APPLIED PHYSICS LETTERS **93**, 221112 (2008)

All-optical routing by light storage in a $Pr^{3+}:Y_2SiO_5$ crystal

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(Received 2 October 2008; accepted 14 November 2008; published online 5 December 2008)

We experimentally demonstrate an all-optical routing based on light storage in a $Pr^{3+}:Y_2SiO_5$ crystal. Under electromagnetically induced transparency, the optical information of the probe light pulse can be stored in the crystal. By simultaneously switching on two retrieve control fields in the release process, the stored optical information from one light channel can be distributed into two light channels. Such an all-optical routing in solids may have practical applications in quantum information and all-optical network. © *2008 American Institute of Physics*.

[DOI: 10.1063/1.3041645]

Light is the fastest and most robust carrier of information. The ability to control light is important in both classical and quantum communications. By using electromagnetically induced transparency (EIT),[1] researchers have experimentally demonstrated the storage and retrieve of a light pulse.[2,3] In the three-level lambda-type EIT system, a weak probe pulse can be completely halted in the atoms by switching off the control field, and subsequently released by the reverse process. Subsequently, many interesting studies on light storage are reported.[4–9] However, most experimental studies on light storage have been carried out in atomic gases. For practical applications, a solid medium is preferred. Compared with atomic gases, solid mediums have obvious advantages, such as compactness, absence of atomic diffusion, and high density of atoms. So the experimental studies in solids are more valuable than that in atomic gases. Currently, EIT,[10] quantum routing,[11] slow light,[12] light storage,[12–14] and stimulated Raman adiabatic passage[15,16] have been experimentally reported in solids.

In quantum information and all-optical network, it is necessary to have devices such as quantum repeater and all-optical routing, where optical information can be transferred and distributed in a controlled fashion between different light channels.[7,8] Routing and wavelength-division multiplexing of optical information have many practical applications, for example, they can be used to interface optical communication line of different wavelengths and distribute optical information between different light channels. In this letter, we experimentally demonstrate an all-optical routing based on light storage in a $Pr^{3+}:Y_2SiO_5$ (Pr:YSO) crystal. Under the condition of EIT, the optical information of the probe pulse is stored in the crystal. By simultaneously switching on two retrieve control fields in the release process, the original optical information carried by one light channel is distributed into two light channels. This all-optical routing may have practical application in the quantum information processing and all-optical network.

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 10 GHz at 1.4 K. The spin inhomogeneous width for the 10.2 MHz transition is 30 kHz at 1.6 K. We call ω_{p1}, ω_{c1}, ω_{c2}, and ω_r the probe, control-1, control-2, and repump field, respectively.

The experimental arrangement is illustrated in Fig. 2. A Coherent-899 ring laser (R6G dye) is used as the light source. The laser output is split into four beams: ω_{p1}, ω_{c1}, ω_{c2}, and ω_r. Acousto-optic modulators (AOMs) are used to upshift the frequency. The applied cw laser powers of ω_{p1}, ω_{c1}, and ω_r are 0.7, 3.3, and 0.5 mW, respectively. The laser beams ω_{p1}, ω_{c1}, ω_{c2}, and ω_r are upshifted at 200, 189.8, 185.2, and 222.1 MHz from the dye laser frequency, respectively. All four beams are linearly polarized and focused into the sample with the angle of about 10 mrad. The alignments of laser beams ω_{p1}, ω_{c1}, and ω_{c2} satisfy the phase-matching condition ($\vec{K}_{p2}=\vec{K}_{p1}+\vec{K}_{c2}-\vec{K}_{c1}$) for the generation of ω_{p2} at the position indicated on L2. 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 $4\times4\times3$ mm^3, and optical *B*-axis is along 3 mm. The light propagation direction is almost parallel to the optical *B*-axis of the crystal.

