Direct Measurement of Light Speed Reduction in a Rubidium Vapour Medium Coherently Prepared by Electromagnetically Induced Transparency *

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We have experimentally observed the reduction of light speed in a rubidium vapour medium coherently prepared by electromagnetically induced transparency. The light speed reduction was deduced by directly measuring the time delay of a probe light when it passed through the medium. The time delay varies with the intensity of the coupling laser, and the typical time delay we recorded was 1.8 μs, corresponding to a light speed of 56000 m/s.

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In the quantum mechanical evolution of atomic states, coherence between the atomic states plays a very important role. Meanwhile quantum coherence results in quantum interference, thus modifies the response of an atomic medium to light. In this way, linear and nonlinear optical properties of the medium can be controlled and modified by coherently preparing the atomic states. Electromagnetically induced transparency (EIT),[1,2] coherent population trapping[3] and amplification without inversion[4] are the effects due to the atomic coherence resulting from the coherent interaction between multi-level atoms and laser fields. EIT has attracted great attention of many researchers[5−9] because of its significant new applications, such as weak light nonlinear optics,[10] photon switch,[11] four-wave mixing,[12] ultra-slow group velocity of light,[13,14] and information storage or retrieval.[15] There are two types of experimental demonstration of ultra-slow group velocity of light, one is indirect measure of the group velocity via dispersion,[16−18] the other is direct measure of the light speed reduction by time retardation,[19−21] and the most significant progress is light storage realized recently both in vapour cell[22] and in cold atoms.[23] In a cold atomic medium, the interaction time between atoms and light field is longer due to the low velocity of cold atoms, so that the coherence relaxation time of atoms is longer. On the other hand, Doppler broadening in cold medium is very small compared with the hot one, which results in a narrow EIT peak and steep dispersion, it is more easily to observe light speed reduction experimentally. However, the disadvantage is that the size of the cold atom cloud is small and thus the probe intensity must be weak enough, which is difficult to observe directly the time delay of whole light pulse due to bad signal-to-noise ratio, the profile of probe pulse is not a continuous one but a fitted one from scatter data as shown in Ref. [22]. Meanwhile cold atom demands setting up a complex magneto-optical trap. In hot atomic vapour cells, the experimental set-up is simple, because the coherence relaxation time is relatively short, light speed reduction is usually not obvious. One must use quick chopper to produce short probe pulse, and quick enough response detector to receive signals. Otherwise one can only indirectly derive the group velocity of probe light via refractive index of medium or other methods. Here we report a simpler and easier method to measure directly light speed reduction in vapour cells. Differing from early direct measurements of light speed reduction[20,21] which adopted the D_1 line (795 nm) of ^{87}Rb, we adopt the D_2 line (780 nm) of ^{85}Rb which has more up-levels and smaller level intervals. We use a long vapour cell with length of 10 cm to increase the optical thickness, and control the vapour cell temperature to 80° C. Rubidium atoms in the vapour was excited by lasers and prepared with the EIT mechanism. The delay time of a probe light was measured to be in the order of μs, allowing a direct record with usual choppers and detectors.

Our experimental set-up is shown in Fig. 1, and schematic diagram of the energy levels of ^{85}Rb is shown in Fig. 2. Coupling light is taken from a Ti:sapphire laser (Coherent MBR-110). The diameter of the coupling beam is 3 mm, and laser intensity can be controlled via a neutral density attenuator. The probe beam is provided by an extended-cavity-stabilized diode laser (TOPTICA DL100), the laser beam is chopped by an acousto-optic modulator (AOM). We choose the first-order beam of the AOM as the probe light. A pinhole is used to limit the probe-beam diameter to 1 mm. Both the coupling and probe beams are linearly polarized, and their polarizations are perpendicular to each other. Laser frequencies are stabilized by using saturated absorption spectroscopy,[24] the linewidth of lasers are less than 1 MHz. The coupling and probe beams are combined via a polarizing beamsplitter, and then copropagated

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through a 10 cm long rubidium vapour cell. Two quarter-wave plates (QWP) are placed in front and behind the vapour cell respectively, the first QWP is used to produce the σ^--polarized coupling beam and the σ^+-polarized probe beam, the second one is used to regain the original linear polarizations of the coupling and probe beams before they are separated by the other PBS. An avalanche photodiode (C30902E) is used to detect the probe signals. A homemade temperature controller controls the temperature of the cell. We use a simple ferric sleeve covering around the cell as a magnetic shield. A weak beam taking from the probe laser bypasses the vapour cell and directly hits to another avalanche photodiode, the signal is used as a time reference. A digital oscilloscope (TDS210) views the waveforms of the probe and reference beams.

