Generation and storage of double slow light pulses in a solid*

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We experimentally study the generation and storage of double slow light pulses in a Pr^{3+}:Y_2SiO_5 crystal. Under electromagnetically induced transparency, a single signal pulse is stored in the spin coherence of the crystal. By simultaneously switching on two control fields to recall the stored information, the spin coherence is converted into two slow light pulses with distinct frequencies. Furthermore, the storage and controlled retrieval of double slow light pulses are obtained by manipulating the control fields. This study of double slow light pulses may have practical applications in information processing and all-optical networks.

Keywords: slow light, light storage, double light pulses, electromagnetically induced transparency

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1. Introduction

The slowing and storage of light pulses in a coherently driven medium have become a recent hot topic because of their potential applications in classical and quantum information.[1−11] The technique of electromagnetically induced transparency (EIT) has been proposed to control quantum states of light.[1,2] By using EIT, researchers have experimentally demonstrated the slowing and storage of a classical light pulse,[3,4] and also have stored and retrieved nonclassical state of light in atomic ensembles.[5−7] This EIT light-storage technique is based on the quantum state transfer between light and matter, which has a promising prospect for applications in both classical and quantum information processing. In a typical EIT experiment, the atomic system exhibits a single three-level lambda scheme and is used only to realize the coherent control of a single light pulse. The slowing and storage of double light pulses are more encouraging compared with one single light pulse. For example, double slow light pulses can increase interaction time between light and matter and generate large cross-phase modulation.[12] The coherent control of double light pulses makes it possible to manipulate the photonic quantum bit.[13] By using a four-level tripod scheme, researchers have reported the slowing and storage of double light pulses in experiment.[13−15] In atomic gases with a four-level double-lambda scheme, the slowing and storage of double light pulses are also demonstrated experimentally by using four-wave mixing (FWM).[16,17]

Most experiments on slow light and light storage are carried out in atomic gases. However, low density and atomic diffusion of atomic gases limit their practical application in information processing. There is a strong motivation to control light-matter interaction with a more practical system, such as solid-state devices. Solid-state systems have properties of high density and compactness and are easily integrated in

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communication networks, which make them very attractive for applications in quantum memories and quantum repeaters. In addition, atomic ensembles in solids are naturally trapped in solid-state matrix, which prevents the decoherence caused by the motion of the atoms in atomic gases. So the experimental studies in solids are more valuable than those in atomic gases. Solids doped with rare-earth ions, such as Pr^{3+}:Y_2SiO_5 (Pr:YSO), exhibit excellent coherence properties at low temperature, both for the optical and the spin transitions.[18] Slow light and light storage of a single light pulse has been reported in rare-earth-doped solids.[19−21] Also, all-optical routing,[22] enhanced four-wave mixing,[23,24] stimulated Raman adiabatic passage,[25] quantum storage based on reversible inhomogeneous broadening[26,27] have been experimentally demonstrated in solids.

In this paper, we experimentally study the generation and storage of double slow light pulses in a four-level double-lambda scheme of a Pr:YSO crystal. Slow light and light storage can be understood in terms of a dark-state polariton and the polariton interconverts from an optical excitation mode to an atomic coherence mode by changing the control beam Rabi frequency.[2] In the present work, by using EIT, a single signal pulse is stored in the ground-state spin coherence of the crystal. When the spin coherence mode is converted into an optical field mode, two slowed optical signal modes with distinct frequencies are generated by switching on two control fields. Further, by switching off these two control fields, two slowed signal pulses are simultaneously stored in the crystal and these two optical modes are converted into the stored spin coherence. This work demonstrates experimentally the possibility that the dark polariton and stored spin coherence may consist of two optical modes with distinct frequencies. The generation and storage of double slow light pulses may have important applications in image processing, quantum information and remote sensing.[17]

2. Pr:YSO levels and experimental setup

Figure 1 shows an energy-level diagram of Pr:YSO. The crystal consists of 0.05% Pr-doped YSO. The relevant optical transition is $^3H_4 \rightarrow {}^1D_2$, which has a resonant wavelength of 605.977 nm. The ground ($^3H_4$) and the excited ($^1D_2$) states each have three degenerate hyperfine states. The inhomogeneous width of the optical transition is about 5 GHz, which is much wider than the hyperfine splitting. The spin inhomogeneous width for the 10.2-MHz transition is about 30 kHz. We call ω_{s1}, ω_{c1}, ω_{c2}, and ω_r the signal, control-1, control-2 and repump field, respectively.

