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Steep optical-wave group-velocity reduction and "storage" of light without on-resonance electromagnetically induced transparency

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We report on experimental investigation of optical-pulse group-velocity reduction and probe-pulse "regeneration" using a Raman scheme. This scheme, which does not rely on the commonly used on-one-photon-resonance electromagnetically induced transparency (EIT) process, has many advantages over the conventional method that critically relies on the transparency window created by an EIT process. We demonstrate significant reduction of the group velocity, less probe-field loss, reduced probe-pulse distortion, and high probe-pulse regeneration efficiency.

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Electromagnetically induced transparency (EIT) is a process where a destructive interference between electromagnetically created resonances cancels the absorption of an electromagnetic wave that traverses the medium. The commonly used EIT scheme [1] involves a three-level atomic system interacting with two laser fields that are both tuned onto one-photon resonances [2]. This scheme has been extensively used in almost every recent study on the group-velocity reduction, atomic spin-wave excitation, and probe-pulse regeneration in a resonant medium [3–5]. Strictly speaking, this ideal on-one-photon-resonance EIT is applicable only to a three-level model. In reality, however, the situation is more complicated because no ideal three-level system exists. The effects of nearby hyperfine states often contribute significantly to wave propagation, thereby greatly altering the response of the system to the optical wave. Indeed, it has been shown [6] that in the case of the sodium D_2 line, the probe-field loss due to nearby hyperfine states generally dwarfs that of the pure three-level system and causes nearly an 80% reduction of probe-field intensity. Even with the atomic species that have larger hyperfine splittings (e.g., rubidium), the loss and the pulse broadening are still non-negligible. Moreover, the stringent requirement of having both the probe and coupling lasers tuned onto resonance remains. This latter requirement is the major obstacle that prevents the EIT scheme from being applied to the solids at room temperature, where the broad energy-band structures render "tuning to the resonance line center" rather meaningless. To search for a better scheme, we note that on-resonance EIT is not a prerequisite for achieving significant group-velocity reduction. Indeed, dramatic modification of the dispersion properties of the medium can be achieved without the on-resonance condition that is required under the conventional EIT operation [7,8].

In this paper we report experimental results on significant group-velocity reduction and probe-pulse regeneration without using the conventional EIT scheme. We describe a Raman scheme that has many advantages over the conventional one-photon on-resonance EIT scheme. The inclusion of a non-negligible one-photon detuning opens many possibilities, such as not only a reduction of the probe-field loss, but even probe-field gain. We will show that by using a conventional vapor cell with properly chosen parameters, this scheme can greatly reduce probe-field attenuation, achieve high-efficiency probe-pulse regeneration, and result in smaller probe-pulse broadening. To the best of our knowledge, none of these features have been reported in the literature.

Our experiment is carried out in a vapor cell that is filled with pure ^{87}Rb atoms, whose partial energy-level diagram is depicted in the top panel of Fig. 1. The experiment is performed using the D_1 line of the $5^2S_{1/2}$, $F=2 \rightarrow 5^2P_{1/2}$, $F=2$ transition, with two ground states $|0\rangle = |F=2, m_F=2\rangle$, $|1\rangle = |F=2, m_F=0\rangle$, and one excited state $|2\rangle = |F'=2, m_F=1\rangle$. The experimental setup is shown in lower panel of Fig. 1. The temperature of the cell, which is 10 cm long and heated with a nonmagnetic wire, is typically in the range of 50–70 °C and is temperature stabilized for uniform atomic density. The estimated full width of the Doppler broadened $|0\rangle \rightarrow |2\rangle$ transition at this temperature is about 560 MHz. In order to ensure long lifetimes of the atomic Zeeman coher-

