Slow-light information conversion
in a rare-earth-ion-doped solid

Yun-Fei Fan\(^1\), Hai-Hua Wang\(^1,2,4\), Rong Wang\(^1\), Xiao-Gang Wei\(^1,3\),
Ai-Jun Li\(^1\), Zhi-Hui Kang\(^1\), Jin-Hui Wu\(^1\), Han-Zhuang Zhang\(^1\),
Hual-Liang Xu\(^2\) and Jin-Yue Gao\(^1,4\)

\(^1\) College of Physics, Jilin University, Changchun, Jilin 130012,
People’s Republic of China
\(^2\) State Key Laboratory on Integrated Optoelectronics, College of Electronic
Science and Engineering, Jilin University, Changchun, Jilin 130012,
People’s Republic of China
\(^3\) Quantum Engineering Center, Beijing Institute of Control Devices,
Beijing 100854, People’s Republic of China
E-mail: haihua@jlu.edu.cn and jygaoo@mail.jlu.edu.cn

New Journal of Physics 13 (2011) 123008 (8pp)
Received 5 August 2011
Published 6 December 2011
Online at http://www.njp.org/
doi:10.1088/1367-2630/13/12/123008

Abstract. We report the experimental observation of a slow-light information
conversion via electromagnetically induced transparency (EIT) in a rare-earth-
ion-doped solid. Under the EIT-based slow-light regime, by manipulating the
spectrum of the control fields, the slowed light pulse is transformed into two
different frequency-spatial channels. The pulse shapes and energies in two output
channels are further studied. This slow-light information conversion can be used
as a controllable frequency-spatial multiplexing of the quantum state of the
optical field and will be important in information processing and all-optical
networks.

Contents

1. Introduction 2
2. \(\text{Pr}:\text{YSO}\) levels and the experimental setup 2
3. Experimental results and discussion 4
4. Conclusions 7
Acknowledgments 7
References 7

\(^4\) Authors to whom any correspondence should be addressed.
1. Introduction

Light waves are ideal and robust carriers of information, but it is not easy to efficiently slow and store them. Electromagnetically induced transparency (EIT) has become a rather powerful tool for manipulating both classical and quantum states of light fields [1]. EIT-based light manipulation techniques allow us to control light–matter interaction well through coherently enhanced optical nonlinearities with negligible absorption [2]. In a typical EIT scheme, the light signal can be slowed and stored by adiabatically manipulating the Rabi frequency of the control light [3–9]. It is interpreted as the formation of a dark-state polariton whose optical excitation mode can be transferred into its atomic spin coherence mode and vice versa [3]. Currently, most studies on EIT-based light manipulation are carried out on atomic gases. There is a strong motivation to control light–matter interaction with more practical systems, such as solid-state devices. Solid-state systems with the properties of high density and compactness are easily integrated into communication networks, which makes them very attractive for applications in quantum information and all-optical networks. Slow-light storage [10–14], all-optical routing [15], enhanced four-wave mixing [16, 17], stimulated Raman adiabatic passage [18], quantum storage based on atomic frequency combs and reversible inhomogeneous broadening [19, 20] have been experimentally demonstrated in solids.

Future information communication and all-optical networks will be based on light waves. A key property of a network is the ability to transfer (or distribute) light information between optical modes in a controlled fashion. This is important not only for routing light information, but also for interfacing communication lines of different wavelengths. Recently, information channel conversion and a beam splitter based on atomic coherence were proposed and demonstrated experimentally. Yelin and coworkers have proposed a multiple beam splitter for a single photon by using fractional stimulated Raman adiabatic passage [21]. Lvovsky and coworkers have studied the adiabatic information transfer between different optical states in rubidium atomic vapor [22, 23]. Walsworth and coworkers have demonstrated a beam splitter by using slow light and rapid transport of atomic coherence in a wall-coated atomic vapor cell [24].

In this paper, we experimentally demonstrate a controllable slow-light information conversion via EIT in a Pr\(^{3+}\) : Y\(_2\)SiO\(_5\) (Pr : YSO) crystal. The ultimate goal of this research is a controllable frequency-spatial multiplexing of the quantum state of the optical field. Such multiplexing could be useful in routing quantum information and in interfacing quantum communication lines of different frequency-spatial modes between each other and with memory-based quantum repeaters. As a step towards this ultimate goal, we deal with an experimental investigation of the specific pulsed regime of the four-wave mixing in the four-level double-lambda configuration. The specific current goal is to study the propagation of a pulsed weak classical signal field and its transformation into different frequency-spatial modes. The input weak classical signal pulse is first slowed under EIT conditions. Then the slowed pulse is partially transformed into different frequency-spatial modes in the presence of two strong control fields partially overlapping in time. Some important characteristics of both initial and transformed frequency-spatial modes, such as the pulse shapes and their energies, are studied as the function.

