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The connection between electromagnetically induced transparency in the Zeeman configuration and slow light in hot rubidium vapor

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Abstract
We experimentally studied Zeeman electromagnetically induced transparency (EIT) resonances and slow light propagation in hot Rb vapor. Propagation of weak σ^- polarized light pulses in the presence of stronger σ^+ polarized background through Rb vapor was realized using a single laser beam and the Pockels cell. The dependences of slow light group velocity and fractional pulse delay on the overall laser beam intensity and temporal pulse length showed that lower optical power and longer light pulses lead to improved EIT and slow light features. The connection between EIT and slow light was also investigated showing that narrower and more contrasted EIT resonances are necessary for further decreasing a group velocity.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Coherent effects in Doppler broadened alkali atom vapors have been thoroughly investigated over the past decade. Coherent population trapping [1] and electromagnetically induced transparency (EIT) [2] have been observed and characterized in either the pump–probe or Zeeman configuration [3, 4]. In the latter case, EIT is based on Zeeman coherences between magnetic sublevels of a given hyperfine state of the alkali atom electronic ground state. The amplitudes and widths (full-width at half-maximum, FWHM) of the EIT resonances are limited by the average atom time-of-flight through the laser beam. To prolong the interaction time and thus the lifetime of the dark states, an inert buffer gas is added to atomic vapor in order to slow the diffusion of the coherently prepared atoms through the laser beam [5]. In such buffer gas cells, narrower EIT resonances compared to the vacuum cells and very steep dispersion of the index of refraction are obtained. This results in low group velocities $v_g = \frac{c}{n+\omega\frac{\partial n}{\partial\omega}}$ of the light pulses or the so-called slow light phenomena [6]. We define an absolute time delay $\Delta\tau$ as the time difference between arrivals of the pulse slowed down in the Rb cell and the reference pulse. The fractional time delay η is defined as the ratio of an absolute time delay to the temporal pulse length τ_{pulse}.

In the gaseous atomic systems, ultra-low group velocities have been demonstrated experimentally in Bose–Einstein condensates [7] and thermal atomic vapor [8].

In this paper, we present the measurements of slow light in the Zeeman EIT configuration in hot Rb vapor contained in a buffer gas cell. The overall laser intensity and the temporal pulse lengths were varied in order to obtain maximal fractional delay of light pulses with minimum distortion. The dependence of the slow light effect on the EIT features [9] is also shown for our experimental setup.

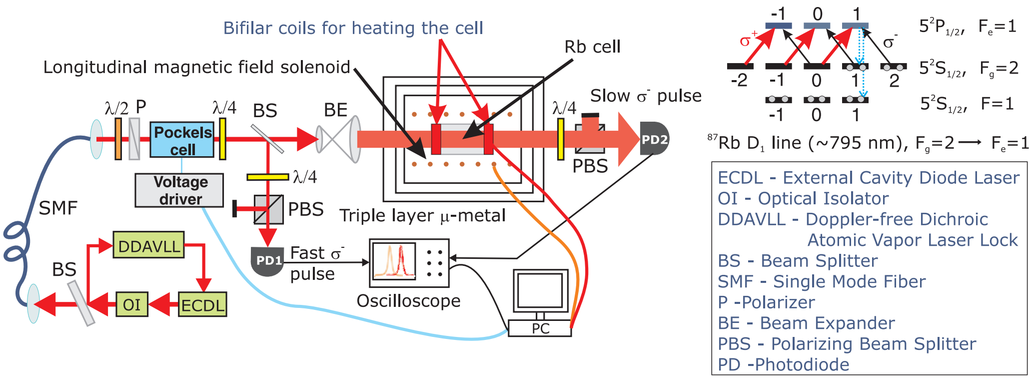

Figure 1. The experimental setup and the atomic transition used in the experiment. The computer controls the cell temperature, the external longitudinal magnetic field and the polarization pulses for the Pockels cell.

