Controllable beating signal using stored light pulse*

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We experimentally study the controllable generation of a beating signal using stored light pulses based on electromagnetically induced transparency (EIT) in a solid medium. The beating signal relies on an asymmetric procedure of light storage and retrieval. After storing the probe pulse into the spin coherence under the EIT condition, two-color control fields with opposite detunings instead of the initial control field are used to scatter the stored spin coherence. The controllable beating signal is generated due to alternative constructive and destructive interferences in the retrieved signal intensities. The beating of the two-color control fields is mapped into the beating of weak probe fields by using atomic spin coherence. This beating signal will be important in precise atomic spectroscopy and fast quantum limited measurements.

Keywords: beating signal, slow light, light storage, electromagnetically induced transparency

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1. Introduction

Coherent manipulation of the light quantum state has become a recent hot topic because of its applications in quantum information and quantum network. It is well known that electromagnetically induced transparency (EIT) has been a powerful novel method to slow and store a weak light pulse in the coherently-driven medium.[1–15] It can be explained by the formation of a dark-state polariton whose optical component is transferred into a spin coherence component and vice versa.[2] This EIT-based light manipulation also works for nonclassical states of light fields, such as the squeezed vacuum and entangled states.[7,8] Recently, the beating signal in an EIT system has attracted much attention. The beating signal from the interference between the control and the probe fields is observed to manifest the coherent phase information in EIT-based light storage.[16,17] The beating signal by the stored light is also used to measure the atomic spin transition frequency.[18,19] The beating signal in a multiple lambda-type system is observed to study the collapses of the dark-state polariton.[20,21] Furthermore, Bao *et al*.[22] proposed the dynamic generation of beating signals by using an asymmetric procedure of light storage and retrieval in a tripod-type scheme. The beating signal is expected to achieve a sub-shot noise precision and have important implementation in quantum limited measurement of magnetic fields and atomic transition frequencies.

Atomic gases have been extensively used as the experimental media of EIT-based light manipulation. For practical applications, solid-state media are more interesting. They provide spatially fixed interaction centers, which are free of atomic diffusion caused by the motion of the atoms in the atomic gases. Moreover, solid-state systems have the properties of large density and scalability, and are easily integrated in communication networks. In particular, rare-earth-doped solids have gained considerable interest in the field of information processing.[23–26] They provide advantageous spectroscopic features, such as narrow homogeneous width and long spin coherence time, which enable the implementation of optical data processing. Some experiments of coherent manipulations of light fields in solid-state media have been reported.[27–31]

In this paper, we experimentally study a controllable beating signal using EIT-based light storage in a Pr^{3+}: Y_2SiO_5 (Pr:YSO) crystal. This beating signal relies on an asymmetric procedure of light storage and retrieval. Under the EIT condition, the probe light pulse is first slowed, and then stored into the spin coherence by switching off the control field. In the retrieval process, two-color control fields with opposite detunings instead of the initial control field are used to scatter the stored spin coherence. Owing to the frequency matching effect of two-photon resonance,[19] the retrieved signals exhibit two optical components with different frequencies. Thus, the

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beating signal is generated due to the alternative constructive and destructive interferences in the retrieved signal intensities. The beating signal arises from the interference between two optical components in dark-state polariton. It is noted that the beating of the two-color control fields is mapped into the beating of the weak probe fields by using the atomic spin coherence in the EIT-based light storage. Such an interferometric beating signal can be used to monitor the frequencies and stabilities of the control laser fields, and find potential applications in precise atomic spectroscopy and fast quantum limited measurements.[18,19]

