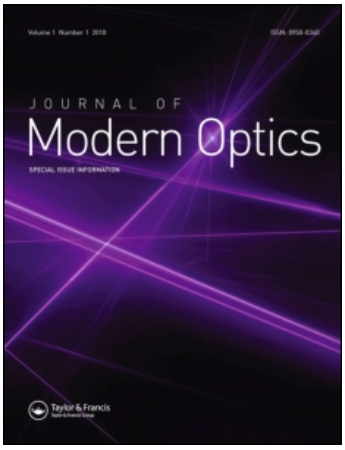

Journal of Modern Optics
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713191304

Group velocity study in hot ^{87}Rb vapour with buffer gas

Eugeniy E. Mikhailov[a]; Yuri V. Rostovtsev[a]; George R. Welch[a]
[a] Department of Physics, Texas A&M University, College Station, Texas, USA

To cite this Article Mikhailov, Eugeniy E. , Rostovtsev, Yuri V. and Welch, George R.(2003) 'Group velocity study in hot ^{87}Rb vapour with buffer gas', Journal of Modern Optics, 50: 15, 2645 — 2654
To link to this Article: DOI: 10.1080/09500340308233590
URL: http://dx.doi.org/10.1080/09500340308233590

JOURNAL OF MODERN OPTICS
2003, VOL. 50, NO. 15–17, 2645–2654

Taylor & Francis
Taylor & Francis Group

Group velocity study in hot ^{87}Rb vapour with buffer gas

EUGENIY E. MIKHAILOV, YURI V. ROSTOVTSEV
and GEORGE R. WELCH

Department of Physics, Texas A&M University,
College Station, Texas 77843-4242, USA

(*Received 20 February 2003; revision received 10 May 2003*)

Abstract. We study the behaviour of the group velocity of light under conditions of electromagnetically induced transparency (EIT) in a Doppler broadened medium. Specifically, we show how the group delay (or group velocity) of probe and generated Stokes fields depends on the one-photon detuning of drive and probe fields. We find that for atoms in a buffer gas the group velocity decreases with positive one-photon detuning of the drive fields, and increases when the fields are red detuned. This dependence is counter-intuitive to what would be expected if the one-photon detuning resulted in an interaction of the light with the resonant velocity subgroup.

1. Introduction

Electromagnetically induced transparency (EIT) has been the subject of numerous theoretical and experimental studies [1–8]. Materials displaying EIT have many interesting properties, such as narrow resonance width and steep dispersion resulting in ultra-low light group velocity [9–11]. These properties make EIT interesting for several practical applications, such as frequency standards [12], precision magnetometry [13], enhanced nonlinear optics [14–17] and quantum information storage [18–20].

The group velocity of light in media can be expressed as [21]

$$v_g = \frac{d\omega}{dk} = \frac{c - \omega[\partial n(\omega, k)/\partial k]}{n(\omega, k) + \omega[\partial n(\omega, k)/\partial \omega]} = \tilde{v}_g - v_s, \tag{1}$$

where c is the speed of light in vacuum, ω is the frequency of the field, n is the index of refraction in the medium, k is the vacuum wave number, and we have defined

$$\tilde{v}_g = \frac{c}{n(\omega, k) + \omega[\partial n(\omega, k)/\partial \omega]} \tag{2}$$

and

$$v_s = \frac{\omega[\partial n(\omega, k)/\partial k]}{n(\omega, k) + \omega[\partial n(\omega, k)/\partial \omega]}. \tag{3}$$

Here and below we use the convention that terms with a tilde (˜) denote values in the moving reference frame and terms with no tilde denote values in the laboratory frame.

Journal of Modern Optics ISSN 0950-0340 print/ISSN 1362-3044 online © 2003 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/0950034032000120777

The first term, $\tilde{v}_g$, is due to frequency dispersion and the second term, v_s, is due to spatial dispersion. Because of spatial dispersion, the group velocity is different for atoms with different speeds v_a. This is easily seen because in the moving frame $\tilde{\omega} = \omega - kv_a$ (we take v_a positive for an atom moving in the same direction as the light propagation), from which we see that $v_g = d\omega/dk = \tilde{v}_g + v_a$. This is just the Galilean transformation from the moving frame of the atoms to the laboratory frame. Thus, a mono-velocity atomic beam moving in the opposite direction from the light propagation direction slows the group velocity.

