Light-Drag Enhancement by a Highly Dispersive Rubidium Vapor

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(Received 14 October 2015; published 6 January 2016)

The change in the speed of light as it propagates through a moving material has been a subject of study for almost two centuries. This phenomenon, known as the Fresnel light-drag effect, is quite small and usually requires a large interaction path length and/or a large velocity of the moving medium to be observed. Here, we show experimentally that the observed drag effect can be enhanced by over 2 orders of magnitude when the light beam propagates through a moving slow-light medium. Our results are in good agreement with the theoretical prediction, which indicates that, in the limit of large group indices, the strength of the light-drag effect is proportional to the group index of the moving medium.

DOI: 10.1103/PhysRevLett.116.013601

The phenomenon of light dragging by a moving host medium has been known for many years. It was first predicted by Fresnel [1] on the basis of an elastic aether theory and was observed experimentally by Fizeau [2]. This effect, sometimes called Fresnel drag, can be explained by the special theory of relativity. Fresnel's theory ignores the effect of dispersion of the refractive index of the medium. The influence of dispersion on the light-drag effect was first predicted by Lorentz [3]. Zeeman and his collaborators performed a series of experiments over a period of more than 10 years [4–10] to measure the drag effect accurately. They observed the predicted contribution of dispersion on the light-drag effect by moving a 1.2-m-long glass rod at speed 10 m/s. However, in normal materials with low dispersive properties, the effect of dispersion is so small that the magnitude of this contribution can be disputed [11]. In the intervening years the Fresnel drag effect has been investigated many times for different purposes, for instance, for improving the measurement's accuracy [12,13], differentiating it from competing effects such as the Sagnac effect [14,15], dragging massive particles such as neutrons [16], and proposing dielectric analogs of gravitational effects [17].

Highly dispersive materials, including alkali atomic vapors, can enable the propagation of light pulses with extremely small group velocities [18–20]. This phenomenon, known as the slow-light effect, has received much attention in the past two decades [21]. Special relativity implies that the group velocity of light changes as one moves the slow-light material through which light propagates. This effect can be used to control the group velocity of laser pulses in a slow-light medium [22,23]. It has also been shown theoretically that the light-drag effect can be significantly enhanced using a slow-light material [24,25]. Moreover, a recent experiment demonstrated that spinning a slow-light material enhances the image rotation induced by rotary photon drag effect [26].

In this Letter we investigate the change in phase velocity of a light beam propagating through a slow-light material that results from moving the material along the direction of propagation. In our experiment, the slow-light material is a hot rubidium (Rb) vapor. We show experimentally that the dispersive contribution to the drag effect (which is usually considered to be a correction term for low-dispersion materials) is the dominant contribution in our case. Our results indicate an enhancement of the drag effect proportional to the group index of the medium, which in our case is $n_g \approx 330$.

As light enters a nondispersive medium with refractive index n, its phase velocity with respect to the reference frame attached to the medium changes to c/n. If the medium moves at speed v, light is dragged in the direction of motion. In effect, the phase velocity of light with respect to the stationary laboratory frame is given by the relativistic addition of the two velocities v and c/n [27],

$$u = \frac{c/n \pm v}{1 + v/nc} \simeq \frac{c}{n} \pm v\left(1 - \frac{1}{n^2}\right), \tag{1}$$

where n is the refractive index of the moving medium. Throughout this Letter, we follow the convention that the upper and lower signs correspond to the medium moving along the direction of propagation and opposite to it, respectively. The approximation in Eq. (1) is valid for $v \ll c$. Equation (1) also assumes that the medium moves parallel to the light beam.

In a dispersive medium, the formula above has to be modified. Because of the Doppler effect, the frequency of the light ν as measured in the laboratory frame becomes $\nu' \simeq \nu(1 \mp v/c)$ as measured in the frame of the moving medium. Then, to first order in v/c, the refractive index for the moving medium is found to be

$$n(\nu') \simeq n(\nu) \mp \nu \frac{dn}{d\nu}\frac{v}{c}, \qquad (2)$$

where $n(\nu)$ is the refractive index measured when the medium is at rest. By substituting $n(\nu')$ from Eq. (2) into Eq. (1), and keeping terms to first order in v/c, one obtains for the phase velocity in the moving medium

$$\begin{aligned} u &\simeq \frac{c}{n(\nu)} \pm v\left(1 - \frac{1}{n(\nu)^2} + \frac{n_g - n(\nu)}{n(\nu)^2}\right) \\ &\equiv \frac{c}{n(\nu)} \pm \Delta u. \end{aligned} \qquad (3)$$

