Dynamic control of retrieval contrast in a Λ-type atomic system*

Zhang Xiao-Hang(张晓航)[a)], Bao Qian-Qian(鲍倩倩)[a)], Zhang Yan(张 岩)[a)], Su Ming-Che(苏铭彻)[b)], Cui Cui-Li(崔淬砺)[a)†], and Wu Jin-Hui(吴金辉)[a)]

[a)] *College of Physics, Jilin University, Changchun* 130012, *China*

[b)] *College of Computer Science and Technology, Jilin University, Changchun* 130012, *China*

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We propose an efficient scheme for optimizing the optical memory of a sequence of signal light pulses in a system of ultracold atoms in Λ configuration. The memory procedure consists of write-in, storage, and retrieval phases. By applying a weak microwave field in the storage stage, additional phase-dependent terms are included, and the contrast of the output signal pulses can be dynamically controlled (enhanced or suppressed) through manipulating the relative phase φ between optical and microwave fields. Our numerical analysis shows that the contrast is enhanced to the most extent when $\varphi = 1.5\pi$. In addition, the contrast is in proportion to the Rabi frequency of the microwave field with a certain relative phase.

Keywords: electromagnetically induced transparency, optical memory, relative phase

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1. Introduction

In the past few decades, the quantum phenomenon of electromagnetically induced transparency (EIT)[1] has been attracting deep interest in view of its strong dispersion within the transparency (spectral) window, promising a range of potential applications including nonlinear optics,[2−5] quantum information processing,[6] optical switching,[7,8] highly sensitive interferometry or sensing,[9] slow light propagation,[10,11] and optical storage.[12−15] Since Hau *et al.* observed the spectacular reduction of group velocity to 17 m/s in an ultracold gas of Na atoms, the slowing of light by EIT has attracted much attention.[10] Furthermore, Chanelière *et al.*[16] and Eisaman *et al.*[17] have demonstrated the transfer of quantum states between atoms and single photons by using the storage of light pulses. However, there are still some limitations in the process of light storage and transmission, such as loss of light intensity, distortion of signal pulses, and decrease of their contrast. When a pulse sequence passes through an EIT media, both its intensity and contrast keep decreasing. Moreover, a rectangular pulse sequence turns into a Gaussian sequence. The receptor may confuse the high and low under low contrast. All the limits mentioned above influence the identification accuracy of signals. It is apparent that the low contrast of these signal pulses causes enormous difficulty in keeping fidelity at an acceptable level for identifying the origin information after the transmission and storage in EIT systems.

In this paper, we present a simple method to optimize the EIT-based optical memory organized for a sequence of signal light pulses in a Λ-type atomic system. The memory procedure includes write-in, storage, and retrieval phases. By applying an additional weak coherent field (microwave) in the storage stage, the amplitude of the retrieval signal (probe) pulses can be increased or decreased by controlling the relative phase φ between the optical and microwave fields.[18−20] The contrast of retrieval signal pulses can also be enhanced or depressed periodically depending on the relative phase. Our numerical calculations show that the contrast can be enhanced to the most extent when $\varphi = 1.5\pi$. In addition, it is found that

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†Corresponding author. E-mail: cuicuili@jlu.edu.cn

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the contrast is in proportion to the Rabi frequency of the microwave field at certain relative phase. Lastly, we analyse the underlying physics of the enhancement of contrast in detail.

2. Theoretical model and basic equations

We consider an ensemble of ultracold atoms with a length of L, which is coherently driven into a three-level Λ-type configuration, as shown in Fig. 1(a). The transition from level $|1\rangle$ ($|2\rangle$) to level $|3\rangle$ is probed (coupled) by a weak (strong) laser beam with a frequency $\omega_{\rm p}$ ($\omega_{\rm c}$) and amplitude $E_{\rm p}$ ($E_{\rm c}$). In stages I and III, the strong coupling beam is adiabatically switched off and on to perform the "write-in" and "read-out" procedures of the probe beam. During the storage time (stage II), we couple the two lower levels, $|1\rangle$ and $|2\rangle$, with an additional weak microwave beam to affect the atomic spin coherence, and further the amplitude and contrast of the retrieval probe beam. These three beams propagate along the z direction and can be described by the following time-space dependent electric fields:

$$\begin{aligned} &\boldsymbol{E}_n(z,t) = \hat{\varepsilon}_n(E_n\,{\rm e}^{-{\rm i}\omega_n t+{\rm i}k_n z}+{\rm c.c}),\\ &n={\rm c,p,m}, \end{aligned} \tag{1}$$

where $\hat{\varepsilon}_n$ and k_n are the unit polarization vector and wave number, respectively.