In a dense Doppler broadened medium, it is possible to obtain slower or even zero group velocity [21, 22] for the probe field in a Λ configuration of strong drive and weak probe fields when both are red detuned but maintain the two-photon resonance condition. The following conditions on the power of the drive field must be satisfied

$$\Omega \gg (\gamma\gamma_{cb})^{1/2}, \tag{4}$$

$$\Omega \ll k_d v_T \left(\frac{\gamma_{cb}}{\gamma}\right)^{1/2}, \tag{5}$$

where Ω is the Rabi frequency of the drive laser and k_d is its wave vector, v_T is the average thermal velocity, γ is the decay rate of the upper level and γ_{cb} is the decay rate of coherence between the lower (ground) levels.

Equation (4) is just the usual condition for EIT for individual atoms. Equation (5) is applicable only for the case where the drive field is weak enough that EIT occurs only for a narrow spread of atomic velocities. In this case, the intensity of the drive field is not large enough to pump all atomic velocity subgroups into the dark state. This means that the optical pumping rate $|\Omega|^2\gamma/\Delta^2$, for atoms having one-photon detuning Δ, is less than the relaxation rate γ_{bc}, between levels b and c. Therefore $|\Omega|^2\gamma/\Delta^2 < \gamma_{bc}$ implies that EIT does not occur for all moving atoms and the light interacts with a quasi atomic beam. When these conditions are satisfied, one can choose a velocity sub-group of atoms with a particular average velocity (in the direction of light propagation) and narrow velocity spread $\Delta v \approx (\Omega/k_d)(\gamma_{cb}/\gamma)^{1/2}$. This is accomplished by changing the one-photon detuning of the drive laser field while maintaining two-photon resonance. In this case, the centre of the quasi-beam of moving atoms is determined by the simple Doppler relation

$$v_a = c\frac{\Delta}{\omega_d}, \tag{6}$$

where ω_d is the drive laser frequency. Naturally we would expect atoms moving with the atomic quasi-beam to increase the group velocity, and atoms moving in the opposite direction to 'drag' light with them, or decrease the total group velocity.

The intuitive picture described above is quantified rigorously in [21]. In the present paper, we experimentally study these theoretical predictions by measuring the dependence of the group velocity on probe-field one-photon detuning for different experimental conditions.

A common method of increasing the dispersion in an EIT medium is to lengthen the ground-state coherence lifetime, thereby decreasing the linewidth of the EIT resonance. The coherence lifetime is often limited by the interaction time

of the atoms with the lasers. Common methods for increasing this lifetime are by introducing a buffer gas to confine the atoms [1, 3, 23, 24], using wall coatings in the cell so that coherence is preserved between successive interactions of the atoms and the lasers [25–30], and by cooling and trapping the atoms [31, 32].

We have found that for EIT conditions in a sample with buffer gas (with linewidth on the order of several kiloHertz and group velocity on the order of a few tens to hundreds of $m\,s^{-1}$) the probe field has a slower group velocity when it is blue detuned with respect to resonance and higher group velocity for red detuning. This result is opposite to the intuitive picture described above, and to that of Kocharovskaya *et al.* in [21].

2. Experiment

2.1. *Set-up*

A schematic of the experimental set-up is shown in figure 1. One external cavity diode laser (ECDL) is used as the source of a strong driving field and another as a weak probe. The drive and probe lasers are combined and pass through a cell containing isotopically enhanced ^{87}Rb vapour. The ^{87}Rb density is varied by changing the temperature of the cell. A three layer magnetic shield (MS) screens out the laboratory magnetic field.

The lasers are phase locked to each other with a frequency offset that is tunable about the ground level hyperfine splitting of ^{87}Rb (6835 MHz). The lasers are spatially mode-matched with a single-mode optical fibre. The drive laser is tuned to the $5S_{1/2}(F = 2) \rightarrow 5P_{1/2}(F' = 2)$ transition of ^{87}Rb and the probe laser is tuned to the $5S_{1/2}(F = 1) \rightarrow 5P_{1/2}(F' = 2)$ transition as shown in figure 2.