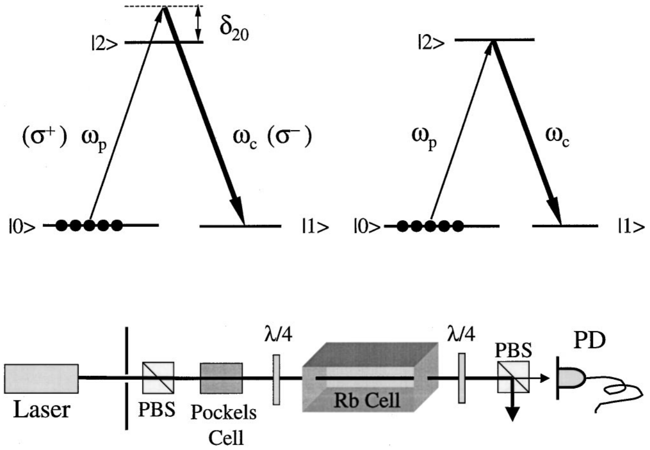

FIG. 1. Upper panel: three-level EIT scheme (right), and three-level Raman scheme (left). Energy-level designations for Raman scheme: $|0\rangle = |F=2, m_F=-2\rangle$, $|2\rangle = |F'=2, m_F=-1\rangle$, and $|1\rangle = |F=2, m_F=0\rangle$. Lower panel: Experimental setup.

ence, we use a triple-layer magnetic shield. The Rb cell is also filled with 5 torr of He^4 buffer gas so that the Rb atoms stay in the path of the laser beams for several hundreds of microseconds due to elastic collisions with He atoms. Both the coupling (σ^-) and probe (σ^+) lasers, derived from a single extended-cavity diode laser, have a diameter of 2 mm in the vapor cell. We first turn the control laser onto resonance to optically pump the atoms to state $|0\rangle$. After optical pumping is performed, we switch the control laser to a predetermined one-photon detuning. At the same time we slightly rotate the polarization of the input light to create a weak σ^+ probe light pulse (duration $\tau = 7.3\ \mu s$) using a fast Pockels cell made from an 80-mm-long $LiNbO_3$ crystal. We chose the power of the control and probe lasers to give single-photon Rabi frequencies of $\Omega_{21} = \Omega_c(\sigma^-) = 2\pi \times 15$ MHz and $\Omega_{20} = \Omega_p(\sigma^+) = 2\pi \times 1.3$ MHz, respectively. These choices of power and pulse duration ensure that during the presence of the probe pulse there is negligible population transfer; a necessary condition for a simplified perturbative treatment of the system that was used to guide our choice of experimental parameters. Under these conditions, we have $\Delta_{ac}\tau > 1$ ($\Delta_{ac} = |\Omega_{21}|^2/\delta_{20}$ is the ac Stark shift due to the control laser), and $|\delta_{20}| \gg |\Omega_{21}|$. Ideally, one would prefer to have the laser detuned several Doppler line widths while maintaining a large ac Stark shift. However, due to the limited output power of our control laser, we are unable to detune very far from state $|2\rangle$, while still producing a sizable ac Stark shift. Therefore, the above-described choice of parameters represents a reasonable compromise in view of our experimental constraints.

