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Dynamic generation and coherent control of beating stationary light pulses by a microwave coupling field in five-level cold atoms

Qian-Qian Bao [a], Yan Zhang [b], Cui-Li Cui [c], Shao-Ying Meng [a], You-Wei Fang [a], Xue-Dong Tian [d,*]

[a] College of Physics, Liaoning University, Shenyang 110036, PR China
[b] School of Physics, Northeast Normal University, Changchun 130024, PR China
[c] College of Physics, Jilin University, Changchun 130012, PR China
[d] College of Physics and Technology, Guangxi Normal University, Guilin 541004, PR China

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A B S T R A C T

We propose an efficient scheme for generating and controlling beating stationary light pulses in a five-level atomic sample driven into electromagnetically induced transparency condition. This scheme relies on an asymmetrical procedure of light storage and retrieval tuned by two counter-propagating control fields where an additional coupling field, such as the microwave field, is introduced in the retrieval stage. A quantum probe field, incident upon such an atomic sample, is first transformed into spin coherence excitation of the atoms and then retrieved as beating stationary light pulses exhibiting a series of maxima and minima in intensity due to the alternative constructive and destructive interference. It is convenient to control the beating stationary light pulses just by manipulating the intensity and detuning of the additional microwave field. This interesting phenomenon involves in fact the coherent manipulation of dark-state polaritons and could be explored to achieve the efficient temporal splitting of stationary light pulses and accurate measurement of the microwave intensity.

1. Introduction

Techniques for controlling the propagation and interaction of weak light signals, especially electromagnetically induced transparency (EIT) [1] method, can be used to reduce light speed and extend the interaction time attainable within an atomic medium. EIT-based slow [2–5] and stored [6–11] light pulses have been extensively investigated for various applications in low-light-level nonlinear optics [12–15] and quantum information manipulation [16,17]. Particularly, EIT-based light storage scheme can be used to transfer quantum states between photons and atoms, serving as quantum memory for photons [18,19]. However, this light storage technique has a disadvantage that the optical component will disappear during the light storage process. The stationary light pulse (SLP), as another form of stopped light, was originally proposed by adding a standing-wave (SW) control field to regular Λ-type EIT system in a hot gaseous atomic medium [20], which is especially promising as its optical component remains present during light storage [21] . At first, the formation of the SLP was attributed to the fact that the well-developed bandgap created by the SW control field prevents the probe field propagation [22,23]. However, subsequent works showed that one could obtain a double-color SLP when applying two counter-propagating control fields with different frequencies [24–26]. The analysis on SLPs was that shape-preserving EIT propagation in both directions could add up to prevent propagation. It worth noting that the SLP in a cold atomic sample has significant loss and diffusion because of the higher-order spin and optical coherence components [27–29]. To avoid this disadvantage, a four-level double-Λ EIT system was adopted to be coupled with the two-color counter-propagating control fields, in which case the two-color SLP with less decay could be attained during the light storage duration [24–26]. Then the coherent control of double-color SLP has been investigated intensively [30–33], such as manipulating its phase [34] and splitting it in the temporal or spatial modes [35,36]. However, it still might be a question of a practical importance how to modify the properties of the retrieved SLP in a controlled way by processing the atomic coherence excitation during the storage stage or manipulating the coupling fields in the release stage. Recently, on the other hand, that beating signals can be observed as a manifestation of the preserved phase information during light storage and retrieval, which arise from the interference between a pair of weak probe fields [37], a weak probe field and a moderate coupling field [38,39], or two components of a

* Corresponding author.
E-mail address: snowtxd@mailbox.gxnu.edu.cn (X.-D. Tian).

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probe field [40,41]. Such interferometric beating observed in a light storage experiment is essential due to its potential application in the fast quantum-limited measurements of magnetic-field amplitudes and atomic transition frequencies.

In this paper, we present an alternative scheme for robust generation and manipulation of beating SLPs via EIT-based light storage technique in a five-level atomic medium coupled by two counter-propagating control fields and a weak microwave field. At first, the probe field enters into the sample at a slow velocity under EIT with only a forward (FW) control field switched on. Then we smoothly turn off the FW control field, the probe light field will be adiabatically converted into a purely atomic spin excitation confined in the cold atoms. After a proper storage time, by simultaneously turning on the FW and backward (BW) control fields and applying an additional microwave coupling field, the probe field is retrieved as two beating signals with opposite directions. Our numerical calculations show that beating SLPs can be generated and then released out of the atomic sample. The complex evolution of this beating SLPs is here analyzed in terms of the "dark-state polariton (DSP)" [6,7], which is a quasi-particle constituted of optical elements and atoms. Furthermore, the beating frequency and contrast can be controlled by manipulating the intensity and detuning of the additional microwave field. This scheme enables us to modulate the shape of the SLP and thus could improve quantum interference between weak light signals and interactions with atoms. Such controllable temporal modulation and splitting of the SLP in our system may find applications in quantum information processing and communication, especially for the robust time-bin quantum communication architecture.