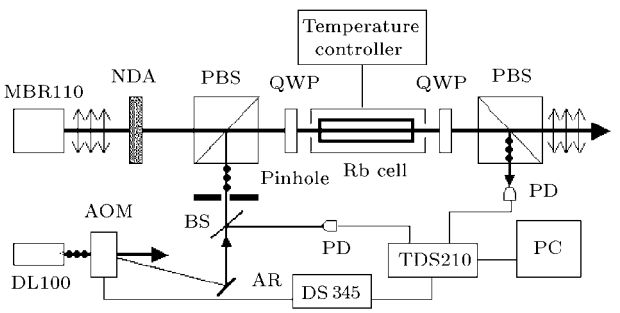

Fig. 1. Diagram of experimental set-up. QWP: quarter-wave plates; PBS: polarizing beamsplitter; NDA: neutral density attenuator; AR: all-reflection mirror; BS: beamsplitter; PD: avalanche photodiode; TDS210: digital oscilloscope; DS345: signal generator.

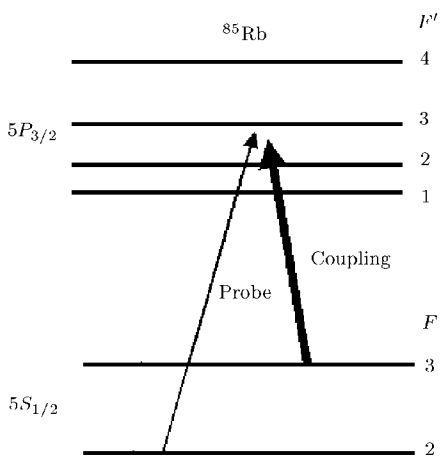

Fig. 2. Energy level configuration of ^{85}Rb for the electromagnetically induced transparency.

We tuned the coupling laser to near resonance with transition $5\,S_{1/2}\ F = 3 \rightarrow 5\,P_{3/2}F' = 3$ of ^{85}Rb D_2 line, and scanned the probe laser across the transition of $5\,S_{1/2}F = 2 \rightarrow 5\,P_{3/2}F'$. The Rabi frequency of probe laser Ω_p is less than 5 MHz, while the Rabi frequency Ω_C of the coupling laser varied from 30 MHz to 55 MHz. When the frequencies of coupling and probe beams satisfied the Raman resonance condition, the EIT phenomenon appeared. The temperature of sample cell was controlled to 80°C, and atomic number density is $2 \times 10^{12}\,\mathrm{cm}^{-3}$, a typical EIT spectrum is shown in Fig. 3. The transparency peak is obvious on the Doppler broadening absorption profile. The position and the shape of the EIT peak change with coupling detuning and intensity respectively. We noted that the absorption background of the EIT spectrum (curve (b)) is even deeper than that of non-EIT situation (curve (a)). This is attributed to the optical pumping effect by the coupling beam which pumps atoms on sublevel $5\,S_{1/2}$ $(F = 3)$ to sublevel $5\,S_{1/2}$ $(F = 2)$ and more atoms on the ground state contribute more absorption to the probe beam.

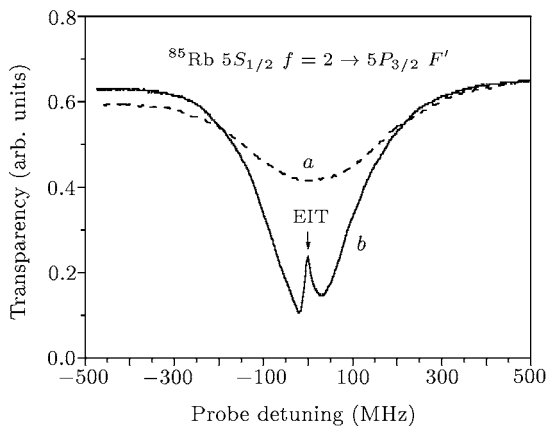

Fig. 3. Probe absorption spectra around the transition of ^{85}Rb: $5\,S_{1/2}\ F = 2 \rightarrow 5\,P_{3/2}F'$. Curve a is the Doppler broadening absorption profile of probe light; curve b is the electromagnetically induced transparency spectrum of probe light when a coupling field is applied to near resonance with transition of $5\,S_{1/2}F = 3 \rightarrow 5\,P_{3/2}F' = 3$. The background of absorption profile of curve b is lower than that of curve a due to the optical pumping effect.