2. Pr:YSO levels and experimental setup

Figure 1 shows the level scheme of Pr ions. The optical transition $^3H_4 \rightarrow {}^1D_2$ with a resonance wavelength of 605.977 nm is used to demonstrate the EIT-based light storage. The ground ($^3H_4$) and the excited ($^1D_2$) states each are split into three hyperfine states by the low-symmetry crystal field. The optical inhomogeneous width is about several GHz, and the spin inhomogeneous width of the 10.2-MHz transition is about 30 kHz. The EIT lambda-type atomic system consists of two ground states ($|1\rangle$ and $|2\rangle$) and an excited state ($|3\rangle$). The control field ω_c couples the transition $|1\rangle \rightarrow |3\rangle$, and the probe field ω_p couples the transition $|2\rangle \rightarrow |3\rangle$. The repump field ω_r couples the transition $^3H_4(\pm 5/2) \rightarrow {}^1D_2(\pm 5/2)$, and is used to pump the populations to levels $|1\rangle$ and $|2\rangle$. Two-color control fields (ω_{c1} and ω_{c2}) with opposite detunings (Δ_1 and Δ_2) are applied to the transition $|1\rangle \rightarrow |3\rangle$ to generate beating signals.

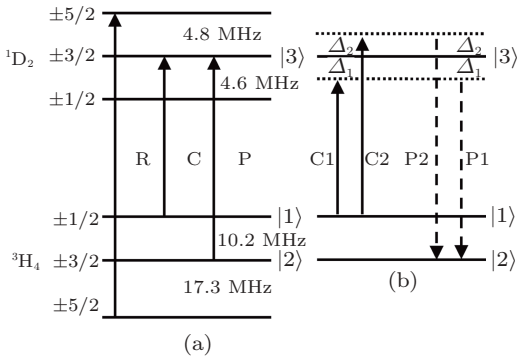


Fig. 1. Coupling schemes of Pr ions (a) in the EIT-based storage stage and (b) in the beating signal stage.

The experimental setup is shown in Fig. 2. A single-mode coherent 899-29 dye laser provides the laser radiation. The output laser is split into required laser beams by beam splitters. Each laser beam is guided through an acousto-optic modulator (AOM) with 200 MHz center frequency, which is used to control the intensity, frequency and temporal profile of the light field. All laser beams are linearly polarized and focused into the sample with a small angle. The Pr:YSO crystal with a dopant concentration of 0.05% is placed inside a cryostat cooled to the temperature of 3.5 K. The crystal has three optical axes labeled D1, D2 and b; its dimensions are 4 mm×4 mm×3 mm along D1×D2×b. The direction of light propagation is chosen along the b axis.

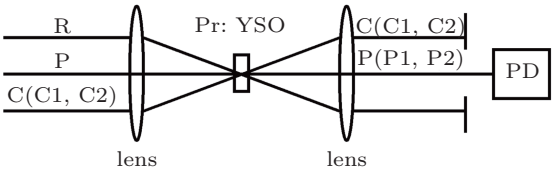


Fig. 2. Schematic diagram of the experimental setup.

3. Experimental results and discussion

In the initial preparation, the pulse sequences similar to those in Ref. [25] are used to prepare populations to level $|2\rangle$. Then the control pulse ω_c and the probe pulse ω_p are used to demonstrate the EIT-based light storage. The powers of ω_c and ω_p are 4.7 mW and 0.3 mW, respectively. Due to the steep dispersion induced by EIT, the probe pulse is first compressed in space and slowed in time in the crystal, as shown in Fig. 3(a). Under the EIT condition, the dark-state polariton consisting of the probe light field and the atomic spin coherence is described as a moving quasiparticle[2,4] defined by the transformation

$$\psi(z,t) = \cos\theta(t)\Omega_p(z,t) - \sin\theta(t)\sqrt{\kappa}\rho_{12}(z,t),$$
$$\cos\theta(t) = \frac{\Omega_c(t)}{\sqrt{\Omega_c^2(t)+\kappa}}, \quad \sin\theta(t) = \frac{\sqrt{\kappa}}{\sqrt{\Omega_c^2(t)+\kappa}}. \quad (1)$$

