a], Tao-Tao Hu [a], Chun-Fang Sun [a], Tai-Yu Zheng [a,*]

[a] *School of Physics, Northeast Normal University, Changchun 130024, PR China*
[b] *College of Physics, Jilin University, Changchun 130012, PR China*
[c] *College of Physics and Electronic Engineering, Hainan Normal University, Haikou 571158, PR China*

ARTICLE INFO

Article history:
Received 17 June 2014
Received in revised form
4 January 2015
Accepted 5 January 2015
Available online 7 January 2015

Keywords:
Stationary light pulses
Coherent phase modulation
Reversible light storage
Electromagnetically induced transparency

ABSTRACT

We study the dynamic control of stationary light pulses generated in a sample of cold atoms driven into the double-Λ configuration with two ground levels coupled by a weak microwave field. This microwave field can modify the spin coherence of two ground levels through its phase and amplitude, and then increase or decrease the intensity of a stationary light pulse generated from this spin coherence. Such phase-modulation technique is essential to maximize the effective interaction time between light and matter in photonic information processing and therefore facilitate the achievement of enhanced optical nonlinearities at low-light levels.

1. Introduction

In the past few decades, there has been widespread concerns on the reversible light storage or memory in atomic ensembles due to its important applications and significant advantages in long-distance quantum networks and photonic quantum information processing [1,2]. Among numerous effects of light–matter interactions, electromagnetically induced transparency (EIT), a phenomenon referring to the resonant absorption suppression of a weak light field via quantum destructive interference, has been considered as a key technique to achieve coherent manipulation of light storage and retrieval dynamics [3,4]. In the typical EIT system of three-level Λ configuration, a weak probe pulse can be well stored (retrieved) into (from) a collective excitation of atomic spin coherence by adiabatically switching off (on) a strong coupling field [5]. Modifying the Λ-type EIT system by introducing an additional microwave field to connect the two ground levels, for instance, it is viable to control on demand the amplitude of a retrieved probe pulse depending on both initial phase and coupling strength of this microwave field [6–12]. One main problem of this EIT-based technique lies in that there are vanishing optical components during the light storage duration so that one cannot implement information processing via sufficient optical nonlinearities.

In 2003, Bajcsy et al. first showed that stationary light pulses (SLPs) could be attained in the EIT regime by replacing a traveling-wave (TW) coupling field with a standing-wave (SW) coupling field in a hot atomic gaseous [13]. Dynamic generation of SLPs from a collective excitation of atomic spin coherence maintains nonvanishing optical components and facilitates photonic information manipulation when probe light pulses are stored in the EIT media [14]. Since SLPs significantly increase the interaction time between light and matter even with extremely weak optical components, they have an obvious advantage in achieving nonlinear optics and information processing at low-light levels, such as long-range interactions between photonic qubits and single-photon information processing [15]. However, we have to deal with one severe problem of SLPs: in the typical Λ-type EIT system driven by a SW coupling field, significant loss and diffusion responsible for the fast decay of SLPs in cold atoms are increasingly remarkable in the presence of many high-order Fourier components of spin coherence and optical coherence [16,17]. To overcome this difficulty, one efficient way is to adopt a four-level double-Λ EIT system driven by two counter-propagating coupling fields where the non-degenerate four-wave mixing is explored to attain relatively robust two-color SLPs with less loss and diffusion during the light storage duration [18,19]. But the decay of two-color SLPs in a double-Λ EIT system is still somewhat fast [20] so that it is essential to find a good method to maximize the

---

* Corresponding author.
E-mail address: zhengty@nenu.edu.cn (T.-Y. Zheng).

http://dx.doi.org/10.1016/j.optcom.2015.01.013
0030-4018/© 2015 Elsevier B.V. All rights reserved.