2. Pr : YSO levels and the 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 \(^3\text{H}_4 \rightarrow ^1\text{D}_2\), which has a resonant wavelength of 605.977 nm. The ground \(^3\text{H}_4\) and the excited \(^1\text{D}_2\) state 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 $\omega_p$, $\omega_c$, $\omega_r$ the probe, control-1, control-2 and repump field, respectively.

The experimental setup is similar to that of [17]. A Coherent-899 ring laser (R6G dye) is used as the light source. The laser output is split into four beams, $\omega_p$, $\omega_c$, $\omega_r$ by beam splitters. The applied cw laser powers of $\omega_p$, $\omega_c$ and $\omega_r$ are 0.4, 4.2 and 0.9 mW, respectively. By acousto-optic modulators (AOMs), the laser beams $\omega_p$, $\omega_c$ and $\omega_r$ are upshifted 210.2, 200 and 232.3 MHz from the dye laser frequency, respectively. All four beams are linearly polarized and focused to the sample with an angle of about 15 mrad, as shown in figure 2(a).
Figure 3. The slow-light information conversion for various $\omega_{c2}$ switch-on times. The intensity of the control field $\omega_{c2}$ is 4.0 mW.

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 $4 \text{ mm} \times 4 \text{ mm} \times 3 \text{ mm}$, and the optical $B$-axis is along $3 \text{ mm}$.

3. Experimental results and discussion

The control-1 and repump fields are first switched on for 7 ms each and then the populations are prepared to $^3\text{H}_4(\pm 3/2)$ level owing to the optical pump effect. To demonstrate EIT-based slow light, the control-1 and Gauss-shaped probe pulse are applied to the medium. These two fields $\omega_{p1}$ and $\omega_{c1}$ interact with the related levels of Pr ions, which form an EIT three-level lambda scheme, as shown in figure 1. Under EIT conditions, the medium exhibits steep dispersion, and the probe pulse $\omega_{p1}$ can be slowed. The slowing of the probe pulse is shown in figure 2(b). The dot line is the scaled-down reference pulse, which corresponds to the input probe pulse in the absence of other laser fields. The solid line is the slowed probe pulse. In the present experimental conditions, the probe pulse experiences a time delay of $41 \mu$s.

During the propagation of the slowed probe pulse in the crystal, we switch on an additional control field $\omega_{c2}$ to obtain the slow-light information conversion (or beam splitter). The applied pulse sequences are shown in figure 2(b). It is noted that the control field $\omega_{c2}$ is switched on when the slowed probe pulse appears. When the control field $\omega_{c2}$ is switched on, the original EIT lambda scheme is converted into an EIT double-lambda scheme. In such an EIT scheme, the dark-state polariton consists of two optical modes ($\omega_{p1}$ and $\omega_{p2}$), which can interconvert by manipulating the corresponding control field [22]. Due to the interaction between the slowed probe pulse and the two control fields, the slowed probe pulse is split into two different frequency-spatial channels ($\omega_{p1}$ and $\omega_{p2}$). This information conversion can be understood by
Figure 4. (a–c) The two output light pulses for three different intensities of the control field $\omega_{c2}$. (d) The splitting ratio of two light signals.

slow-light four-wave mixing. The generation of the new light signal $\omega_{p2}$ meets the phase-matching condition $\vec{K}_{p2} = \vec{K}_{p1} + \vec{K}_{c2} - \vec{K}_{c1}$, as shown in figure 2(a). So the propagating direction and the frequency of the newly generated signal $\omega_{p2}$ can be controlled by the additional control field $\omega_{c2}$. The maximum intensity of the signal $\omega_{p2}$ corresponds to zero detuning ($\Delta = 0$) of the control field $\omega_{c2}$. Figure 3 shows the information conversion using EIT-based slow light for various $\omega_{c2}$ switch-on times. Before the control field $\omega_{c2}$ is switched on, the front part of the slowed probe pulse has left the crystal. Thus, this part does not experience the conversion operation, and its shape is not changed. By controlling the $\omega_{c2}$ switch-on time, the different parts of the slowed probe pulse are split into two different frequency-spatial channels. The initial optical information carried by the input optical mode $\omega_{p1}$ is transferred to the two optical modes $\omega_{p1}$ and $\omega_{p2}$.