Here, ρ_{12} is the atomic spin coherence between states $|1\rangle$ and $|2\rangle$; Ω_p is the Rabi frequency of the probe field; Ω_c is the Rabi frequency of the control field; and $\kappa = 3n\lambda^2\gamma_r c/8\pi$, where n is the ion density, λ is the wavelength, γ_r is the natural linewidth of the optical transition and c is the free-space speed of light. The dark-state polariton is a mixture of an optical component and an atomic spin component; its mixing angle can be

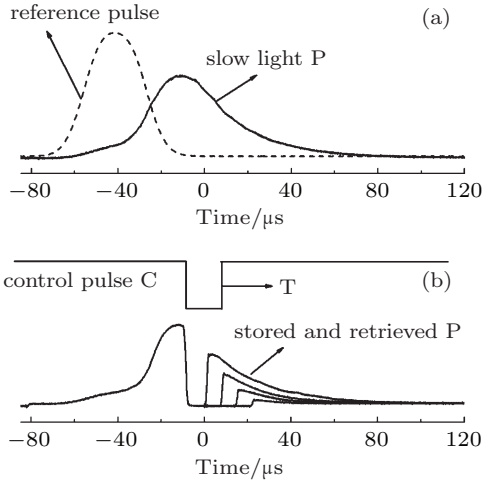


Fig. 3. (a) Slow light demonstration. (b) The storage and retrieval of the probe pulse for different storage time.

changed by changing the Rabi frequency of the control field. By switching off the control field, the coherent information of the probe pulse can be reversibly mapped onto the atomic spin coherence. After switching back on the initial control field, the atomic spin coherence is converted back into the retrieved probe signal. Figure 3(b) shows the EIT-based light storage for different storage times. The intensity of the retrieved probe pulse decreases with the storage time increasing. The obtained results are similar to those of atomic vapor in Ref. [4].

In the above demonstration, we store and retrieve the probe pulse using the same control field. It has been reported that an additional control field at a different frequency can be used to retrieve the stored optical information.[5,25] In the experiment, to obtain the beating signal, two-color control fields instead of the initial control field are used to scatter the stored spin coherence. Two-color control fields ω_{c1} and ω_{c2} propagate along the initial propagating direction of ω_c. They have opposite detunings, which are set to $\Delta_1 = -\Delta_2$. The powers of the control fields ω_{c1} and ω_{c2} are 2.5 mW and 2.2 mW, respectively. Due to the interaction between the two-color fields and the stored spin coherence, the retrieved signals exhibit two optical components with different frequencies (ω_{p1} and ω_{p2}). The beating signal is generated due to the alternative constructive and destructive interferences in the retrieved signal intensities. Figure 4 shows the generation of beating signals for different detunings of ω_{c1} and ω_{c2}. The frequency $\Delta\omega$ of the beating signal is determined by the frequency difference between retrieved signals ω_{p1} and ω_{p2}. The retrieved frequency meets the frequency matching effect in the EIT-based light storage,[19] and each retrieved optical component is obtained under the condition of two-photon resonance. Thus, the frequency difference $|\Delta_1| + |\Delta_2|$ between two-color control fields determines the beating frequency $\Delta\omega = |\Delta_1| + |\Delta_2|$. By changing the frequency difference between the two-color control fields, variable beating frequencies are obtained. This controllable beating signal arises from the interference between the two optical components in the dark-state polariton. It can be used to monitor the frequencies of the control fields, and will be important in precise atomic spectroscopy.

