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Negative group velocity of a light pulse in cesium vapour

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Abstract. **Electromagnetically induced absorption in cesium vapour causes an extremely strong anomalous dispersion, leading to the propagation of radiation at a low negative group velocity V_g. As a result, a resonance light pulse appears from the medium before than a nonresonance pulse. The advance time measured in the experiment corresponds to the group velocity $V_g \approx -c/3600$, which is an order of magnitude lower than that reported by Wang L.J., et al. Nature, 406, 277 (2000).**

Keywords: *anomalous dispersion, negative group velocity of light, slow light, electromagnetically induced transparency.*

Experiments on the slowing down and stopping of light [1, 2] have attracted much attention, and stimulated interest in studies of the propagation of light in media with a strong dispersion. A wave packet propagates in an absorbing medium at the group velocity $V_g = c/(n + \nu dn/d\nu)$, where c is the speed of light in vacuum; n is the refractive index; and ν is the light frequency. For a strong normal dispersion ($dn/d\nu > 0$), the group velocity is several orders of magnitude smaller than the speed of light in vacuum, which was clearly demonstrated in [1]. In the case of an anomalous dispersion ($dn/d\nu < 0$), the group velocity can be larger than c. This does not contradict the special theory of relativity, which restricts only the propagation velocity of a signal by the speed of light in vacuum. Moreover, in the case of a sufficiently strong anomalous dispersion ($|\nu dn/d\nu| \gg n$), the group velocity V_g takes negative values. As a result, a resonance light pulse comes out of the medium before it enters it completely, thus 'being ahead' of a nonresonance pulse, which propagates at the velocity c. The advance time is given by $\Delta T = (L/c - L/V_g) > 0$, where L is the extension of the resonance medium. If $|V_g| \ll c$, then the advance ΔT can be readily determined even for $L \sim 1$ cm.

This phenomenon, which contradicts to our common view, was observed for the first time in a linearly absorbing medium [3]. Recently, the propagation of a light pulse at the velocity $V_g \approx -c/310$ was observed in cesium vapour due to an anomalous dispersion in the spectral region between two resonances of the Raman amplification [4].

In this paper, we study the propagation of a resonance light pulse at a negative group velocity in an atomic medium, where a strong anomalous dispersion was produced due to coherent electromagnetically induced absorption (EIA) [5, 6]. A strong anomalous dispersion is usually associated with a strongly absorbing optically dense medium. However, even comparatively small variations in absorption and, hence, in the refractive index within a very narrow spectral region result in an extremely strong anomalous dispersion [7]. Note that the limiting width of the EIA resonance is determined by the relaxation time of the sublevels of the ground state rather than of the excited state, which makes it a few orders of magnitude narrower than the width of Doppler-free resonances of saturated absorption.

The optical scheme of the experiment is shown in Fig. 1. Atomic cesium vapour in a sealed off glass cell of length 2 cm and diameter 1.4 cm was used as a resonance medium. The buffer gas pressure did not exceed 10^{-4} Torr. The concentration of cesium atoms was varied in the range $(0.2 - 7) \times 10^{11}$ cm^{-3} by changing the cell temperature. An ambient magnetic field was reduced with a magnetic shield by a factor of 500. A solenoid, inside which the cell was placed, produced a homogeneous longitudinal magnetic field in the medium.

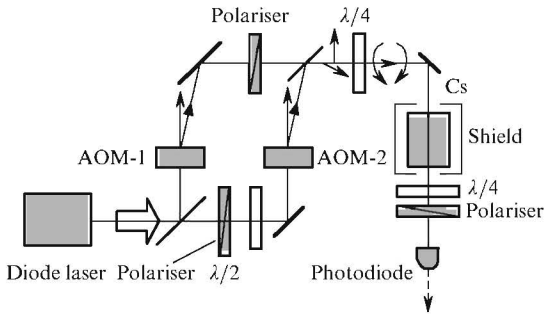

Figure 1. Optical scheme of the experiment.