Before presenting our data, let us briefly state some of the main features that are expected in the Raman scheme for a set of conditions that ensure the validity of an adiabatic treatment [7,8]. When $\Delta_{ac}\tau \gg 1$, we expect the propagation velocity of the probe pulse to be independent of detuning, but linearly proportional to the power of the control laser. In addition, we expect a significant reduction of probe-field loss. Figure 2 is a plot of probe-pulse intensity at the exit of the cell as a function of time. To better illustrate the advantages of the Raman scheme, we present measurements of both the Raman scheme and the conventional EIT scheme under the same operational parameters. Three features are immediately apparent. First, a significant reduction of the group velocity is achieved, and the data show that the slowdown effect of the proposed Raman scheme is almost the same as that of the conventional EIT scheme. The second feature exhibited in Fig. 2 is the dramatic reduction of the probe-field loss compared to the conventional scheme. In the case of the EIT scheme, the probe field has suffered nearly a 99% loss in intensity, whereas in the Raman case, this loss is only about 58%, yielding a signal nearly forty times more intense than the conventional EIT case. We have examined the detuning range from 500 MHz to 1.2 GHz. At a detuning of 1.2 GHz, we found that the Raman scheme preserves nearly 99% of the intensity of the original probe pulse, but the group velocity is about a factor of 10 faster than that obtained with the EIT scheme. This is perhaps the most important advantage of the Raman scheme over the conventional EIT scheme since the large Raman detuning readily allows it to be applied in solid-state materials, a territory that prohibits a meaningful application of the conventional EIT scheme because of the broad energy-band structure [9–11]. The third feature apparent in Fig. 2 is the smaller probe-pulse broadening. In the Raman scheme, this broadening is about 10%; whereas in the EIT scheme, it is about 40%. The smaller pulse time width broadening of Raman scheme is due to the large Doppler spectral width of the upper state [12]. It can be shown theoretically, and has been observed experimentally [3–5], that in the conventional EIT scheme the probe pulse is always broadened during propagation even in a pure three-level system. This occurs because when the ac Stark shift induced by the control-laser Rabi frequency is not substantially larger than the upper-state lifetime, as in the case of all slow light related experiments, the atomic dispersion function at the probe frequency cannot be treated in a linear-response theory. The consequence is that nonlinear contributions to the dispersion function lead to pulse broadening regardless of whether the medium is hot or cold. In the Raman case, however, the dynamics are changed by the fact that the one-photon detuning also plays a role in determining the size of the nonlinear contribution, resulting in less pulse broadening, as shown in Fig. 2. Experimentally, we also found that in the detuning range studied (0.5–1.2 GHz), the group velocity is insensitive to the detuning. Near the end of the range, i.e., near 1.2 GHz detuning, we observed an increase in the group velocity. In addition, we have observed that the group velocity scales linearly with the power of the control laser. These observations are in good agreement with theoretical predictions for the control-laser power used in our experiment.

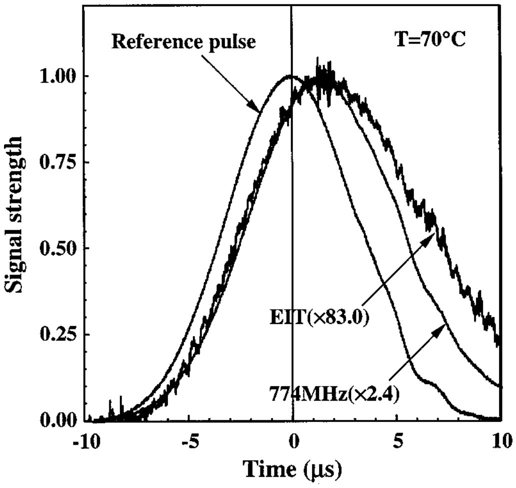

FIG. 2. A plot of the probe pulse as a function of time for an on-resonance EIT scheme, and for a Raman scheme and with a detuning of $\delta_{20} = 774$ MHz. The EIT data have been magnified by a factor of 83, and the probe profile for the Raman scheme was magnified by 2.4. The estimated group velocity is about $c/10^4$. The closeness of the peak positions indicates that under the driving conditions used the group velocity is insensitive to the detuning, as the theory predicts.

The group velocity achievable with a Raman scheme in a typical three-level system is about the same as the EIT scheme, and becomes slightly faster (typically within a factor