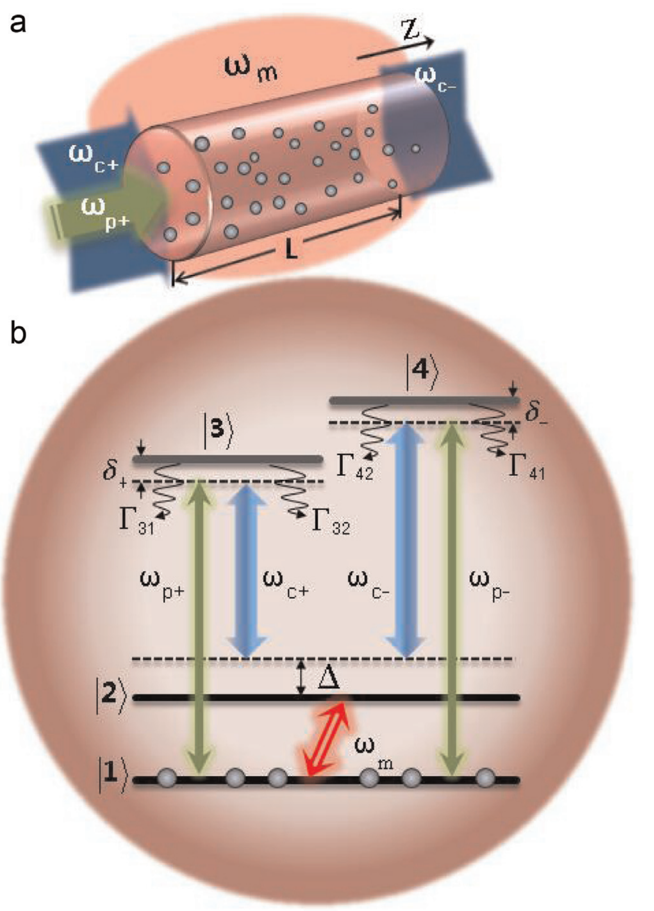

Fig. 1. (a) Schematic illustration of a cold atomic sample of length L driven by the external optical (ω_{c+}, ω_{c-}, ω_{p+}) or microwave (ω_m) fields. (b) Schematic diagram of a four-level double-Λ system of ^{87}Rb atoms interacting with two counter-propagating weak probe fields $\omega_{p\pm}$, two counter-propagating strong driving fields $\omega_{c\pm}$ and a weak microwave field ω_m.

interaction time between light and matter by further reducing loss and diffusion.

Here we present a practical method to manipulate the intensity of a two-color SLP by applying a weak microwave field to connect the two ground levels in a double-Λ system of cold atoms (see Fig. 1). This microwave field is turned on after the light storage and before the SLP generation to control the atomic spin coherence in a periodic way. We find that the SLP intensity depends critically on this additional microwave field and can be maximally increased to reduce its loss and diffusion for an initial microwave phase $\phi_m \simeq 0.5\pi$. In addition, our numerical results show that the generated SLP maintains its temporal shape in the presence of a sufficiently weak microwave field. Therefore our microwave manipulation scheme is promising for achieving long light–matter interaction times and may find applications in nonlinear light information processing.

2. Model and equations

We consider a short sample of length L containing an ensemble of cold ^{87}Rb atoms [see Fig. 1(a)] driven into the four-level double-Λ configuration [see Fig. 1(b)] with levels $|4\rangle$, $|3\rangle$, $|2\rangle$ and $|1\rangle$ referring to state $|5P_{1/2}, F=2\rangle$, $|5P_{1/2}, F=1\rangle$, $|5S_{1/2}, F=2\rangle$ and $|5S_{1/2}, F=1\rangle$, respectively. A strong coupling field of Rabi frequency Ω_{c+} (Ω_{c-}), carrier frequency ω_{c+} (ω_{c-}), and initial phase ϕ_{c+} (ϕ_{c-}) acts upon the transition $|3\rangle \leftrightarrow |2\rangle$($|4\rangle \leftrightarrow |2\rangle$) while propagating forward (backward) along the $\vec{z}$ direction. The transition $|3\rangle \leftrightarrow |1\rangle$ is probed by a forward weak (pulsed) field of Rabi frequency Ω_{p+}, carrier frequency ω_{p+}, and initial phase ϕ_{p+} while propagating forward along the $\vec{z}$ direction. As a result of resonant four-wave mixing, a backward weak (pulsed) field of Rabi-frequency Ω_{p-}, carrier frequency ω_{p-}, and initial phase ϕ_{p-} will be generated on the transition $|4\rangle \leftrightarrow |1\rangle$ and propagate backward along the $\vec{z}$ direction. A weak microwave field is further applied to modify the spin coherence between ground levels $|1\rangle$ and $|2\rangle$ with Rabi frequency Ω_m, carrier frequency ω_m, and initial phase ϕ_m along the $\vec{z}$ direction. Relevant detunings in this closed system are defined as $\Delta = \omega_{p+} - \omega_{c+} - \omega_{21} = \omega_{p-} - \omega_{c-} - \omega_{21}$, $\delta_+ = \omega_{p+} - \omega_{31}$ and $\delta_- = \omega_{p-} - \omega_{41}$ restricted by energy conservation.

Under electric-dipole and rotating-wave approximations, we can write down the interaction Hamiltonian to obtain following density matrix equations:

$$
\begin{aligned}
\partial_t\rho_{11} &= iG_{m}^{*}\rho_{21} - iG_{m}\rho_{12} + iG_{p+}^{*}\rho_{31} - iG_{p+}\rho_{13} + iG_{p-}^{*}\rho_{41} - iG_{p-}\rho_{14} + \Gamma_{31}\rho_{33} + \Gamma_{41}\rho_{44}\\
\partial_t\rho_{22} &= iG_{m}\rho_{12} - iG_{m}^{*}\rho_{21} + iG_{c+}^{*}\rho_{32} - iG_{c+}\rho_{23} + iG_{c-}^{*}\rho_{42} - iG_{c-}\rho_{24} + \Gamma_{32}\rho_{33} + \Gamma_{42}\rho_{44}\\
\partial_t\rho_{33} &= iG_{p+}\rho_{13} - iG_{p+}^{*}\rho_{31} + iG_{c+}\rho_{23} - iG_{c+}^{*}\rho_{32} - \Gamma_{31}\rho_{33} - \Gamma_{32}\rho_{33}\\
\partial_t\rho_{12} &= -(\gamma_{21} - i\Delta)\rho_{12} - iG_{c+}\rho_{13} - iG_{c-}\rho_{14} + iG_{p+}^{*}\rho_{32} + iG_{p-}^{*}\rho_{42} + iG_{m}^{*}(\rho_{22} - \rho_{11})\\
\partial_t\rho_{13} &= -(\gamma_{31} + i\delta_+)\rho_{13} - iG_{c+}^{*}\rho_{12} + iG_{m}^{*}\rho_{23} + iG_{p-}^{*}\rho_{43} + iG_{p+}^{*}\left(\rho_{33} - \rho_{11}\right)\\
\partial_t\rho_{14} &= -(\gamma_{41} + i\delta_-)\rho_{14} + iG_{m}^{*}\rho_{24} - iG_{c-}^{*}\rho_{12} + iG_{p+}^{*}\rho_{34} + iG_{p-}^{*}\left(\rho_{44} - \rho_{11}\right)\\
\partial_t\rho_{23} &= -(\gamma_{32} - i\Delta + i\delta_+)\rho_{23} + iG_{m}\rho_{13} - iG_{p+}^{*}\rho_{21} + iG_{c-}^{*}\rho_{43} + iG_{c+}^{*}\left(\rho_{33} - \rho_{22}\right)\\
\partial_t\rho_{24} &= -(\gamma_{42} - i\Delta + i\delta_-)\rho_{24} + iG_{m}\rho_{14} - iG_{p-}^{*}\rho_{21} + iG_{c+}^{*}\rho_{34} + iG_{c-}^{*}\left(\rho_{44} - \rho_{22}\right)\\
\partial_t\rho_{34} &= -\left[\gamma_{43} - i\delta_+ + i\delta_-\right]\rho_{34} + iG_{p+}\rho_{14} - iG_{p-}^{*}\rho_{31} + iG_{c+}\rho_{24} - iG_{c+}^{*}\rho_{32}
\end{aligned}
\tag{1}
$$

constrained by $\rho_{ab} = \rho_{ba}^{*}$ and $\sum \rho_{aa} = 1$, where Γ_{ab} describes the population decay rate from level $|a\rangle$ to level $|b\rangle$ while γ_{ab} denotes the coherence dephasing rate on the transition $|a\rangle \leftrightarrow |b\rangle$. In addition, we have $\gamma_{43} = (\Gamma_{31} + \Gamma_{32} + \Gamma_{41} + \Gamma_{42})/2$, $\gamma_{41} = \gamma_{42} = (\Gamma_{41} + \Gamma_{42})/2$, $\gamma_{31} = \gamma_{32} = (\Gamma_{31} + \Gamma_{32})/2$, and $G_{p\pm,c\pm,m} = \Omega_{p\pm,c\pm,m}\exp(i\phi_{p\pm,c\pm,m})$. Note also that our double-Λ system is sensitive to the relative phase $\Phi = \phi_{c+} - \phi_{p+} + \phi_{p-} - \phi_{c-} + \phi_m$ because it cannot be eliminated from Eq. (1) in the presence of a closed-loop interaction formed by the coupling, probe fields [10,21]. In what follows, we will set $\Phi = \phi_m$ with the consideration that $\phi_{p+} + \phi_{c-} = \phi_{c+} + \phi_{p-}$ due to the phase matching requirement in the nonlinear process of SLP generation.

In the slowly-varying envelope approximation, the propagation dynamics of both forward (incident) and backward (generated) probe fields are determined by the following two coupled *Maxwellian* wave equations:

$$
\begin{aligned}
\frac{\partial G_{p+}}{\partial z} &= -\frac{1}{c}\frac{\partial G_{p+}}{\partial t} + i\frac{\gamma_{31}\alpha_+}{2}\rho_{31}\\
\frac{\partial G_{p-}}{\partial z} &= +\frac{1}{c}\frac{\partial G_{p-}}{\partial t} - i\frac{\gamma_{41}\alpha_-}{2}\rho_{41}
\end{aligned}
\tag{2}
$$

where $\alpha_+ = N|d_{13}|^2\omega_{31}/(2\varepsilon_0 c\hbar\gamma_{31})$ and $\alpha_- = N|d_{14}|^2\omega_{41}/(2\varepsilon_0 c\hbar\gamma_{41})$ are propagation constants with N being the atomic density. Eqs. (1) and (2) will be numerically solved in the next section with real parameters of ^{87}Rb atoms to examine various effects of the weak microwave field on a two-color SLP.

3. Results and discussion

In this section we consider a dynamic process where two counter-propagating coupling fields are modulated into four successive steps as shown in Fig. 2(a) with the propagation dynamics of both forward and backward probe pulses illustrated in Fig. 2(b). In step I, the forward coupling field Ω_{c+} is turned on to guide the forward probe pulse Ω_{p+} to enter the atomic sample at a very