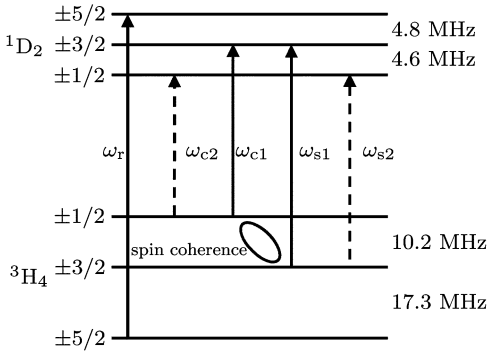


Fig. 1. The related energy level diagram for Pr:YSO.

The experimental setup is shown in Fig. 2, which is similar to that of Ref. [15]. A coherent-899 ring laser (R6G dye) is used as the light source. The laser output is split into four beams ω_{s1}, ω_{c1}, ω_{c2}, and ω_r by beam splitters. The applied cw laser powers of ω_{s1}, ω_{c1}, ω_{c2}, and ω_r are 0.4, 3.4, 3.6, and 0.8 mW, respectively. By four acousto–optic modulators (AOMs), the laser beams ω_{s1}, ω_{c1}, ω_{c2}, and ω_r are upshifted 210.2, 200, 195.4, and 232.3 MHz from the dye laser frequency, respectively. All four beams are linearly polarized and focused into the sample with an angle of about 15 mrad. The Pr:YSO crystal is placed inside a cryostat (Cryomech PT407) and the temperature is kept at 3.5 K. The size of the crystal is 4 mm × 4 mm × 3 mm, and the optical B-axis is along 3 mm.

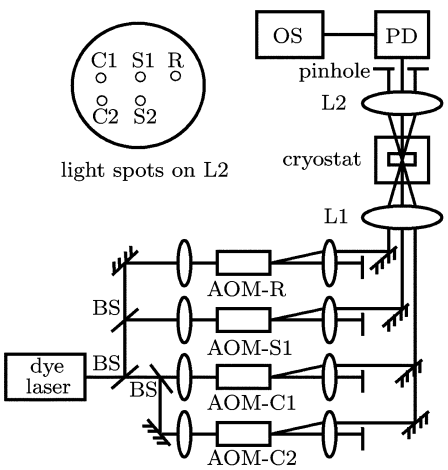


Fig. 2. Schematic diagram of the experimental setup.

3. Experimental results and discussion

For experimental preparation, the control-1 and repump fields are firstly switched on for 10 ms each, followed by a 5-μs dark time. After this step, the populations are prepared to $^3H_4(\pm 3/2)$ level owing to the optical pump effect. Then the control-1 and signal pulses are applied to the crystal. These two fields interact with the related levels of Pr ions, which form an EIT three-level lambda scheme, as shown in Fig. 1. Under EIT condition, the medium exhibits steep dispersion and the signal pulse can be slowed. The signal pulse experiences a time delay of 38 μs, as shown in Fig. 3(a). When the slowed signal pulse is contained in the medium, the storage and retrieval of the slowed signal pulse is obtained by switching off and back-on the control-1 field. Figure 3(b) shows a typical light storage based on EIT. The left part of the signal shows the portion of the slowed signal pulse which had left the crystal before the control-1 field is switched off. The right part of the signal shows the portion of the slowed signal pulse that is stored and then retrieved from the crystal. The gap in the signal indicates the storage time. The retrieved signal carries the coherent information of the original slowed signal due to the conversion between the spin coherence and the optical mode.

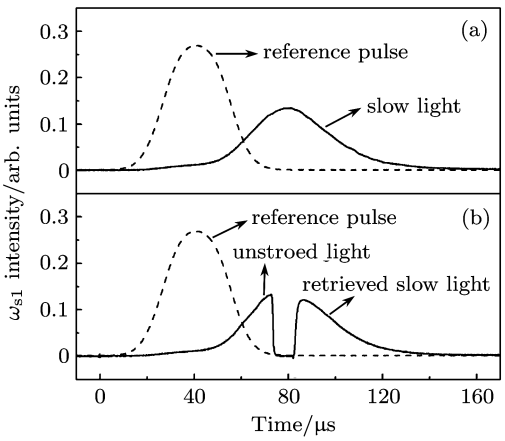


Fig. 3. Slow light and light storage of the signal pulse ω_{s1}. The Gauss-shape pulse with $1/e$ full widths of 43 μs is used as the signal pulse.