The shapes and splitting ratio of the two output light signals $\omega_{p1}$ and $\omega_{p2}$ depend strongly on the intensity of the control field $\omega_{c2}$. Figures 4(a)–(c) show two output light pulses for a constant $\omega_{c1}$ intensity and various $\omega_{c2}$ intensities. The temporal width of two output signals decreases with the increment of $\omega_{c2}$ intensity. The width of the output signal is inversely proportional to the spectral width of the EIT windows [7]. When the control field $\omega_{c2}$ is applied to the medium, the width of the EIT windows is determined by the sum of the squares of all control Rabi frequencies [22]. So the increment of the intensity of the control field $\omega_{c2}$ leads to the decrement of the temporal width of two output light signals. The splitting ratio is defined by the energy ratio of two output light signals $\omega_{p2}$ and $\omega_{p1}$. As discussed in [22], in such an atomic system the intensity of each output signal is linearly proportional to that of the associated control field.
So the splitting ratio of two output signals is determined by the intensity ratio of the two control fields $\omega_{c2}$ and $\omega_{c1}$. The splitting ratio is studied by keeping $\omega_{c1}$ intensity constant and varying $\omega_{c2}$ intensity. Figure 4(d) shows the splitting ratio as a function of the intensity of the control field $\omega_{c2}$. It is seen that the splitting ratio of two output light signals is linearly proportional to the intensity of the control field $\omega_{c2}$. The increment of $\omega_{c2}$ intensity leads to the increment of the $\omega_{p2}$ energy and the decrement of the $\omega_{p1}$ energy. The applied strongest power of $\omega_{c2}$ is 8 mW in the present experiment. In this case, the highest achievable ratio between the energies of the converted pulse ($\omega_{p2}$) and the slowed pulse ($\omega_{p1}$) is about 1.7, and the ratio between the energies of the converted pulse ($\omega_{p2}$) and the initial probe pulse ($\omega_{p1}$) is about 0.15. If more intense $\omega_{c2}$ is applied, a higher energy ratio can be achieved.

This information conversion is related to the controllable retrieval of stored light pulses. Zibrov et al have performed the first experiment of a stored light and its retrieval in a different frequency-spatial mode using Rb vapors [6]. Here the optical information is transferred and distributed during the propagation of the slowed light pulse, thus avoiding the stored-light operation. For comparison, we also demonstrate the double-channel retrieval of the stored light pulses in the Pr : YSO crystal. Figure 5(a) shows the storage and retrieval of the slowed probe pulse $\omega_{p1}$ by switching the control field $\omega_{c1}$ off and then back on. The left part is the portion of the probe pulse that has left the medium before the control field is switched off. The right part is the portion of the probe pulse that is stored in and subsequently retrieved from the medium. The gap indicates the storage time. To demonstrate double-channel retrieval, two control fields, $\omega_{c1}$ and $\omega_{c2}$, are simultaneously switched back on in the retrieval. Then the stored light pulse is retrieved into two different frequency-spatial channels, $\omega_{p1}$ and $\omega_{p2}$, as shown in figures 5(b) and (c).

The above experiments are based on the coherent transfer of optical states proposed by Lvovsky and coworkers [22], and have been implemented in Rb vapors [23]. Here we report the experimental demonstration in a rare-earth-ion-doped solid. A doped solid generally provides large inhomogeneous broadening of optical transitions, but the isolated and narrow
absorption lines can be obtained by using the spectral hole-burning effect [10], which enables the implementation of coherent manipulation of optical fields. In this demonstration, the first control field is kept constant in time, and the second control field is subsequently switched on. This allows for the direct transformation of the initial optical mode during its propagation, thus avoiding switch-off of the control field and the store-light operation. In particular, the transformed optical mode is not spatially separated from the initial optical mode in [23]. In our case, the transformed mode not only has a different frequency, but is also spatially separated from the initial mode. This will be important for practical applications in information processing.

4. Conclusions

In summary, we have experimentally demonstrated a slow-light information conversion via EIT in a Pr : YSO crystal. The slowed weak classical pulse in the EIT-driven crystal is transformed into two different frequency-spatial channels, by applying two strong control fields partially overlapping in time. The pulse shapes and the energies in both initial and transformed frequency-spatial modes are further studied. The measurements have been carried out using a weak classical signal pulse. It is believed that this method also works for quantized optical fields [22, 23]. The ultimate goal of this research is to obtain a controllable frequency-spatial multiplexing of the quantum state of the optical field. It is expected that a quantum state of the entering signal field can be traced in both the initial and transformed frequency-spatial modes at the exit of the medium. Such multiplexing could be used to route quantum information and to interface quantum communication lines of different frequency-spatial modes between each other and with memory-based quantum repeaters.