We now study the storage and retrieval of the above generated beating signal. After the two-color control fields are used to generate the beating signal, the atomic system is converted into an EIT double lambda-type scheme, which consists of two optical components ω_{p1} and ω_{p2} in the dark-state polariton. Under such an atomic system, two optical components and their beating signals can be stored into the spin coherence by manipulating the control fields.[6,11] When the beating signal propagates in the crystal, by switching off the two-color control fields, the beating signal can be converted into the spin coherence and stored in the crystal. By switching back on the two-color control fields, the spin coherence is converted back into an optical component, and the beating signal is retrieved. Figure 5(a) shows the storage and retrieval of the generated beating signal. In this case, the detunings of the two-color control fields are set to $|\Delta_1| = |\Delta_2| = 0.15$ MHz and the beating frequency is 0.3 MHz. The gap between the two beating signals indicates the storage time. The front beating signal has passed through the medium before switching off the two-color control fields, and does not experience the storage. The back beating signal is the part of the initial beating signal that is stored and subsequently retrieved. The retrieved beating signal maintains the same temporal profile as the back portion of the initial beating signal. Its reduced intensity is caused by the dephasing of the spin coherence. The beating signal has been used to manifest the preservation of the coherence phase information in the storage.[16,17] In Figs. 5(b)–5(d), we also find that the retrieved beating frequency can be different from that before the storage. In the retrieval of the stored beating signal, variable beating frequencies are obtained by changing the detunings of the switching-back-on two-color control fields, which relies on the frequency matching of two-photon resonance.

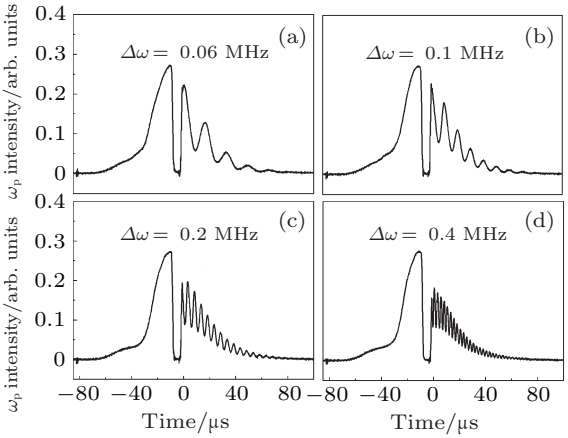


Fig. 4. Generation of beating signals for different beating frequencies. The frequency differences $|\Delta_1| + |\Delta_2|$ of two-color fields are (a) 0.06 MHz, (b) 0.1 MHz, (c) 0.2 MHz and (d) 0.4 MHz.

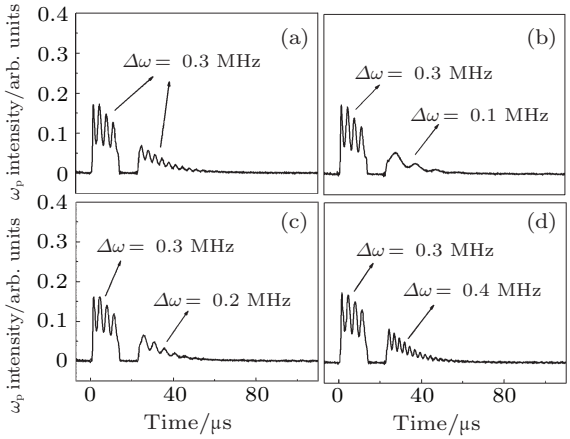


Fig. 5. Storage and retrieval of the beating signal. The front beating signal does not experience the storage. The back beating signal is the part of the initial beating signal that is stored and subsequently retrieved. The frequency differences $|\Delta_1| + |\Delta_2|$ between the switching-back-on two-color control fields are (a) 0.3 MHz, (b) 0.1 MHz, (c) 0.2 MHz and (d) 0.4 MHz.

4. Conclusion

In this paper, we experimentally demonstrate a controllable beating signal by using EIT-based light storage in a solid-sate medium. By using two-color control fields to retrieve the stored spin coherence, the beating signal is generated due to the alternative constructive and destructive interferences in the retrieved signal intensities. This beating signal arises from the interference between two optical components in the dark-state polariton. In this method, by using the spin coherence in the EIT-based light storage, the beating of two strong control fields is mapped into the beating of weak probe fields. The demonstration is performed using classical light pulses. It is believed that this method also works for quantized optical fields and will find applications in precise atomic spectroscopy and fast quantum limited measurements.

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