The configuration of drive and probe lasers shown in figure 2 is called a Λ configuration. In this case, the lasers optically pump all atoms in the desired velocity subgroup into a dark state superposition of the ground levels, giving rise to strong coherence between these lower levels. Scattering of the drive field on this coherence results in the generation of a fairly strong Stokes component (new field)

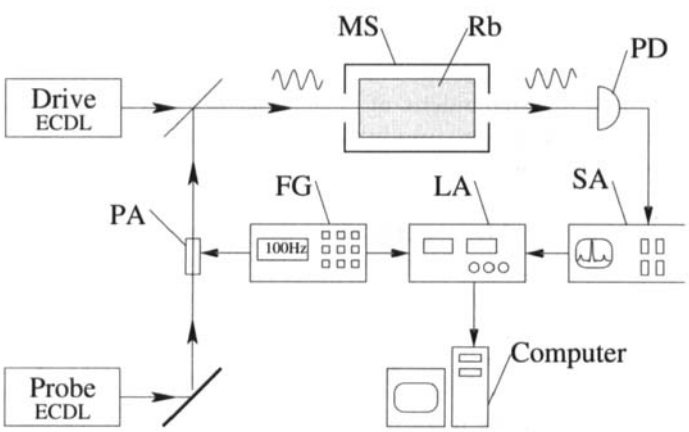

Figure 1. Schematic of the experimental set-up. MS is the magnetic shield, PD is the fast photodiode, PA is the power attenuator, FG is the frequency generator, LA is the lock-in amplifier and SA is the spectrum analyser.

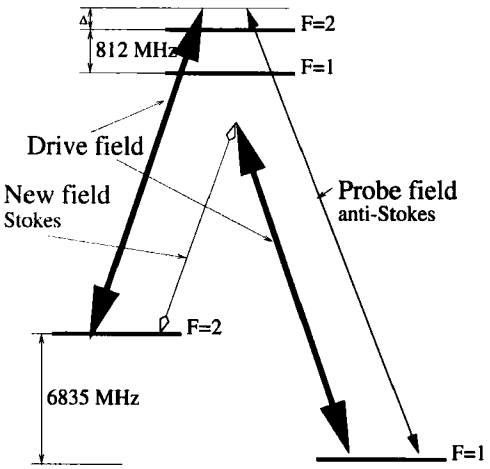

Figure 2. Relevant levels in ^{87}Rb.

in the medium (shown in figure 2). The generation of this new field near two-photon resonance of the drive and probe field is described in [4, 10, 36].

The transmitted drive and probe fields and the generated Stokes field are detected separately by heterodyne detection on a fast photodetector. This is done by splitting off part of the drive field from the main beam before entering the cell. This component is shifted up in frequency by a small amount (60 MHz), and combined with the beams exiting the cell before the photodetector. The photocurrent thus contains beat signals at various RF frequencies, separated by 60 MHz, in the vicinity of the 6835 MHz separation of the drive and probe. By separately analysing these components with a spectrum analyser (SA), we extract the transmitted probe and generated new fields independently. This technique is described in [10, 33].

2.2. *Time delay and group velocity measurement procedure*

We extract the group velocity in the medium by modulating the intensity of the probe field before the cell and observing the time delay before this modulation is observed in the transmitted field. Experiments have been conducted with Gaussian-shaped (temporal) pulses and with sinusoidal modulation. We find that the delay time is independent of the probe field modulation technique as long as the bandwidth of the modulation does not exceed the transmission linewidth of the EIT resonance.

The modulation is generated by use of a frequency generator (FG) which drives an acousto-optical (AO) modulator in the probe laser. The deflected beam from the AO is blocked, so the AO serves as a probe power attenuator (PA in figure 1). We also measure the time delay of the generated new field.