In the above retrieval of stored information, the stored spin coherence mode is converted into a single slowed optical mode ω_{s1} because one retrieve control field ω_{c1} is applied. It is possible to achieve two slowed optical modes in the retrieve process if two retrieve control fields with distinct frequencies are applied to the medium. Figure 4 shows the generation of such double slow light pulses. When two retrieve control fields ω_{c1} and ω_{c2} are applied to scatter the spin coherence, the original EIT three-level lambda scheme is converted into an EIT four-level double-lambda scheme. In this double-lambda scheme, the output slow light signals can be controlled by the associated control fields.[28] Thus, as the polariton is reconverted back into an optical field, two slowed optical modes with distinct frequencies (ω_{s1} and ω_{s2}) are generated due to the interaction between the two retrieve control fields and the stored spin coherence. The generation of new slow light signal ω_{s2} meets the phase-matching condition $\boldsymbol{K}_{s2} = \boldsymbol{K}_{s1} + \boldsymbol{K}_{c2} - \boldsymbol{K}_{c1}$, as shown in Fig. 2. It is noted that the dark polariton consists of two optical modes in the present case, compared with a single optical mode in a three-level lambda scheme. Although a single signal pulse is initially stored in a three-level lambda scheme, we achieve two slowed light pulses by manipulating the retrieve control fields in a four-level double-lambda scheme. Double slow light pulses have been proposed to increase nonlinear interaction time between light and matter and to generate a large cross-phase modulation,[12] which has numerous applications in quantum information processing.

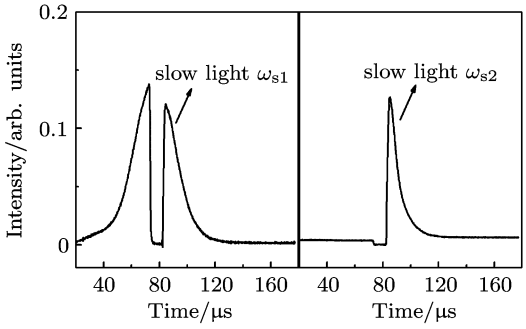


Fig. 4. The generation of double slow light pulses ω_{s1} and ω_{s2}. Two control fields ω_{c1} and ω_{c2} are used to scatter the spin coherence.

We then turn to the storage and retrieval of double slow light pulses in an EIT four-level double-lambda scheme, as shown in Fig. 5. According to the dark-state polariton theory of light storage,[2,17,28] when the two slow light pulses are contained in the medium, they are simultaneously stored in the crystal by simultaneously switching off two control fields. In the storage process, the double slow light pulses are converted into the stored spin coherence mode, which consists of the coherent optical information of two

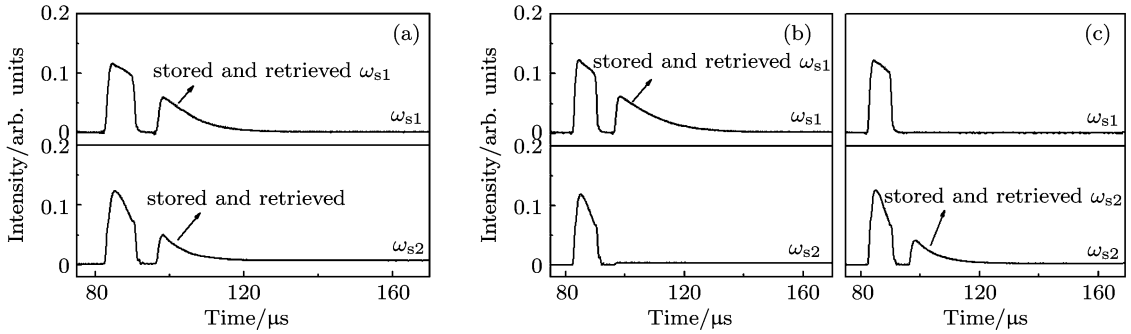


Fig. 5. The storage and controlled retrieval of double slow light pulses ω_{s1} and ω_{s2}. (a) The control fields ω_{c1} and ω_{c2} are simultaneously switched on in the retrieval of stored double light pulses. In Figs. (b) and (c) the control fields ω_{c1} and ω_{c2} are switched on in the retrieval of stored double light pulses, respectively.

optical modes. By manipulating the corresponding control fields in the further retrieval process, the stored double light pulses can be simultaneously or selectively retrieved from the crystal. After a storage time, by simultaneously switching back on the two control fields, the spin coherence mode is reconverted into two optical modes and the stored double light pulses are simultaneously retrieved, as shown in Fig. 5(a). The retrieved double light pulses maintains the same temporal profile as the back portion of double slow light pulses and its reduced intensity is caused by the dephasing of spin coherence. When one (ω_{c1} or ω_{c2}) of the control fields is applied in the retrieval process, one (ω_{s1} or ω_{s2}) of the stored double light pulses is retrieved on demand, as shown in Figs. 5(b) and 5(c). So, by launching the corresponding control fields, the stored double light pulses can be retrieved with the desired frequencies and at the demanded moment. Storage and controlled retrieval of double slow light pulses make it possible to manipulate photonic qubits,[7,13] which may have practical applications in quantum information and quantum network.