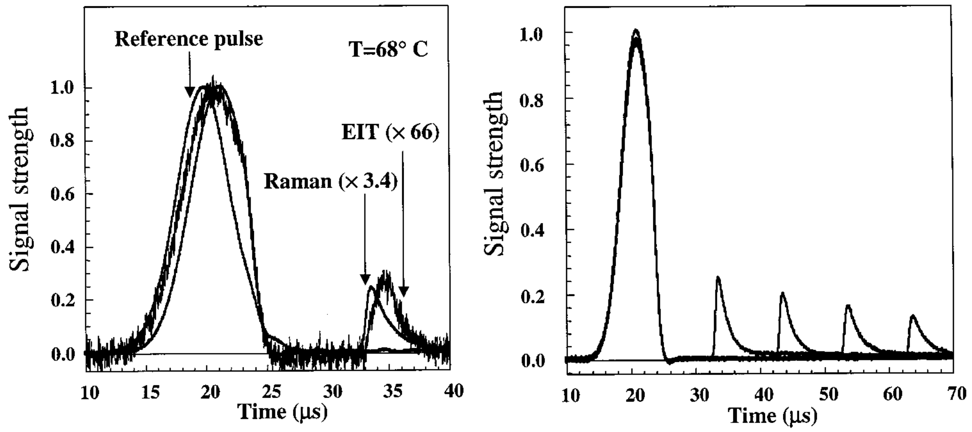

FIG. 3. Left panel: ‘‘storage of light’’ using a Raman and an on-resonance EIT scheme. Parameters are similar to that of Fig. 2. Notice the broadened pulse and significantly lower and noisier ‘‘probe pulse’’ regenerated under the EIT scheme. Right panel: Successive probe-pulse regeneration using a series of control-laser pulses. The clean probe pulses clearly show that the Raman method is superior to the EIT method under the present conditions.

of 4) as the detuning increases. This slight difference, however, is a reasonable price to pay for achieving significantly lower loss, less pulse broadening, and interesting pulse-propagation dynamics introduced by the sizable one-photon detuning. These advantages are expected to hold for cold vapors, hot vapors, and even solid medium.

To further demonstrate the significant advantages of the Raman scheme, we investigated the ‘‘storage’’ of probe photons. In Fig. 3, we show the ‘‘storage’’ and ‘‘recovery’’ of a probe pulse obtained using the Raman scheme and compare it with the conventional EIT scheme under the same conditions. The first striking feature of Fig. 3 (left panel) is again the significantly lower loss in Raman scheme. In fact, under the same experimental conditions, signals from the on-resonance EIT scheme are very weak and noisy. In contrast, notice the clean pulse shape obtained using the Raman method. On the right panel, we show a series of probe-pulse ‘‘recoveries’’ with several control-laser pulses turned on at different delay times. The cleanly regenerated probe pulse is a clear evidence that the Raman scheme is superior to the EIT scheme. Under the same conditions, the EIT method produces a series of pulses (not shown) that are barely above the noise level.

We emphasize that an on-resonance EIT scheme is not necessary for achieving group-velocity reduction. The role of the EIT process is mainly to reduce one-photon absorption so that the probe pulse can travel with low loss in an otherwise opaque medium, allowing one to measure the significant group-velocity reduction at low control-laser power. In the Raman scheme this is achieved with a nonvanishing one-photon detuning at the expense of higher control-laser power. The advantages of the Raman scheme are very obvious when it is applied to solid medium for group-velocity reduction. This is because the broad energy-band structure encountered in solids at room temperature makes the on-one-photon-resonance condition required by the conventional EIT scheme very difficult to satisfy. Any part of the energy band that is not strongly overlapped by the coupling laser will not be driven transparent, and hence will collectively contribute to the process as a loss mechanism. However, in the case of the Raman scheme, the one-photon detuning can be chosen to be much larger than the energy bandwidth, thereby preserving the probe-pulse intensity while achieving a comparable reduction in group velocity and yielding a much higher probe-pulse recovery efficiency. This could make our technique very useful in novel optical device designs that may have potential applications to telecommunications.

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[11] We emphasize that in our work the probe and coupling laser detunings are changed together, so that the two-photon resonance is strictly enforced and only the one-photon detuning was varied.

[12] From Eq. (7c) of Ref. [7] above, it is seen that the $\mathrm{Im}[D_2]$, which enters the pulse duration of the probe field during the propagation, is proportional to the spectral width of the upper state.