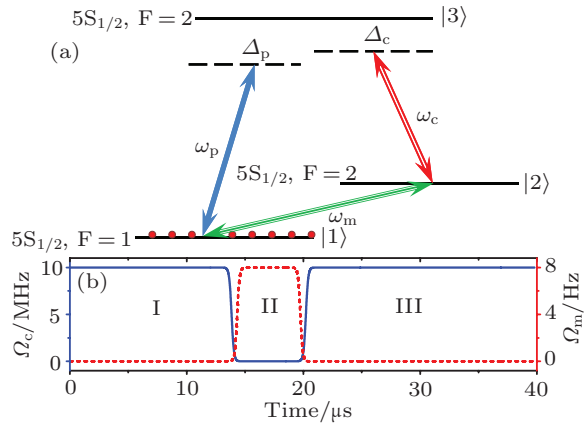


Fig. 1. (colour online) (a) Schematic level diagram of a three-level Λ atomic system driven by two optical fields and a microwave field. The levels refer to the D_2 lines of a ^{87}Rb atom. (b) Time modulation of the coupled (blue solid) and microwave (red dashed) fields.

Under the dipole and rotating-wave approximations, the system can be modeled with the following interaction Hamiltonian:

$$H_{\rm I} = \hbar\begin{bmatrix} 0 & -\Omega_{\rm m}^*\,{\rm e}^{-{\rm i}\varphi} & -\Omega_{\rm p}^* \\ -\Omega_{\rm m}\,{\rm e}^{{\rm i}\varphi} & \Delta_{\rm p}-\Delta_{\rm c} & -\Omega_{\rm c}^* \\ -\Omega_{\rm p} & -\Omega_{\rm c} & \Delta_{\rm p} \end{bmatrix}, \tag{2}$$

where $\Omega_{\rm p} = E_{\rm p}d_{31}/2\hbar$, $\Omega_{\rm c} = E_{\rm c}d_{32}/2\hbar$, and $\Omega_{\rm m} = E_{\rm m}d_{21}/2\hbar$ are the probe, coupling, and microwave Rabi frequencies, respectively. $d_{ij} = d_{ji}^*$ is the dipole moment of transition $|i\rangle \leftrightarrow |j\rangle$. And $\Delta_{\rm p} = \omega_{31} - \omega_{\rm p}$ and $\Delta_{\rm c} = \omega_{23} - \omega_{\rm c}$ are the probe and coupling field detunings due to corresponding atomic transitions. To fully describe the dynamical evolution of the atomic system, we further derive from Eq. (2) the following optical Bloch equations for density matrix elements:

$$\begin{aligned} \partial_t\rho_{11} =& -{\rm i}(\Omega_{\rm m}\,{\rm e}^{{\rm i}\varphi}\rho_{12}+\Omega_{\rm p}\rho_{13}\\ &-\Omega_{\rm m}^*\,{\rm e}^{-{\rm i}\varphi}\rho_{21}-\Omega_{\rm p}^*\rho_{31})\\ &+\Gamma_{31}(1-\rho_{11}-\rho_{22})+\Gamma_{21}\rho_{22}, \end{aligned} \tag{3}$$

$$\begin{aligned} \partial_t\rho_{22} =& -{\rm i}(\Omega_{\rm m}^*\,{\rm e}^{-{\rm i}\varphi}\rho_{21}+\Omega_{\rm c}\rho_{23}\\ &-\Omega_{\rm m}\,{\rm e}^{{\rm i}\varphi}\rho_{12}-\Omega_{\rm c}^*\rho_{32})\\ &+\Gamma_{32}(1-\rho_{22})-\Gamma_{21}(\rho_{11}-\rho_{22}), \end{aligned} \tag{4}$$

$$\begin{aligned} \partial_t\rho_{12} =& -{\rm i}[\Omega_{\rm m}^*\,{\rm e}^{-{\rm i}\varphi}(\rho_{11}-\rho_{22})-(\Delta_{\rm p}-\Delta_{\rm c})\rho_{12}\\ &+\Omega_{\rm c}\rho_{13}-\Omega_{\rm p}^*\rho_{32}]-\gamma_{12}\rho_{12}, \end{aligned} \tag{5}$$