Acknowledgments

The authors acknowledge financial support from the National Basic Research Program (grant no. 2011CB921603), the NSFC (grant numbers 10904048, 11074097, 10974071, 11004079 and 11004080), the China Postdoctoral Science Foundation (grant no. 2011M500924) and the Basic Research Program of Jilin University.

References

[1] Harris S E 1997 Electromagnetically induced transparency Phys. Today 50 36
[2] Fleischhauer M and Imamoglu A 2005 Electromagnetically induced transparency: optics in coherent medium Rev. Mod. Phys. 77 633
[3] Fleischhauer M and Lukin M D 2000 Dark-state polaritons in electromagnetically induced transparency Phys. Rev. Lett. 84 5094
[4] Liu C, Dutton Z, Behroozi C H and Hau L V 2001 Observation of coherent optical information storage in an atomic medium using halted light pulses Nature 409 490
[5] Phillips D F, Fleischhauer A, Mair A, Walsworth R L and Lukin M D 2001 Storage of light in atomic vapor Phys. Rev. Lett. 86 783
[6] Zibrov A S, Matsko A B, Kocharovsky O, Rostovtsev Y V, Welch G R and Scully M O 2002 Transporting and time reversing light via atomic coherence Phys. Rev. Lett. 88 103601

New Journal of Physics 13 (2011) 123008 (http://www.njp.org/)
[7] Lukin M D and Imamoglu A 2000 Nonlinear optics and quantum entanglement of ultraslow single photons Phys. Rev. Lett. 84 1419
[8] Choi K S, Deng H, Laurat J and Kimble H J 2008 Mapping photonic entanglement into and out of a quantum memory Nature 452 67
[9] Camacho R M, Vudyasetu P K and Howell J C 2008 Four-wave-mixing stopped light in hot atomic rubidium vapour Nat. Photonics 3 103
[10] Turukhin A V, Sudarshanan V S, Shahriar M S, Musser J A, Ham B S and Hemmer P R 2001 Observation of ultraslow and stored light pulses in a solid Phys. Rev. Lett. 88 023602
[11] Longdell J J, Fraval E, Sellars M J and Manson N B 2005 Stopped light with storage times greater than one second using electromagnetically induced transparency in a solid Phys. Rev. Lett. 95 063601
[12] Wang H H, Wei X G, Wang L, Li Y J, Du D M, Wu J H, Kang Z H, Jiang Y and Gao J Y 2007 Optical information transfer between two light channels in a Pr$^{3+}$ : Y$_2$SiO$_5$ crystal Opt. Express 15 16044
[13] Ham B S 2008 Observation of delayed all-optical routing in a slow light regime Phys. Rev. A 78 011808
[14] 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 Slowing and storage of double light pulses in a Pr$^{3+}$ : Y$_2$SiO$_5$ crystal Opt. Lett. 34 2596
[15] Ham B S 2004 Experimental demonstration of all-optical 1$\times$2 quantum routing Appl. Phys. Lett. 85 893
[16] Ham B S and Hemmer P R 2000 Coherence switching in a four-level system: quantum switching Phys. Rev. Lett. 84 4080
[17] Wang H H, Du D M, Fan Y F, Li A J, Wang L, Wei X G, Kang Z H, Jiang Y, Wu J H and Gao J Y 2008 Enhanced four-wave mixing by atomic coherence in a Pr$^{3+}$ : Y$_2$SiO$_5$ crystal Appl. Phys. Lett. 93 113003
[18] Klein J, Beil F and Halfmann T 2007 Robust population transfer by stimulated Raman adiabatic passage in a Pr$^{3+}$ : Y$_2$SiO$_5$ crystal Phys. Rev. Lett. 99 113003
[19] Afzelius M et al 2010 Demonstration of atomic frequency comb memory for light with spin-wave storage Phys. Rev. Lett. 104 040503
[20] Lauritzen B, Minar J, deRiedmatten H, Afzelius M, Sanguoard N, Simon C and N. Gisin N 2010 Telecommunication-wavelength solid-state memory at the single photon level Phys. Rev. Lett. 104 080502
[21] Wang T, Kostrun M and Yelin S F 2004 Multiple beam splitter for single photons Phys. Rev. A 70 053822
[22] Appel J, Marzlin K P and Lvovsky A I 2006 Raman adiabatic transfer of optical states in multilevel atoms Phys. Rev. A 73 013804
[23] Vewinger F, Appel J, Figueroa E and Lvovsky A I 2007 Adiabatic frequency conversion of optical information in atomic vapor Opt. Lett. 32 2771
[24] Xiao Y H, Klein M, Hohensee M, Jiang L, Phillips D F, Lukin M D and Walsworth R L 2008 Slow light beam splitter Phys. Rev. Lett. 101 043601