2. Model and equations

We consider a medium of length l consisting of cold atoms coherently driven into a five-level system as shown in Fig. 1(a). The FW (BW) control field drives transition $|2\rangle \longleftrightarrow |3\rangle$ ($|2\rangle \longleftrightarrow |4\rangle$) with frequency $\omega_{c+}(\omega_{c-})$ and frequency detuning $\Delta_{c+}(\Delta_{c-})$, and has Rabi frequency defined as $\Omega_{c+} = \mathbf{E}_{c+} \cdot \mathbf{d}_{32}/2\hbar$ ($\Omega_{c-} = \mathbf{E}_{c-} \cdot \mathbf{d}_{42}/2\hbar$) with $\mathbf{d}_{\mu\nu}$ being the dipole moment on transition $|\mu\rangle \leftrightarrow |\nu\rangle$. The other two dipole-allowed transitions $|1\rangle \leftrightarrow |3\rangle$ and $|1\rangle \leftrightarrow |4\rangle$ are probed, respectively, by the FW and BW quantum fields

$$\hat{E}_{p\pm}(z,t) = \epsilon_{p\pm}\sqrt{\frac{\hbar\omega_{p\pm}}{2\varepsilon_0 V}}\,\hat{F}_{p\pm}(z,t)e^{-i\omega_{p\pm}t+ik_{p\pm}z}, \tag{1}$$

with $\epsilon_{p\pm}$ being the polarization vectors, $\omega_{p\pm}$ the carrier frequencies, V the quantization volume, and $\hat{F}_{p\pm}(z,t)$ the slowly-varying dimensionless operators. In addition, $g_{p+} = \sqrt{\omega_{p+}/2\hbar\varepsilon_0 V}\epsilon_{p+} \cdot \mathbf{d}_{31}$ ($g_{p-} = \sqrt{\omega_{p-}/2\hbar\varepsilon_0 V}\epsilon_{p-} \cdot \mathbf{d}_{41}$) is the real coupling constant of the FW (BW) quantum probe field. The four fields coupling with levels $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$ form a four-level double-Λ system. A microwave field with the frequency ω_m, detuning Δ_m and Rabi frequency Ω_m is further applied to extend the double-Λ system into a five-level system with a third ground level $|5\rangle$ involved.

As an example, we may consider cold ^{87}Rb atoms in a static magnetic field and choose states $|5S_{1/2}, F = 1, m_F = 0\rangle$, $|5S_{1/2}, F = 2, m_F = 2\rangle$, $|5P_{1/2}, F = 1, m_F = 1\rangle$, $|5P_{1/2}, F = 2, m_F = 1\rangle$ and $|5S_{1/2}, F = 1, m_F = 1\rangle$ as levels $|1\rangle$, $|2\rangle$, $|3\rangle$, $|4\rangle$ and $|5\rangle$, respectively. Then the wavelengths of the probe and control fields are $\lambda_{p\pm} \simeq \lambda_{c\pm} \simeq 795$ nm, while the wavelength of the microwave field is $\lambda_m \simeq 4.4$ cm. Therefore, we use a microwave field rather than an optical field to connect the transition between level $|2\rangle$ and $|5\rangle$ which has a long lifetime like $|1\rangle$ and $|2\rangle$. This type of five-level system can be represented alternatively in the dressed-state picture of the microwave field [see Fig. 1(b)] to facilitate the analysis of dynamically generated beating SLPs. In this case, the bare-state $|2\rangle$ and $|5\rangle$ will be replaced by dressed-state levels $|a\rangle = \cos\Phi|2\rangle + \sin\Phi|5\rangle$ and $|b\rangle = \cos\Phi|2\rangle - \sin\Phi|5\rangle$ with $\tan\Phi = 2\Omega_m/\left(\sqrt{\Delta_m^2 + 4\Omega_m^2} - \Delta_m\right)$.