In order to observe the propagation feature of the probe light, we fixed the probe laser frequency near the EIT peak, and applied a 1 kHz rectangular wave, which was from a function generator (DS345), to the AOM. The amplitude of the square driving waves was 2 V. We also fed this signal to the oscilloscope as a trigging input. The probe light was then chopped as a series of square wave. Due to the response feature of the AOM and the photodiodes, the front slope of the probe wave was not so steep and the rising time is 2 μs. This did not affect our experimental results seriously. Comparing the start front of the probe wave between the situation with coupling beam present and absent, we found that the probe wave was delayed obviously when we applied coupling beam to the cell (see Fig. 4). It is indicated that under the EIT condition, the group velocity of probe light was reduced. Due to the optical pumping affect (see Fig. 3), the amplitude of the probe wave decreases if coupling beam exists.

When we slightly tuned the probe frequency around the EIT peak, the delay time also changed. The time retardation occurred when we tuned the probe frequency near EIT peak, and the tolerable frequency detuning is about 50 MHz.

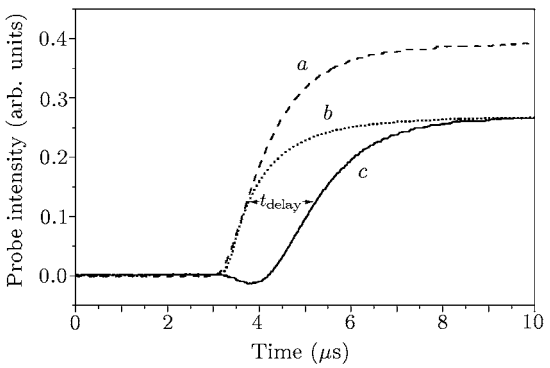

Fig. 4. The front parts of probe wave chopped by AOM. Curve a is the reference signals bypassing the vapour cell; curve b is the probe wave passing through the cell but with coupling laser off; curve c is the probe wave under the EIT condition with coupling laser on, the wave front in curve c is delayed and the amplitude is reduced compared with curve b.

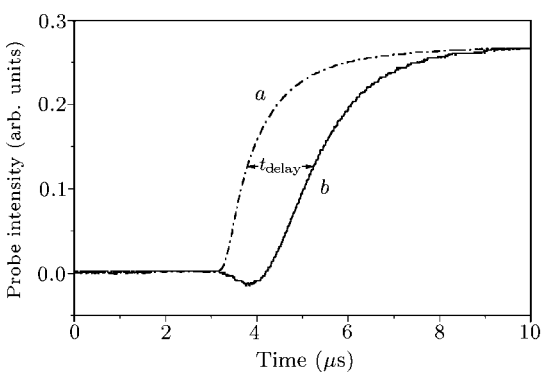

Fig. 5. Time delay measurement of the probe waves with the Rabi frequency of coupling beam of 36 MHz. Curve a is the probe wave under non-EIT condition; curve b is the probe wave under the EIT condition, its amplitude was normalized, and the delay time $t_{\rm delay}$ is 1.5 μs.

Another parameter, which affects the delay time of the probe wave, is the coupling intensity. The corelationship between group velocity v_g and Rabi frequency Ω_C of coupling beam reads[17]

$$v_g \approx \frac{\hbar c \varepsilon_0}{2\omega_P} \frac{|\Omega_C|^2}{|\mu|^2 N},$$

where μ is the electric dipole matrix element between states $5\,S_{1/2}$ $(F = 2)$ and $5\,P_{3/2}$ $(F = 3)$ of ^{85}Rb, N is the atomic density, and ε_0 is the permittivity of free space. We measured the delay time at different coupling intensities. The delay time is the time difference at half height point between the probe waves with coupling beam on and off (Fig. 5). The experimental data are listed in Table 1. It seems that the delay time is indeed inversely proportional to the power of the coupling laser. We obtained the maximum time delay of 1.8 μs when Ω_C was 34 MHz at the optimal probe detuning.

Table 1. Delay time at different coupling laser powers.

Rabi frequency of coupling beam (MHz)	53	44	36	34
Probe time delay (μs)	0.5	1.0	1.5	1.8

In summary, we have directly observed the light speed reduction phenomenon in a relatively simple and easy way, the probe light is delayed obviously when it passes through the coherently prepared rubidium medium in vapour cell. The value of time retardation depends on the coupling intensity; the weaker the coupling laser is, the longer the delay time we obtain. The maximum time delay we recorded was 1.8 ± 0.1 μs, meaning that the light speed was reduced down to 56000 m/s, about 1/5360 times of the light speed in vacuum. As to our present experimental condition, further work will be performed to prolong the coherence relaxation time, thus further to reduce light speed, such as filling some buffer gas into the rubidium cell or daubing paraffin to wall of the cell.

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