$$\begin{aligned} \partial_t\rho_{13} =& -{\rm i}[\Omega_{\rm c}^*\rho_{12}-\Delta_{\rm p}\rho_{13}-\Omega_{\rm m}^*\,{\rm e}^{-{\rm i}\varphi}\rho_{23}\\ &-\Omega_{\rm p}^*(1-2\rho_{11}-\rho_{22})]-\gamma_{13}\rho_{13}, \end{aligned} \tag{6}$$

$$\begin{aligned} \partial_t\rho_{23} =& -{\rm i}[\Omega_{\rm p}^*\rho_{21}-\Delta_{\rm c}\rho_{23}-\Omega_{\rm m}\,{\rm e}^{{\rm i}\varphi}\rho_{13}\\ &-\Omega_{\rm c}^*(1-\rho_{11}-2\rho_{22})]-\gamma_{23}\rho_{23}, \end{aligned} \tag{7}$$

where ρ_{ij} satisfies $\sum\rho_{ii} = 1$ and $\rho_{ij} = \rho_{ji}^*$. Here φ is the relative phase between the optical and microwave fields, Γ_{ij} is the spontaneous decay rate from level $|i\rangle$ to level $|j\rangle$, and γ_{ji} denotes the dephasing rate of the off-diagonal density matrix element ρ_{ji}. We consider a case in which on resonance exits between the coupling field, probe field, and microwave field ($\Delta_n = 0$, n=c, p, m). In the steady-state regime, it is assumed that the coupling field is much stronger than the probe field ($|\Omega_{\rm c}| \gg |\Omega_{\rm p}| \gg |\Omega_{\rm m}|$), almost all of the population remains in the ground state $|1\rangle$, i.e., $\rho_{11} \simeq 1$ and $\rho_{22} \simeq \rho_{33} \simeq 0$.

In the slowly varying envelope approximation,[22] the propagation dynamics of the probe field is determined by the Maxwell wave equation

$$\left(\frac{\partial}{\partial z}+c\frac{\partial}{\partial t}\right)f_{\rm p}(z,t) = \frac{{\rm i}\alpha\gamma_{31}\rho_{31}}{\Omega_{\rm p0}}, \tag{8}$$

where $f_{\rm p}(z,t)$ is the dimensionless pulse envelope, $\Omega_{\rm p0} = E_{\rm p0}d_{13}/2\hbar$ ($E_{\rm p0} = E_{\rm p}/f_{\rm p}(z,t)$) is the maximal Rabi frequency, $\alpha = N|d_{13}|^2\omega_{31}/(2\varepsilon_0 c\hbar\gamma_{31})$ is the propagation constant, N is the atomic density,

ε_0 is the permittivity in vacuum, and c is defined as the speed of light in vacuum. Analogously, we define $\Omega_n = \Omega_{n0} f_n(z,t)$, where n=c, m. Equations (3)–(8) will be numerically solved with realistic parameters for ^{87}Rb atoms in the next section to examine the effect of the microwave field on the contrast of the retrieval probe field.

3. Results and discussion

In what follows, we numerically show how to optimize the EIT-based optical memory organized for a sequence of probe light pulses by manipulating the microwave field. Firstly, we consider a situation in which the envelope of the input probe field is two consecutive Gaussian lines. We plot the relative intensity of the output probe field $I_{\rm p}/I_{\rm p0} = |f_{\rm p}(z,t)|^2$ ($I_{\rm p0} = |E_{\rm p0}|^2$) as a function of time in Fig. 2. A normal EIT-based retrieval field without applying the microwave field is shown as the black solid line. In the presence of the microwave field, the lower-level coherence is affected by the interaction with the microwave field and the relative intensity is changed. As we can see in Fig. 2, the relative intensity can be increased or decreased at different relative phases.