For the experimental preparation of all-optical routing, we prepare the populations on $^3H_4(\pm3/2)$ level by using the light pulse sequences of Ref. 15. A Gauss probe pulse is used

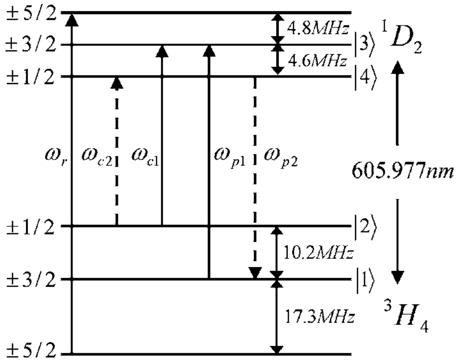

FIG. 1. The related energy-level diagram for Pr:YSO.

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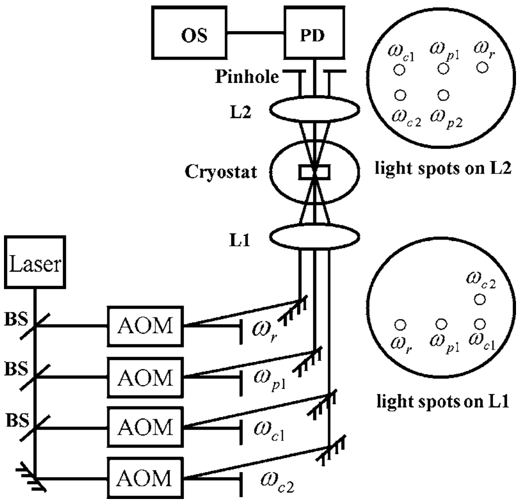

FIG. 2. Schematic of the experimental setup. BS: beam splitter; L: lens; AOM: acousto-optic modulator; PD: photodiode; OS: oscilloscope.

to demonstrate light storage, and its $1/e$ full width is 43 μs. In the step of slow light demonstration, control-1 and repump field are applied to the crystal, and the control-2 field is not applied. The probe pulse is slowed because of the EIT effect. A time delay of about 37 μs is measured, as shown in Fig. 3(a). Based on the slow light, the storage and release of the probe pulse are realized by switching off and on the control-1 field.

Figure 3(b) shows a typical light storage based on EIT. Peak-1 is the portion of the probe pulse ω_{p1} that has left the crystal before the control-1 field ω_{c1} is switched off, which is not affected by the storage operation. Peak-2 is the portion of the probe pulse ω_{p1} that is stored in and subsequently released from the crystal after switching back on the control-1 field ω_{c1}. The gap between peak-1 and peak-2 is the storage time of 10 μs. Because only one retrieve control field ω_{c1} is switched on in the release process, the optical information is distributed into the original light frequency ω_{p1}, and no signal of the frequency ω_{p2} is observed. Figure 3(c) shows the all-optical routing by light storage. In order to distribute the stored optical information into two light channels, we simultaneously switch on two retrieve control fields (ω_{c1} and ω_{c2}) in the release process. In this case, we can see that the stored optical information is released at two different frequencies (ω_{p1} and ω_{p2}). Note that the released signal ω_{p2} has a different propagation direction and different carried frequency compared with the released signal ω_{p1}. The optical information originally carried by one light channel is distributed into two light channels, and then all-optical routing (or beam splitter) is realized. Especially, simultaneous switch-on of the two retrieve control fields can ensure the simultaneous transmission of the optical information at two light channels.

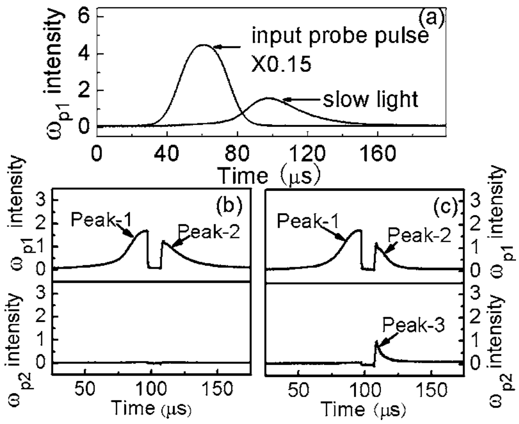

FIG. 3. (a) Slow light demonstration. [(b) and (c)] All-optical routing based on light storage. (b) The control-1 field is switched on in the release process. (c) Two retrieve control fields (ω_{c1} and ω_{c2}) are simultaneously switched on in the released process. The intensity of the control-2 field is 6 mW.