With a sinusoidal modulation of the probe, lock-in detection of the transmitted probe field provides a sensitive measure of the time delay due to the medium. When using lock-in detection in this way, we obtain the time delay from the phase shift of the transmitted probe field intensity relative to the probe intensity before the cell. For a sine wave of frequency f, this phase shift is given by

$$\psi = 2\pi\tau_d f - \psi_0, \tag{7}$$

where τ_d is the time delay introduced by the atoms and ψ_0 is a phase shift introduced by electronics. To eliminate the unknown ψ_0 we measure the phase shift for several different modulation frequencies. The phase shift increases linearly with frequency f and the slope of this line is $2\pi\tau_d$. We extract τ_d with a least-squares fit. We then find the group velocity v_g by setting $v_g = L/\tau_d$, where L is the length of the cell. ($L \approx 1$ cm for our experiment.)

Another experimental technique to simplify the group velocity measurement is to replace the second laser and phase-lock circuitry with an electro-optic modulator (EOM) in the drive laser beam. By applying a narrow tunable microwave signal to the EOM, upper and lower sidebands are generated at the microwave frequency, which we choose to match the 6.835 GHz ground state hyperfine splitting. We tune the laser to the drive transition, so that the upper sideband drives the probe transition and the lower sideband is off-resonance. We choose the microwave amplitude to generate a sideband with power that is 1/10 of the drive power. A careful comparison of the two methods (two phased locked lasers versus one modulated laser) shows no difference in the group velocity measurements. We note that a similar technique is to modulate the laser current, which directly creates sidebands on the laser, has also been successfully employed [34].

We measure the dependence of v_g on one-photon laser detuning $\Delta = \omega_d - \omega_{22}$, where ω_d is the frequency of the drive laser and ω_{22} is the frequency of the $F = 2 \rightarrow F' = 2$ transition. During each such measurement, the frequency difference of the probe and drive lasers is kept constant and equal to ground level splitting (6.835 GHz). The drive laser power is 300 μW and probe power is 3 μW. These measurements may then be repeated for different ^{87}Rb densities (different temperatures of the cell).

2.3. *Experimental results*

We first consider the case where no buffer gas is used, and the ground-state coherence lifetime is limited by the free-flight transit time of the thermal rubidium atoms through the laser beam. In our experiment, the EIT transmission linewidth is 30 kHz and the resulting group velocity on the order of 10 km s^{-1}. Figure 3 shows the dependence of the group velocity as a function of the drive laser frequency in the vicinity of the drive resonance. The group velocity is too large to observe the spatial dispersion effect described in section 1. Another way to see this is to note that the group velocity is much higher than the mean thermal speed of the atoms. In figure 3 the drive detuning spans the full range of the upper-state hyperfine splitting, and the small feature on the left of the spectrum is the result of generating EIT on the upper $F' = 1$ level (see figure 2).

Next we narrow the transmission linewidth with a buffer gas. This increases the dispersion considerably, resulting in reduced group velocity. Figure 4 shows the group velocity as a function of drive laser detuning for similar conditions as figure 3 but with the addition of 3 torr of N_2 buffer gas. The EIT transmission linewidth is only a few kiloHertz and we see that the group velocity has fallen to below 100 m s^{-1}. We also see that increasing the laser beam diameter increases the dispersion and reduces the group velocity as expected.

Figure 5 shows how the group velocity depends on drive laser detuning for increasing atomic density. We observe a lowering of the group velocity for higher density, but in no case do we observe a lowering of the group velocity as the drive laser is detuned red of resonance, which we would expect based on the prediction