A diode laser with an external resonator was used as a source of resonance radiation with a linewidth less than 1 MHz. The power of the collimated radiation of the laser tuned at the D_2 absorption line of cesium (825 nm) was 15 mW. The coherent superposition of magnetic sublevels, which results in an increase in absorption of resonance

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radiation and anomalous dispersion, was obtained due to two-photon transitions in a bichromatic field. Two mutually coherent components of bichromatic radiation (probe and control) with a variable frequency offset were prepared with the help of two acoustooptic modulators (AOMs), to which signals were fed from two radio-frequency generators with the tunable ($\nu_1 = 80 \pm 5$ MHz) and fixed ($\nu_2 = 80$ MHz) frequencies. Thus, the frequency offset $\delta\nu = \nu_1 - \nu_2$ could be varied within 10 MHz.

For the diameter of the cross section of the bichromatic beam of about 1 cm, the intensity of the control and probe components in the medium was 3.2 and 0.6 mW cm^{-2}, respectively. Opposite circular polarisations of the two components were produced with the help of polarisers and a quarter-wavelength plate. By applying a control signal to the corresponding acoustooptic modulator, Gaussian pulses were formed from continuous probe radiation. The intensity of the probe component propagating through the cell was detected with a fast photodiode and a digital oscilloscope, while the control component was rejected with a polariser.

The absorption of the probe component in cesium vapour when the laser was tuned to the maximum of the Doppler line at the $6S_{1/2}(F = 4) \rightarrow 6P_{3/2}$ ($F' = 3, 4, 5$) transitions in the absence of the control component was 60 %. In the presence of the control wave, the absorption of the probe wave increased up to 80 % because of the induced low-frequency coherence of magnetic sublevels, which was prepared due to two-photon Raman $\sigma^- \rightarrow \sigma^+$ transitions in the bichromatic wave (Fig. 2). The resonance of coherent absorption was observed at almost the zero frequency offset $\delta\nu$ in the case of degeneration of magnetic sublevels. The resonance full width at half-maximum was $\Delta\nu \approx 0.25$ MHz.

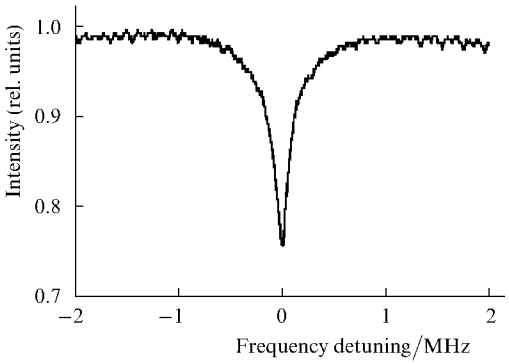

Figure 2. Intensity of the probe component propagated through a cell with Cs vapour in the presence of the control wave as a function of the frequency offset $\delta\nu$ while the laser frequency tuned to the $6S_{1/2}(F = 4) \rightarrow 6P_{3/2}(F' = 5)$ optical transition.

Note that because of the Doppler broadening of the line, radiation interacts with Cs atoms at three optical transitions. The projection V_i of the velocity in resonance velocity groups on the direction of the laser beam is determined by the detuning of the laser frequency ν from the frequency ν_i of the corresponding transition: $V_i = 2\pi(\nu_i - \nu)/k$. The contributions from coherent effects to the absorption of the probe wave in these groups are different. At the cycling $6S_{1/2}(F = 4) \rightarrow 6P_{3/2}(F' = 5)$ transition, the so-called bright coherent superposition of magnetic sublevels is produced, which is responsible for the enhancement of absorption and anomalous dispersion (the conditions for the observation of the EIA effect were formulated in [5]). At the open $6S_{1/2}(F = 4) \rightarrow 6P_{3/2}(F' = 3, 4)$ transitions, the non-absorbing coherence of magnetic sublevels is produced due to the effect of electromagnetically induced transparency [8], which reduces the absorption of the probe component. However, the optical pumping to the resonance $6S_{1/2}(F = 3)$ sublevel of the ground state substantially reduces the population of these resonance groups. Therefore, the contribution of the resonance group interacting at the cycling transition dominates, resulting in an increase in the integrated absorption.