Here n_g is the group index defined as $n_g = n(\nu) + \nu dn/d\nu$. It follows that the phase shift induced by moving the medium with velocity v is given by

$$\Delta\phi \simeq \frac{2\pi v L n^2}{\lambda c}\left(\frac{1}{n} - \frac{1}{n^2} + \frac{n_g - n}{n^2}\right), \qquad (4)$$

where $\lambda = c/\nu$ is the wavelength of light in vacuum, L is the length of the medium, and $n = n(\nu)$ for brevity. Laub [28] derived this formula for a medium with moving boundaries such as a glass rod. However, the first treatment of the light-drag effect including the dispersion of the medium was due to Lorentz [3]. Following Fizeau's experiment, where water flows inside a fixed glass tube, Lorentz derived a slightly different expression for the dragged velocity for fixed boundaries.

Slow-light materials, such as Rb atomic vapor, are known to have large group indices. Thus, Eq. (3) indicates a large enhancement in the light-drag effect, as compared to Eq. (1), for a highly dispersive medium. In the experiment reported below, n is nearly equal to unity. Therefore, $\Delta u \simeq \pm n_g v$; in addition, the difference between Laub and Lorentz's formulas is negligible.

In our experiment, the moving medium is a glass cell of length $L = 7.5$ cm filled with natural Rb. No buffer gas was added to the cell. Natural Rb consists of ^{85}Rb and ^{87}Rb with abundances 72% and 28%, respectively. Rb atoms represent a resonant atomic system and show large group indices near resonance [29].

Heating the Rb cell increases the number density of the atomic vapor, which enables us to achieve large group indices. Figure 1 shows the transmission spectrum around the D_2 line of natural Rb measured at two different temperatures. A tunable continuous wave (cw) diode laser (Toptica DL Pro) with wavelength near 780.2 nm (the Rb D_2 transition line) is used. The laser operates with power 4.2 mW.

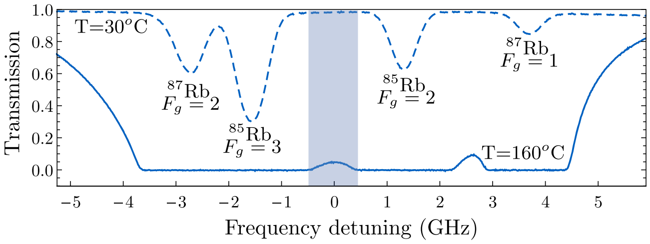

FIG. 1. Transmission spectra of natural Rb near the D_2 transition measured at two different temperatures. Zero detuning is set to the center of the left transmission peak observed at 160 °C. The label beneath each spectral feature gives the isotope and ground-state hyperfine level responsible for that feature [30]. The shaded area shows the region where the experiment is performed (see Fig. 3).

To observe the phase shift induced by the light-drag effect, we use a ring interferometer (also known as a Sagnac interferometer) with the Rb cell moving within one arm as shown in Fig. 2. The two clockwise and counterclockwise beams have the same power with orthogonal polarizations. Thus, they interfere only after the second polarizer. Since the two counterpropagating beams overlap, any phase shift induced by jitter or other noise is applied to both beams and does not influence the interference pattern that reveals the phase shift due to drag. The Rb cell is enclosed in an aluminum box with two glass windows with antireflection coating. To reduce heat dissipation and air turbulence around the box, the box is thermally insulated with a layer of cork sheet. A heating wire wrapped around the cell and a thermocouple attached to the cell control the temperature of the cell with an accuracy of ±1 °C. The aluminum box is mounted on a motor-controlled linear slider that moves right and left at maximum speed of $v = 1$ m/s. A charge-coupled device (CCD) camera is triggered to capture an image of the fringe pattern when the cell is moving at maximum speed. We measure the displacement of the