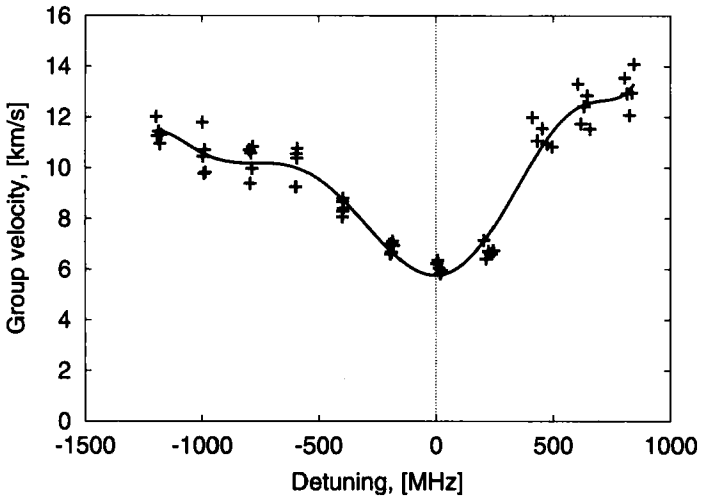

Figure 3. Group velocity versus detuning of ^{87}Rb atoms for the probe field in a cell with no buffer gas. Cell length $L = 47.5$ mm and the density is 3.6×10^{11} cm^{-3}. Drive power input to the cell is 1310 μW and transmitted drive power is 741 μW. Data points are shown by a +. The solid curve is a seventh-order polynomial fit to the data points and is shown only as a guide for the eye.

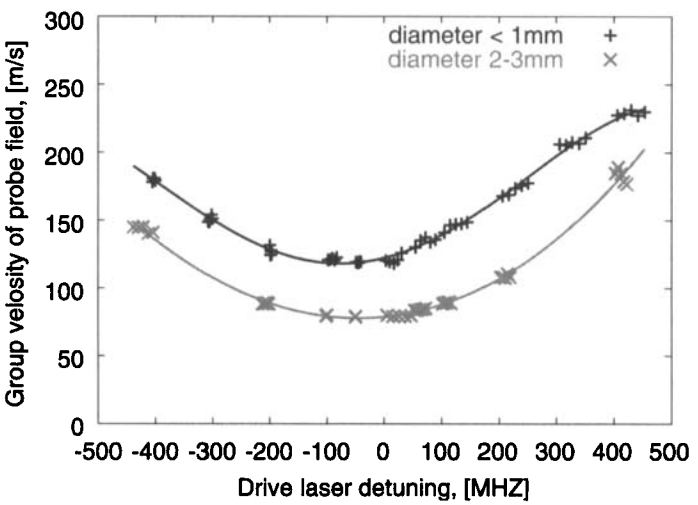

Figure 4. Probe field group velocity versus drive laser one-photon detuning in a cell with 3 torr of N_2 buffer gas. Cell length $L = 10$ mm and the density is 8.7×10^{11} cm^{-3}. The two curves are for beam diameters of 1 and 3 mm, respectively.

of dragging slow light by atoms moving opposite to the laser propagation direction [21]. Conversely, we see the group velocity increase for negative drive laser detuning and a minimum group for one-photon detuning about 100 MHz blue of one-photon resonance (see figure 5).

The explanation of this effect is still not clear, but it is plausible that this counter-intuitive behaviour is caused by velocity changing collisions in the presence of the buffer gas. We note that when the beam diameter decreases, the group

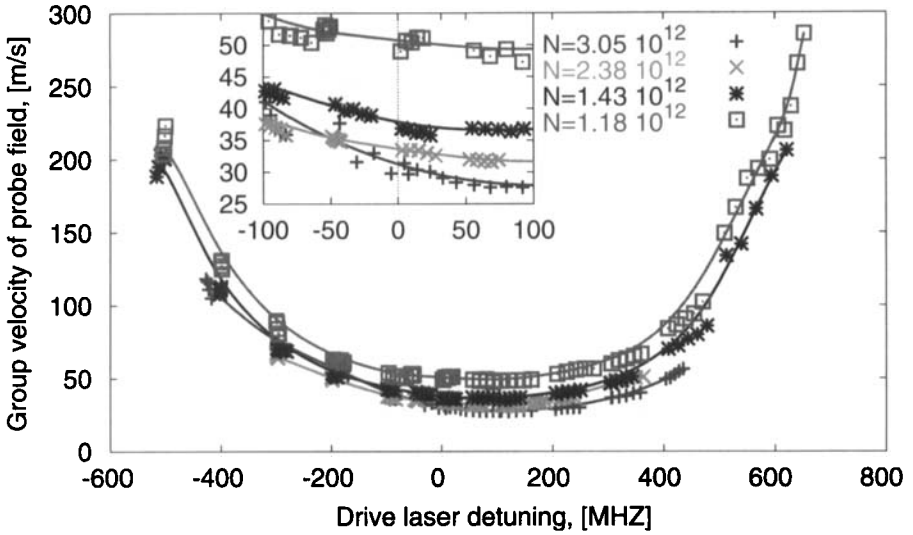

Figure 5. Probe field group velocity versus drive laser one-photon detuning, for the same cell as in figure 4. Drive power is 300 μW and probe power 3 μW. Curves are shown for different atomic density, measured in cm^{-3}. Inset: blow-up of the data in the vicinity of resonance, showing an increase to the red and decrease to the blue of resonance.