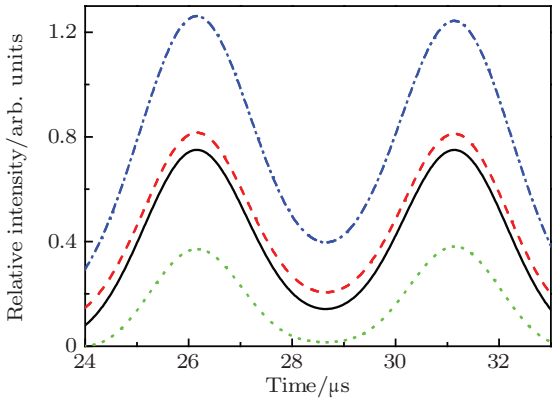


Fig. 2. (colour online) Relative intensity of the probe field at the sample exit as a function of time. The Rabi frequency of the input probe field is $\Omega_{\rm p} = \Omega_{\rm p0}\{\exp[-(t-t_0)^2/\tau^2] + \exp[-(t-2t_0)^2/\tau^2]\}$ with $t_0 = 5$ μs and duration $\tau = 2.0$ μs. The sample length is $L = 3$ mm. The time modulation of the coupling and microwave fields is the same as in Fig. 1. The other parameters are $\Gamma_{21} = \gamma_{12} = 1.0$ kHz, $\Gamma_{31} = \Gamma_{32} = \gamma_{13} = \gamma_{23} = 6.0$ MHz, $\lambda_{\rm p} = 780.792$ nm, $N_0 = 1.0 \times 10^{13}$ cm^{-3}, $d_{31} = 1.465 \times 10^{-29}$ C·m, $\Omega_{\rm c0} = 10$ MHz, $\Omega_{\rm m0} = 0$ (black solid curve), and $\Omega_{\rm m0} = 8$ Hz with $\varphi = 0.5\pi$ (blue dot-dashed curve), $\varphi = 0$ (red dashed curve), and $\varphi = 1.5\pi$ (green dotted curve).

We further define the contrast of the output probe pulses as $\eta = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, where $I_{\max}$ ($I_{\min}$) is the maximum (minimum) intensity of the output pulses. As shown in Fig. 2, the contrast in the absence of the microwave field is 68.13%. When the microwave field is applied, the contrast is 52.13 for $\varphi = 0.5\pi$, 59.67 for $\varphi = 0$, and 92.01 for $\varphi = 1.5\pi$.

We plot the contrast η versus the relative phase in Fig. 3(a). As we can see, the contrast can be periodically enhanced or suppressed depending on the relative phase. When $\varphi = 1.5\pi$, the contrast is enhanced to the most extent. This is also true for different maximum Rabi frequencies of the microwave field (see the black solid, red dashed, and blue dashed-dotted lines in Fig. 3(a)) and other parameters, such as sample length, storage time, propagation constant, and coupling Rabi frequency (not shown here). We also present the dependence of contrast η and the maximum relative intensity of the output pulses $\mathrm{Max}(I_{\rm p}/I_{\rm p0})$ on the maximum Rabi frequency of the microwave field, when the relative phase φ is fixed at 1.5π. As we can see from Fig. 3(b), the contrast is directly proportional to the maximum microwave Rabi frequency before 10 Hz or so. When the Rabi frequency is greater than 10 Hz, the contrast approaches to saturation. In addition, the maximum relative intensity of the output pulses is inversely proportional to the maximum microwave Rabi frequency.

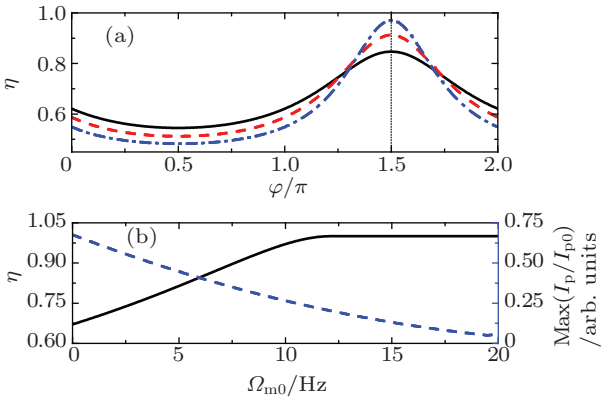


Fig. 3. (colour online) (a) Contrast of the output probe field dependence on relative phase. The parameters are chosen as $\Omega_{\rm m0} = 6$ Hz (black solid), $\Omega_{\rm m0} = 8$ Hz (red dashed), $\Omega_{\rm m0} = 10$ Hz (blue dashed-dotted). (b) The contrast of the output probe field (black solid) and the maximum relative intensity of output field (blue dashed curve) dependence on microwave Rabi frequency, with $\varphi = 1.5\pi$. The other parameters are chosen the same as in Fig. 2.

As the rectangular signal pulse sequence is widely used in optical information processing, we try to analyse its propagation dynamics in ultracold atoms. The comparison between the input and output signal pulse sequences are shown in Fig. 4. It can be seen in

Fig. 4(b) that the contrast of the retrieval signal pulse sequence are $\eta_a = 71.04\%$ (without the microwave field) and $\eta_p = 83.78\%$ (in the presence of the microwave field, $\varphi = 1.5\pi$), respectively. It is obvious that the contrast is greatly enhanced by adding the microwave field with $\varphi = 1.5\pi$.