4. Conclusions

In summary, we have experimentally studied the generation and storage of double slow light pulses in a Pr:YSO crystal with a four-level double-lambda scheme. By manipulating EIT control fields, the stored signal pulse can be retrieved into two slow light pulses with different frequencies. Also, we have studied the storage and controlled retrieval of double slow light pulses by adjusting corresponding control fields. Such a coherent control of double slow light pulses in solids may have practical applications in information processing and all-optical network.

References

[1] Fleischhauer M and Imamoglu A 2005 *Rev. Mod. Phys.* **77** 633
[2] Fleischhauer M and Lukin M D 2000 *Phys. Rev. Lett.* **84** 5094
[3] Liu C Z, Dutton Z, Behroozi C H and Hau L V 2001 *Nature* **409** 490
[4] Phillips D F, Fleischhauer A, Mair A, Walsworth R L and Lukin M D 2001 *Phys. Rev. Lett.* **86** 783
[5] Honda H, Akamatsu D, Arikawa M, Yokoi Y, Akiba K, Nagatsuka S, Tanimura T, Furusawa A and Kozuma M 2008 *Phys. Rev. Lett.* **100** 093601
[6] Eisaman M D, Andre A, Massou F, Fleischhauer M, Zibrov A S and Lukin M D 2005 *Nature* **438** 837
[7] Choi K S, Deng H, Laurat J and Kimble H J 2008 *Nature* **452** 67
[8] Ba N, Gao J W, Tian X X, Wu X and Wu J H 2010 *Chin. Phys.* B **19** 074208
[9] Zhang B, Jiang Y, Wang G, Zhang L D, Wu J H and Gao J Y 2011 *Chin. Phys.* B **20** 050304
[10] Wang N, Zhang Y D and Yuan P 2011 *Chin. Phys.* B **20** 044203
[11] Yang B D, Gao J, Liang Q B, Wang J, Zhang T C and Wang J M 2011 *Chin. Phys.* B **20** 044202
[12] Wang Z B, Marzlin K P and Sanders B C 2006 *Phys. Rev. Lett.* **97** 063901
[13] Karpa L, Vewinger F and Weitz M 2008 *Phys. Rev. Lett.* **101** 170406
[14] MacRae A, Campbell G and Lvovsky A I 2008 *Opt. Lett.* **33** 2659
[15] Wang H H, Fan Y F, Wang R, Wang L, Du D M, Kang Z H, Jiang Y, Wu J H and Gao J Y 2009 *Opt. Lett.* **34** 2596
[16] Boyer V, McCormick C F, Arimondo E and Lett P D 2007 *Phys. Rev. Lett.* **99** 143601
[17] Camacho R M, Vudyasetu R K and Howell J C 2009 *Nature Photonics* **3** 103
[18] Nilsson M, Rippe L, Kroll S, Klieber R and Suter D 2004 *Phys. Rev.* B **70** 214116
[19] Turukhin A V, Sudarshanam V, Shahriar M S, Musser J A, Ham B S and Hemmer P R 2001 *Phys. Rev. Lett.* **88** 023602

[20] Longdell J J, Fraval E, Sellars M J and Manson N B 2005 *Phys. Rev. Lett.* **95** 063601

[21] Wang H H, Kang Z H, Jiang Y, Li Y J, Du D M, Wei X G, Wu J H and Gao J Y 2008 *Appl. Phys. Lett.* **92** 011105

[22] Ham B S 2008 *Phys. Rev.* A **78** 011808

[23] Ham B S and Hemmer P R 2000 *Phys. Rev. Lett.* **84** 4080

[24] Wang H H, Du D M, Fan F Y, Li A J, Wang L, Wei X G, Kang Z H, Jiang Y, Wu J H and Gao J Y 2008 *Appl. Phys. Lett.* **93** 231107

[25] Klein J, Beil F and Halfmann T 2007 *Phys. Rev. Lett.* **99** 113003

[26] de Riedmatten H, Afzelius M, Staudt M U, Simon C and Gisin N 2008 *Nature* **456** 773

[27] Lauritzen B, Minar J, de Riedmatten H, Afzelius M, Sangouard N, Simon C and Gisin N 2010 *Phys. Rev. Lett.* **104** 080502

[28] Appel J, Marzlin K P and Lvovsky A I 2006 *Phys. Rev.* A **73** 013804