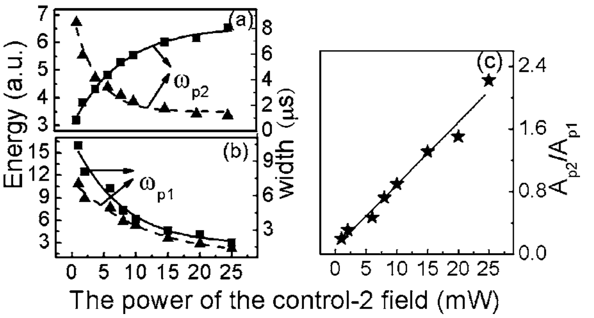

FIG. 4. [(a) and (b)] The energy and temporal width of the released signals vs the intensity of the control-2 field. The squares and triangles correspond to the measured energy and width of the released signals, respectively. (c) The energy ratio of the two released signals ω_{p2} and ω_{p1}. The asterisks correspond to the measured energy ratio. The solid and dashed curves are the theoretical fits.

The shapes of two released signals ω_{p1} and ω_{p2} depend strongly on the intensity of the control-2 field. Figures 4(a) and 4(b) show the energy and temporary width of two released signals versus the intensity of the control-2 field. It is found that the energy of the released signal ω_{p2} increases with the increment of the intensity of the control-2 field; however, the energy of the released signal ω_{p1} decreases with the increment of the intensity of the control-2 field. This is because the intensity of the released signal is proportional to that of the associated control field.[7] The increment of the intensity of the control-2 field leads to the result that the signal with more energy is released into the light channel with frequency ω_{p2}. So the intensity of the associated control field can control the distributing ratio of the signals between different light channels. The temporal width of two released signals decreases with the increment of the intensity of the control-2 field. The width of the released signal is inversely proportional to the spectral width of the EIT windows.[5] When the control-2 field is switched on, the original system becomes a four-level double-lambda atomic system, where the width of the EIT widows is determined by the sum of the squares of all control Rabi frequencies.[7] So the increment of the intensity of the control-2 field leads to the decrement of the temporal width of two released signals.

We study the energy ratio of the released signals in the two light channels, by varying the intensity of the retrieve control-2 field and keeping the intensity of the retrieve control-1 field constant. In such an EIT four-level double-lambda atomic system, the intensity of each released signal is linearly proportional to that of the associated retrieve control field. So the energy ratio (A_{p2}/A_{p1}) of the released signals is determined by the intensity ratio (I_{C2}/I_{C1}) of the corresponding retrieve control fields. Figure 4(c) shows the energy ratio (A_{p2}/A_{p1}) of the released signals ω_{p2} and ω_{p1} as a function of the intensity of the control-2 field. We can see that the energy ratio of the released ω_{p2} and ω_{p1} is linearly proportional to the intensity of the control-2 field. The increment of the control-2 intensity leads to the increment of the energy of the released ω_{p2} and decrement of the energy of the released ω_{p1}, which is consistent with the theoretical expectation. For the control-2 intensity of 25 mW, the transfer efficiencies with respect to the original input pulse and with respect to the slowed pulse without storage are about 0.8% and 11%, respectively. The actual transfer efficiency should be higher because the released signal ω_{p2} propagates in a different direction and is partially absorbed by the crystal.

In summary, we have experimentally demonstrated an all-optical routing based on the technique of light storage in a Pr:YSO crystal. By simultaneously switching on two retrieve control fields to release the stored optical information, the original optical information is distributed into two light channels. This all-optical routing by light storage may have many applications in quantum information and all-optical network.

The authors acknowledge the financial support from the NSFC (Grant Nos. 10334010 and 10774059), the doctoral program foundation of Institution of High Education of China, and the National Basic Research Program (Grant No. 2006CB921103).

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