velocity dependence versus one-photon detuning becomes more shifted to the side of negative detuning (see figure 4). In other words, the behaviour becomes less counter-intuitive. We explain this by noting that for a very narrow beam, fewer velocity changing collisions take place before the atom leaves the laser beam. In any case, it is clear that the discussion of [21] about a quasi mono-velocity beam is not applicable in the case with a buffer gas, since all velocity groups are mixed by velocity changing collisions.

When the density of ^{87}Rb atoms is increased ($\approx 10^{12}\,cm^{-3}$) a highly nonlinear interaction of the drive and probe fields leads to very efficient generation of a Stokes component, or new field [4, 10]. We can measure the intensity of the generated field as a function of two-photon detuning and find the width to be greater than the transmission width of the EIT resonance of the probe field. (Under the conditions in our experiment it is roughly a factor of two wider [33].) Correspondingly, we also measure the time delay between modulation of the probe field before the cell and the resulting modulation of the new field after the cell. For the rubidium cell with buffer gas, this delay time is smaller than for the probe field, meaning that the group velocity of the new field (v_n) is greater than the group velocity of the probe field (v_p). This is no great surprise since the new field is propagating far from one-photon resonance.

As discussed above, as the rubidium density is increased the probe field group velocity decreases. Similar behaviour occurs for the generated new field for low density. However, for large atomic density the group velocity for the new field starts to increase with density. These results are shown in figure 6. This dependence is connected with a propagation effect. The effective generation of new field occurs in the part of the cell where the group velocity is small. As the light propagates through the cell, the drive field intensity decreases until the new field is

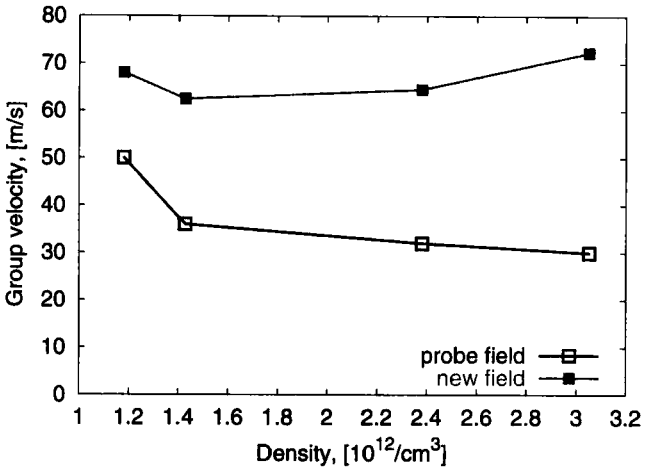

Figure 6. Group velocity versus density of ^{87}Rb atoms for probe and new fields, for the same cell as in figure 4. Drive power is 300 μW and probe power is 3 μW.