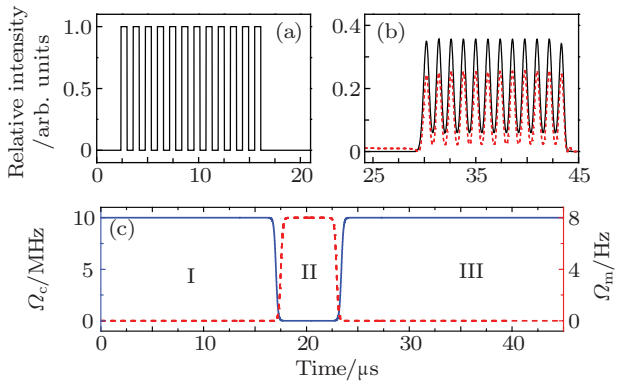


Fig. 4. (colour online) (a) Relative intensity of the rectangular probe sequence at the sample entrance as a function of time. (b) Relative intensity of the probe sequence at the sample exit as a function of time without (black solid) and with a microwave field $\Omega_{m0} = 8$ Hz, $\varphi = 1.5\pi$ (red dashed) in storage stage. (c) Modulation of the coupling (blue solid) and microwave (red dashed) field. The other parameters are the same as in Fig. 2.

The enhancement of contrast is at the cost of the intensity of the probe light. In the storage stage, by coupling the two lower levels with a microwave field with a certain relative phase (e.g., 1.5π), some of the population will transfer from level $|2\rangle$ to level $|1\rangle$, as shown in Figs. 5(a) and 5(b). This may lead to the intensity decrease of the output signal pulse and the increase of the spin coherence ρ_{12}, as shown in Figs. 5(c) and 5(d), which results in the increase of contrast. The stronger the microwave field couples with this kind of φ, the greater the contrast is enhanced. As pointed out in Ref. [21], the probe propagation can be switched from sub-luminal to super-luminal by adjusting the strength of the microwave field. We adjust the microwave field to be very weak so that the temporal shapes of the spin coherence and the retrieval probe pulses can maintain and the group velocity of the probe pulses can keep slow. In order to influence the stored spin coherence, the microwave field should be applied only after the strong coupling field is switched off.

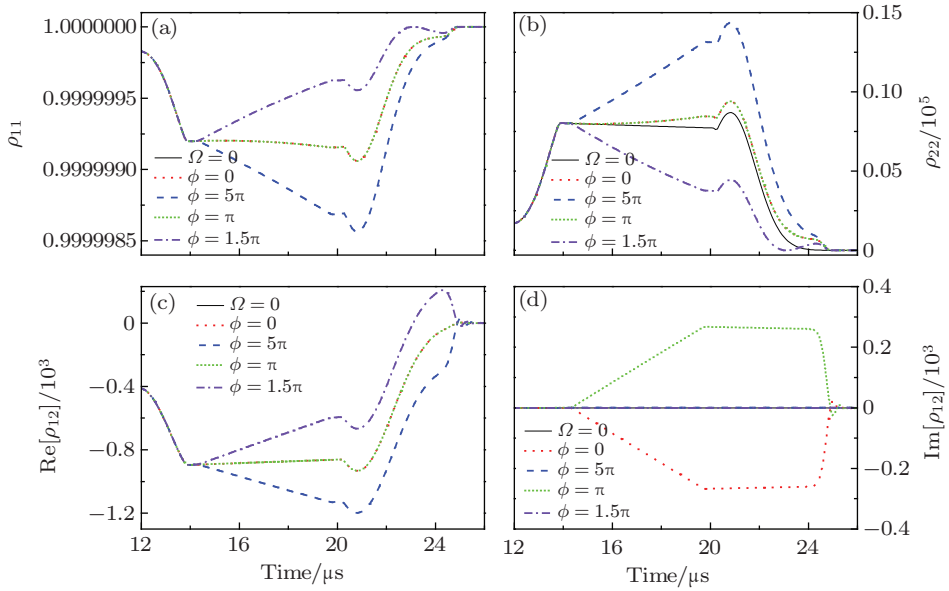


Fig. 5. (colour online) Population of states $|1\rangle$ and $|2\rangle$ and spin coherence ρ_{12} evaluated at $z = 1.0$ mm. The other parameters are the same as in Fig. 2.

4. Conclusion

The decrease of the contrast of a signal sequence is one of the most serious problems during the procedure of light storage and transmission. Our numerical analysis demonstrates that the contrast of a retrieval signal sequence can be enhanced to the most extent by coupling a weak microwave field to the lower levels, and the contrast is in proportion to the Rabi frequency of the microwave field in this situation.

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