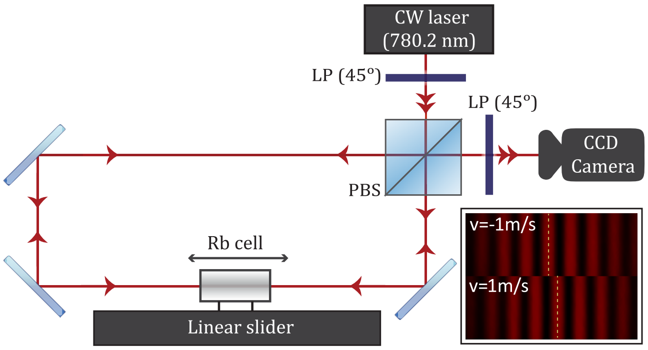

FIG. 2. Ring interferometer used to measure the phase shift induced by light drag. LP is a linear polarizer and PBS is a polarizing beam splitter. The laser is operated at the Rb D_2 transition line, around zero frequency detuning shown in Fig. 1. The inset shows a sample fringe pattern with the maximum fringe displacement observed at 160 °C. The upper and lower fringes are the fringe patterns as the cell moves to the left and right, respectively.

TABLE I. The observed phase shift in the light-drag experiment at the output of the interferometer, $4 \times \Delta\phi$, and the change in phase velocity, Δu, at different temperatures. The third column is the result of the drag experiment, and the last column shows the value expected from Eq. (3) using the values of n_g measured with the setup in Fig. 4.

Temperature (°C)	$4 \times \Delta\phi$ (Rad)	Δu (Drag) (m/s)	Δu (Expected) (m/s)
130	0.60 ± 0.06	75 ± 7.2	81 ± 1.2
135	0.75 ± 0.06	93 ± 8.0	98 ± 1.2
140	1.01 ± 0.07	125 ± 9.1	126 ± 1.4
145	1.25 ± 0.07	155 ± 9.0	166 ± 1.5
150	1.67 ± 0.08	207 ± 10	208 ± 2.0
155	1.99 ± 0.07	247 ± 9.0	252 ± 2.3
160	2.58 ± 0.08	320 ± 9.4	331 ± 2.5

interference fringes. For accurate measurement we misalign the interferometer by only a small amount to image a few fringe lines onto the camera. To increase accuracy, the fringes are recorded and averaged over 50 cycles. The main source of error is air turbulence around the Rb cell. The phase difference between the two beams at the output of the interferometer, induced by the drag effect, is given in Table I. The laser operates at −0.49 GHz frequency detuning (see Fig. 1), and the effect of dragging is measured at seven different temperatures from 130 °C to 160 °C at intervals of 5 °C. Thermal equilibrium was reached between the readings. Uncertainties in Table I are the standard error of the mean of 50 different trials for each temperature.

The displacement of the fringe patterns normalized to the distance between the fringes at the output of the interferometer is given by $\Delta Z = 4 \times \Delta\phi / 2\pi$, where $\Delta\phi$ is given in Eq. (4). The factor of 4 comes from the fact that there are two counterpropagating beams going through the cell and we compare the left moving fringes with the right moving ones. The change in phase velocity due to light drag, Δu, is given in the third column of Table I. It is obtained from Eq. (3) with the help of Eq. (4) and the fact that the refractive index of Rb vapor $n(\nu)$ is equal to unity to good approximation [29]. Figure 3(a) plots the change in phase velocity Δu as a function of temperature.

To confirm that the observed effect is in fact the consequence of dispersion and comes from the group index in Eq. (3), we measured the group index directly for the same wavelength and temperatures. The experimental setup for this measurement is shown in Fig. 4. An electro-optic modulator (EOM) fed by a signal generator is used to produce pulses of 10-ns duration. The group velocity of the laser pulses inside the stationary Rb cell is given by c/n_g. The group delay experienced by the laser pulses is measured by an oscilloscope. The group indices thus obtained are used in Eq. (3) to calculate the expected change in phase velocity. The results are shown in the last column of Table I and in Fig. 3 with blue hollow circles. The uncertainty is determined by repeating the measurements several times and taking the standard error of the mean. It can be seen that the observed drag effect is in very good agreement with the prediction of theory.

For further confirmation of the understanding of the light-drag effect we also measured the light drag as a function of the frequency detuning at a Rb temperature of 160 °C. The measurement is performed in the spectral region shown with the shaded area in Fig. 1. The results are shown in Fig. 3(b), along with the expected effect of the group index.