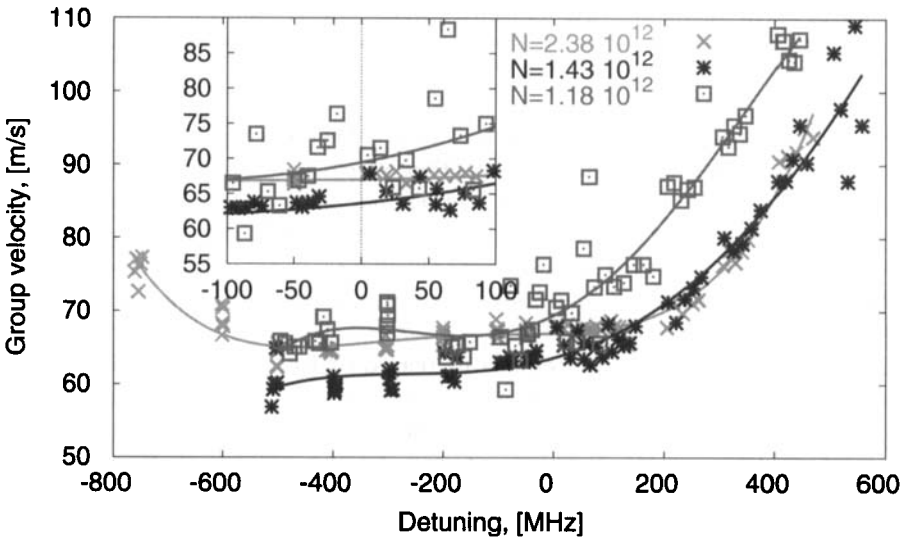

Figure 7. New field group velocity versus drive laser one-photon detuning, for the same cell as in figure 4. Drive power is 300 μW and probe power 3 μW. Curves are shown for different atomic density, measured in cm^{-3}. Inset: blow-up of the data in the vicinity of resonance, showing an increase to the red and decrease to the blue of resonance.

decoupled from the probe. After this point, the new field propagates at nearly the vacuum speed of light. Thus the observed average speed of new field increases with atomic density.

We can also measure the new-field group velocity as a function of drive laser detuning. The results are shown in figure 7. We find that the the group velocity is smaller for negative one-photon detuning than for positive detuning in the vicinity of resonance. This behaviour follows the intuitive predictions of [21].

3. Summary

We observe counter-intuitive dependence of the probe field group velocity versus drive field one-photon detuning for different densities (temperatures) of ^{87}Rb (see figure 5). The group velocity decreases slightly for blue-detuned drive fields and increases slightly for red-detuned fields. We conclude that the predictions of [21] cannot be applied to the case where the EIT linewidth is reduced with a buffer gas, since all velocities are constantly mixing via velocity changing collisions. Unfortunately, without a buffer gas we cannot achieve narrow enough EIT resonances to reach the amount of dispersion needed to get group velocities low enough to observe the effect of dragging the light by atoms.

We find that the group velocity is higher for the generated Stokes field, and that the behaviour as a function of detuning is opposite that of the probe field.

Acknowledgment

We thank A. B. Matsko, I. Novikova, V. Sautenkov and M. O. Scully for useful and stimulating discussions. This work was supported by the Office of Naval Research.

References

[1] BRANDT, S., NAGEL, A., WYNANDS, R., and MESCHEDE, D., 1997, *Phys. Rev.* A, **56,** R1063.
[2] VANIER, J., GODONE, A., and LEVI, F., 1998, *Phys. Rev. A*, **58,** 2345.
[3] ERHARD, M., and HELM, H., 2001, *Phys. Rev.* A, **63,** 043813.
[4] LUKIN, M. D., FLEISCHHAUER, M., ZIBROV, A. S., ROBINSON, H. G., VELICHANSKY, V. L., HOLLBERG, L., and SCULLY, M. O., 1997, *Phys. Rev. Lett.*, **79,** 2959.
[5] AKULSHIN, A. M., BARREIRO, S., and LEZAMA, A., 1998, *Phys. Rev.* A, **57,** 2996.
[6] AKULSHIN, A. M., CELIKOV, A. A., and VELICHANSKY, V. L., 1991, *Opt. Commun.*, **84,** 139.
[7] JAVAN, A., KOCHAROVSKAYA, O., LEE, H., and SCULLY, M. O., 2002, *Phys. Rev.* A, **66,** 013805.
[8] TAICHENACHEV, A. V., TUMAIKIN, A. M., and YUDIN, V. I., 2000, *JETP Lett.*, **72,** 119.
[9] HAU, L. V., HARRIS, S. E., DUTTON, Z., and BEHROOZI, C. H., 1999, *Nature*, **397,** 594.
[10] KASH, M. M., SAUTENKOV, V. A., ZIBROV, A. S., HOLLBERG, L., WELCH, G. R., LUKIN, M. D., ROSTOVTSEV, Y., FRY, E. S., and SCULLY, M. O., 1999, *Phys. Rev. Lett.*, **82,** 5229.
[11] BUDKER, D., KIMBALL, D. F., ROCHESTER, S. M., and YASHCHUK, V. V., 1999, *Phys. Rev. Lett.*, **83,** 1767.
[12] KNAPPE, S., WYNANDS, R., KITCHING, J., ROBINSON, H. G., and HOLLBERG, L., 2001, *J. Opt. Soc. Am.* B *Opt. Phys.*, **18,** 1545.
[13] NOVIKOVA, I., MATSKO, A. B., and WELCH, G. R., 2001, *Opt. Lett.*, **26,** 1016.
[14] HAKUTA, K., MARMET, L., and STOICHEFF, B. P., 1991, *Phys. Rev. Lett.*, **66,** 596.
[15] HEMMER, P. R., KATZ, D. P., DONOGHUE, J., CRONINGOLOMB, M., SHAHRIAR, M. S., and KUMAR, P., 1995, *Opt. Lett.*, **20,** 982.
[16] JAIN, M., XIA, H., YIN, G. Y., MERRIAM, A. J., and HARRIS, S. E., 1996, *Phys. Rev. Lett.*, **77,** 4326.
[17] ZIBROV, A. S., LUKIN, M. D., and SCULLY, M. O., 1999, *Phys. Rev. Lett.*, **83,** 4049.
[18] PHILLIPS, D. F., FLEISCHHAUER, A., MAIR, A., and WALSWORTH, R. L., 2001, *Phys. Rev. Lett.*, **86,** 783.
[19] LIU, C., DUTTON, Z., BEHROOZI, C. H., and HAU, L. V., 2001, *Nature*, **409,** 490.