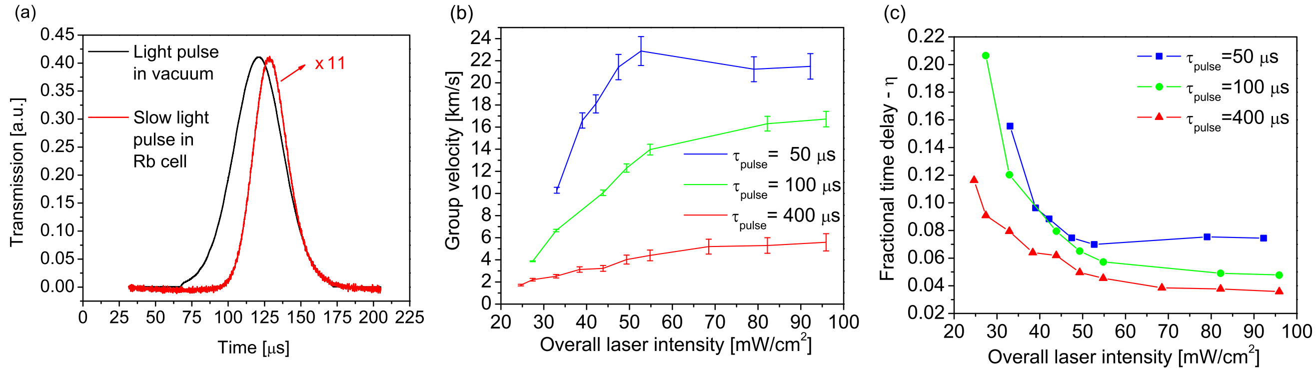

Figure 2. Experimental results of slow light. The power of the σ^- pulse in its peak is 15% of the overall laser power. (a) Black and red pulses denote reference and slow pulses, respectively. The temporal pulse length is 100 μs, the overall laser intensity is 40.5 mW cm^{-2} and the absolute time delay is 8.78 μs corresponding to a group velocity of 9.1 km s^{-1}. The dependence of (b) the group velocity and (c) the fractional time delay of σ^- pulses on the overall laser intensity for different temporal pulse lengths is shown. Blue, green and red curves show the results for pulse lengths of 50, 100 and 400 μs, respectively.

2. Experimental setup

The experimental setup is shown in figure 1. The external cavity diode laser is frequency locked to the hyperfine $F_g = 2 \to F_e = 1$ transition of the D_1 line in ^{87}Rb by using the Doppler-free dichroic atomic vapor laser lock method [10]. The laser beam passes through the 8 cm long Rb cell containing a natural abundance of Rb isotopes and filled with 30 torr of Ne buffer gas. The temperature of the cell is kept at 80 °C. The laser beam diameter is 1.4 mm. The cell is placed in the solenoid used for scanning the axial magnetic field in order to obey two-photon detuning between −400 and +400 kHz. The elliptically polarized laser beam consisting of a weak σ^- signal field and a stronger σ^+ control field is sent to the Rb cell. The Zeeman EIT resonances are obtained by measuring the transmission of σ^- light as a function of two-photon detuning. We next measure slow light propagation. By using the Pockels cell, we slightly rotate the polarization of the input light to create a weak σ^- pulse. Because of the presence of the strong σ^+ field, the resonant σ^- pulse can freely propagate through the otherwise opaque medium but with a substantially reduced group velocity.

3. Results and discussions

Experimental results of slow light propagation are presented in figure 2(a).

The group velocity is simply calculated as $v_g = L/\Delta\tau$, where L is the length of the cell and $\Delta\tau$ is absolute time delay. The group velocity of the σ^- pulse and its fractional time delay as functions of the overall laser intensity for different temporal pulse lengths are shown in figures 2(b) and (c), respectively. The typical Zeeman EIT resonance is shown in figure 3(a).