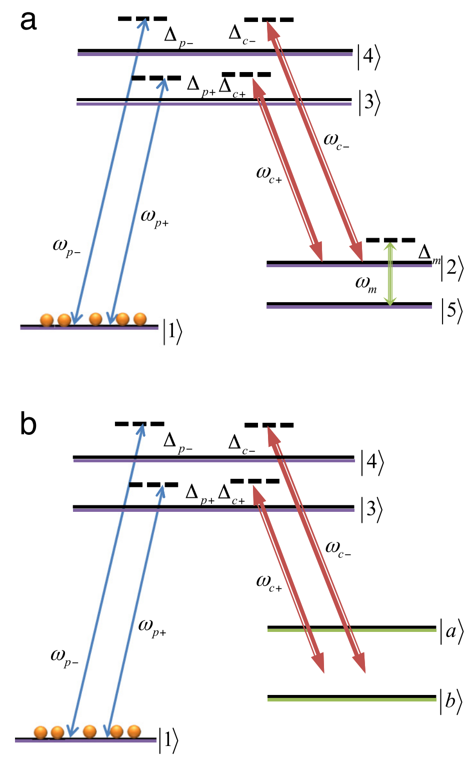

Fig. 1. (Color online) (a) Schematic diagram of a five-level system coupled by a FW classical control field ω_{c+}, a BW classical control field ω_{c-}, and a microwave coupling field ω_m. Transitions from the initially populated ground level $|1\rangle$ to the excited level $|3\rangle$ and the excited level $|4\rangle$ are probed, respectively, by a FW quantum field ω_{p+} and a BW quantum field ω_{p-}. (b) Dressed state picture of the coupled system corresponds to (a).

The cold atoms can be described by the collective atomic operators

$$\hat{\rho}_{\mu\nu}(z,t) = \frac{1}{N_z}\sum_{j=1}^{N_z}\hat{\rho}^j_{\mu\nu}(z,t), \tag{2}$$

where N_z denotes the atomic number in a small volume V_z centered at z while $\hat{\rho}^j_{\mu\nu}(z,t)$ is defined as the atomic flip operator $\left|\mu_j\right\rangle\left\langle\nu_j\right|$. For simplicity and convenience, we further introduce the slowly-varying operators $\hat{\sigma}_{12}(z,t)$, $\hat{\sigma}_{13}(z,t)$, $\hat{\sigma}_{14}(z,t)$, and $\hat{\sigma}_{15}(z,t)$ for four relevant coherence terms

$$\begin{aligned}
\hat{\rho}_{12}(z,t) &= \hat{\sigma}_{12}(z,t)e^{-i(\omega_{p+}-\omega_{c+})t},\\
\hat{\rho}_{13}(z,t) &= \hat{\sigma}_{13}(z,t)e^{-i\omega_{p+}t},\\
\hat{\rho}_{14}(z,t) &= \hat{\sigma}_{14}(z,t)e^{-i\omega_{p-}t},\\
\hat{\rho}_{15}(z,t) &= \hat{\sigma}_{15}(z,t)e^{-i(\omega_{p+}-\omega_{c+}-\omega_m)t}
\end{aligned} \tag{3}$$

whose dynamic evolutions are governed by a set of reduced Heisenberg–Langevin equations

$$\begin{aligned}
\partial_t\hat{\sigma}_{12} &= -\gamma'_{12}\hat{\sigma}_{12} - i\Omega_{c+}\hat{\sigma}_{13} - i\Omega_{c-}\hat{\sigma}_{14} - i\Omega^*_m\hat{\sigma}_{15},\\
\partial_t\hat{\sigma}_{13} &= -\gamma'_{13}\hat{\sigma}_{13} - i\Omega^*_{c+}\hat{\sigma}_{12} - ig_{p+}\hat{F}_{p+},\\
\partial_t\hat{\sigma}_{14} &= -\gamma'_{14}\hat{\sigma}_{14} - i\Omega^*_{c-}\hat{\sigma}_{12} - ig_{p-}\hat{F}_{p-},\\
\partial_t\hat{\sigma}_{15} &= -\gamma'_{15}\hat{\sigma}_{15} - i\Omega_m\hat{\sigma}_{12}
\end{aligned} \tag{4}$$

in the weak probe and adiabatic control limits. In Eq. (4), the complex dephasing rates γ'_{12}, γ'_{13}, γ'_{14} and γ'_{15} are represented as $\gamma'_{12} = \gamma_{12} - i\left(\Delta_{p+} - \Delta_{c+}\right)$, $\gamma'_{13} = \gamma_{13} - i\Delta_{p+}$, $\gamma'_{14} = \gamma_{14} - i\Delta_{p-}$ and $\gamma'_{15} = \gamma_{15} - i\left(\Delta_{p+} - \Delta_{c+} - \Delta_m\right)$ with $\gamma_{\mu\nu}$ being the decay rate of atomic coherence on transition $|\mu\rangle \leftrightarrow |\nu\rangle$. The weak probe assumption allows us to perturbatively solve the original 25 Heisenberg–Langevin equations to the first order in the probe field so that we just need to consider the