The medium has a strong anomalous dispersion near the coherent absorption resonance ($dn/d\nu < 0$). It is in this spectral region that a substantial change in the group velocity of resonance light should be expected. The value of V_g was estimated from the delay of the nonresonance radiation pulse travelling at the velocity c relative to the probe resonance radiation pulse. In this case, the fixed frequency detuning $\delta\nu$ was smaller than the resonance width: $\delta\nu \ll \Delta\nu$. To minimise the distortion of a pulse propagating in a medium, its spectral width should be smaller than the width of the anomalous dispersion. This condition provides equal group velocities for all spectral components of the wave packet, thereby restricting the pulse duration from below. Therefore, the probe-pulse duration for the EIA resonance in Fig. 2 should be longer than $\Delta t \approx 1/(2\pi\Delta\nu) = 0.7$ μs.

Fig. 3 shows probe Gaussian pulses of duration 2.7 μs propagated through the Cs vapour cell in the presence of a continuous control field. When the laser was tuned to the maximum of the Doppler $6S_{1/2}(F = 4) \rightarrow 6P_{3/2}$ line, the pulse amplitude decreased and the pulse maximum shifted. Because the pulse shape was distorted only slightly even for relatively short pulses, it was well approximated by a Gaussian, thereby providing an accurate measurement of the position of its maximum. Due to a nonlinear interaction of the resonance radiation with Cs atoms, the pulse maximum was detected 0.240 ± 0.004 μs earlier than if it travelled over the same distance in vacuum. The advance time ΔT is almost 9 % of the pulse duration. The group velocity measured from ΔT, taking into account the medium length $L = 2$ cm, is $V_g \approx -c/3600$. Because $V_g \approx c \times (\nu dn/d\nu)^{-1}$, the anomalous dispersion of the medium caused by EIA is readily estimated as $dn/d\nu/(\nu V_g) \approx -1.02 \times 10^{-11}$ Hz^{-1}.

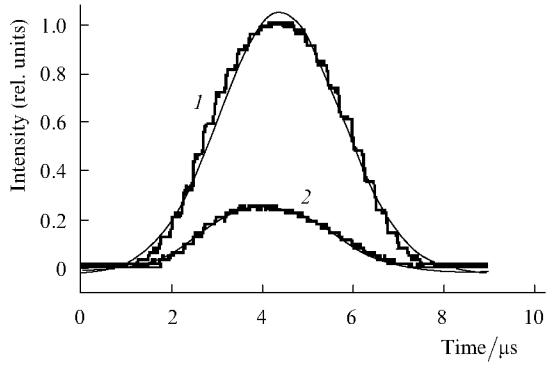

Figure 3. Intensities of probe pulses propagated through a cell with Cs vapour for resonance (*1*) and nonresonance (*2*) radiation obtained by averaging 64 pulses in a digital oscilloscope. Thin curves show calculated profiles. The positions of maxima of the calculated profiles for resonance and nonresonance radiation are 4.404 ± 0.003 μs and 4.165 ± 0.003μs.

The dispersion of the medium, as the group velocity, depends on many parameters. In particular, the anomalous dispersion $|dn/dv|$ increased, while the velocity V_g decreased in magnitude with increasing concentration of cesium atoms. However, this increase in the dispersion is obviously limited. The reduction of the EIA resonance width by increasing the time of interaction of atoms with radiation in a laser trap or in a cell with a buffer gas, which does not destroy the coherence of magnetic sublevels in the ground state, seems to be more promising for a further enhancement of the anomalous dispersion.

Note also that the value of the dispersion presented above is at least an order of magnitude greater than that reported in [4], where the anomalous dispersion of Cs vapour in a special cell with an antirelaxation coating of the walls and a buffer gas was obtained upon 60 % absorption, i.e., in fact due to electromagnetically induced transparency.

Note in conclusion that, despite an 'unnatural' character of the propagation of light at the negative group velocity, this phenomenon by no means contradicts the causality principle and follows from classical electrodynamics [9]. Media with a strong, readily controllable dispersion, which gives rise to great variations in the group velocity of light, are of interest for optical data processing and communication.

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