By measuring the EIT linewidths and amplitudes at different laser intensities, the connection between slow light and EIT features could be established. In figures 3(b) and (c), we present the dependences of slow light fractional time delay on the EIT linewidth and the amplitude to linewidth ratio, respectively.

Group velocities obtained in the experiment are in the range from 1.7 km s^{-1} (overall laser intensity $I = 24.5$ mW cm^{-2} and pulse length $\tau_{\rm pulse} = 400\,\mu$s) up to 23 km s^{-1} ($I = 52.8$ mW cm^{-2}, $\tau_{\rm pulse} = 50\,\mu$s). Fractional pulse delays η lie in the range from 3.5 ($I = 96$ mW cm^{-2}, $\tau_{\rm pulse} = 400\,\mu$s) up to 20.5% ($I = 27.4$ mW cm^{-2}, $\tau_{\rm pulse} = 100\,\mu$s). The linewidths of the EIT resonances decrease from 180 down to 65 kHz as the laser intensity decreases from 110 down to 25 mW cm^{-2}. Due to the increased absorption, measurements below intensities of 20 mW cm^{-2} were not possible. Lower group velocities were obtained for narrower and more contrasted EIT lines as shown in figures 3(b) and (c).

4. Summary

We have studied the Zeeman EIT resonances and slow light propagation in hot Rb vapor and a connection between

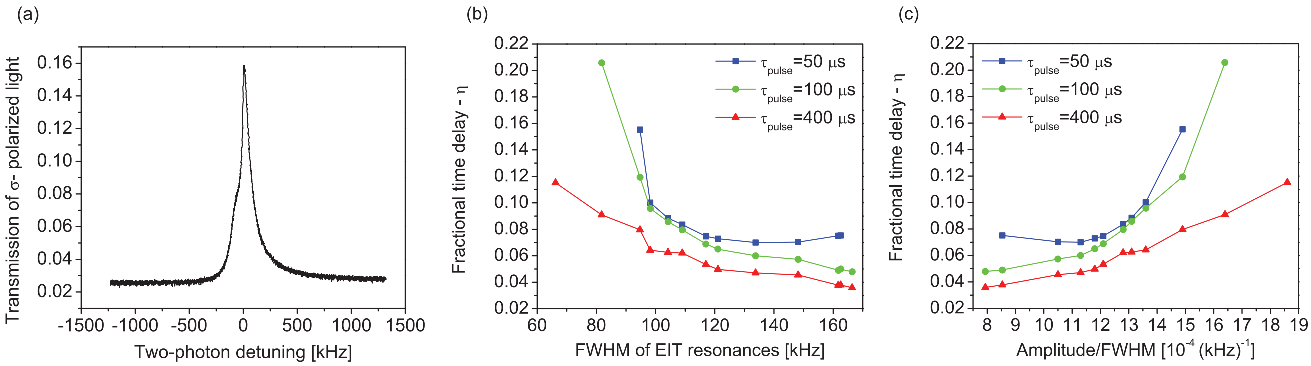

Figure 3. The connection between slow light and the EIT features. (a) The measured EIT resonance for the overall laser intensity of 40.5 mW cm^{-2}. The linewidth and amplitude of the resonance are 98 kHz and 0.13, respectively. The dependence of fractional time delay of slow light pulses on the EIT. (b) The linewidth and (c) amplitude to linewidth ratio for different temporal pulse lengths are shown. Blue, green and red curves show the results for pulse lengths of 50, 100 and 400 μs, respectively.

these coherent phenomena. We observed that decreasing the overall laser intensity leads to lower values of group velocity and fractional time delay. This is in agreement with the analysis in [2]. We also observed a strong dependence of slow light parameters on the temporal length of light pulses. Longer pulses exhibit lower group velocities. We concluded that narrower and more contrasted EIT resonances lead to improved slow light features. In forthcoming work we will investigate how to increase both the transparency of the σ^- optical field and the fractional time delay so that storage of light [11] can be achieved.

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