[20] ZIBROV, A. S., MATSKO, A. B., KOCHAROVSKAYA, O., ROSTOVTSEV, Y. V., WELCH, G. R., and SCULLY, M. O., 2002, *Phys. Rev. Lett.*, **88,** 103601.
[21] KOCHAROVSKAYA, O., ROSTOVTSEV, Y., and SCULLY, M. O., 2001, *Phys. Rev. Lett.*, **86,** 628.
[22] ROSTOVTSEV, Y. V., KOCHAROVSKAYA, O., and SCULLY, M. O., 2002, *J. Mod. Optics*, **49,** 2637.
[23] WYNANDS, R., and NAGEL, A., 1998, *Appl. Phys.* B, **68,** 1.
[24] ERHARD, M., NUSSMANN, S., and HELM, H., 2000, *Phys. Rev.* A, **62,** 061802(**R**).
[25] KANORSKY, S. I., WEIS, A., and SKALLA, J., 1995, *Appl. Phys.* B, **60,** S165.
[26] BUDKER, D., YASHCHUK, V., and ZOLOTOREV, M., 1998, *Phys. Rev. Lett.*, **81,** 5788.
[27] BUDKER, D., ORLANDO, D. J., and YASHCHUK, V., 1999b, *Am. J. Phys.*, **67,** 584.
[28] ROBINSON, H. G., ENSBERG, E. S., and DEHMELT, H. G., 1958, *Bull. Am. Phys. Soc.*, **3,** 9.
[29] BOUCHIAT, M. A., and BROSSEL, J., 1966, *Phys. Rev.*, **147,** 41.
[30] ALEXANDROV, E. B., BALABAS, M. V., BUDKER, D., ENGLISH, D. S., KIMBALL, D. F., LI, C. H., and YASHCHUK, V., 2002, *Phys. Rev. Lett.*, **66,** 042903.
[31] LIPSICH, A., BARREIRU, S., VALENTE, P., and LEZAMA, A., 2001, *Opt. Commun.*, **190,** 185.
[32] CHEN, H. X., DURRANT, A. V., MARANGOS, J. P., and VACCARO, J. A., 1998, *Phys. Rev.* A, **58,** 1545.
[33] MIKHAILOV, E. E., ROSTOVTSEV, Y., and WELCH, G. R., 2002, *J. Mod. Optics*, **49,** 2535.
[34] AFFOLDERBACH, C., NAGEL, A., KNAPPE, S., JUNG, S., WIEDENMANN, D., and WYNANDS, R., 1999, *Appl. Phys.* B, **70,** 407.