At high optical powers one might expect to see the effects of optical pumping and saturation [31]. However, in the temperature range used in this Letter, we did not see any appreciable change in the transmission spectrum when we increased the power from a few microwatts to a few milliwatts. Since the laser frequency is about 1 GHz away from resonances, only the small fraction of atoms that are Doppler shifted into resonance are saturated. Optical hyperfine pumping reduces the absorption by transferring atoms from one hyperfine ground level to another level.

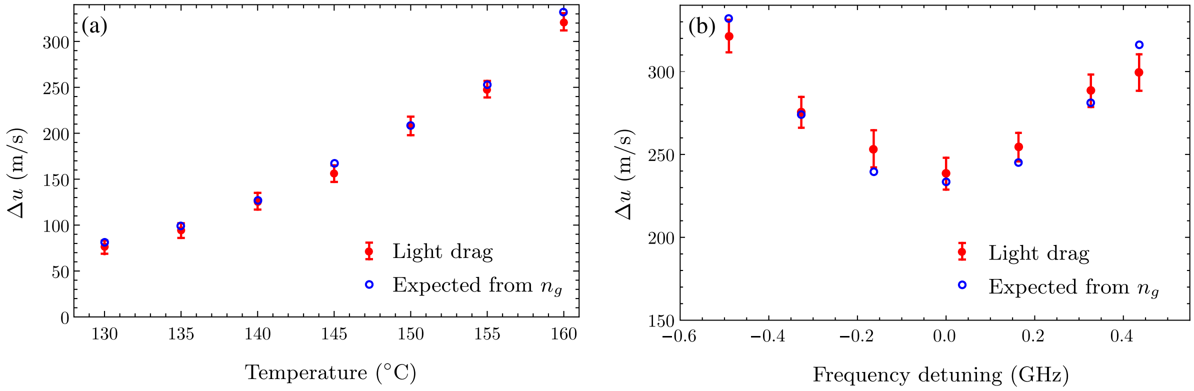

FIG. 3. Change in phase velocity due to light drag, Δu, as a function of (a) temperature and (b) frequency detuning at a Rb temperature of 160 °C. The contribution of dispersion $n_g v$ is shown with blue hollow circles. In (a) the laser is operated at −0.49 GHz frequency detuning (see Fig. 1).

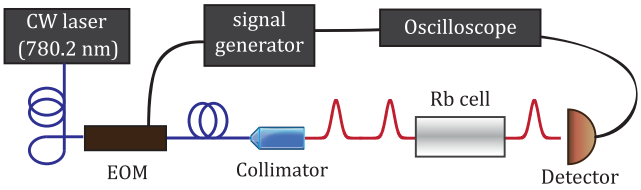

FIG. 4. Experimental setup to measure the group index of the Rb vapor. An electro-optic modulator (EOM) is used to generate laser pulses of 10-ns width, and the time delay is measured by an oscilloscope.

Nevertheless, at high temperatures, atom-atom collisions quickly redistribute population among the hyperfine ground levels. Thus, the effect of optical pumping is diminished by the short relaxation time at high temperatures.

The refractive index of the Rb gas inside the cell is very close to unity ($n \simeq 1$). Thus, the nondispersive contribution to the light-drag effect is due only to the four glass windows fixed to the Rb cell assembly, which have a combined thickness of 2 cm. According to Eq. (4), the contribution of the moving windows in the observed phase shift is about 0.001 rad, which is much smaller than the uncertainty of $\Delta\phi$ in Table I. Therefore, the observed drag effect is due primarily to the dispersion of the Rb vapor. We verified this conclusion by performing additional measurements far from the atomic resonances (where $n_g \approx 1$), and noting that no net displacement of the fringe pattern is detected as the cell was moved (data not shown).

In typical materials with low dispersive properties, the contribution of dispersion in light drag is almost negligible. Zeeman and his colleagues [9] used a 1.2-m-long glass cylinder moving at speed 10 m/s. They observed the phase shift $\Delta\phi = 0.38$ rad, out of which 0.04 rad was the contribution of dispersion.

In a nondispersive medium, Eq. (1) implies that the speed of light cannot be changed by more than the translational speed of the medium. However, one sees from Eq. (3) that by using a highly dispersive medium, one can exceed this limit. In our experiment, the speed of light is changed by $n_g \times v \simeq 330$ m/s, where v is 1 m/s, indicating an enhancement of more than 2 orders of magnitude as compared to dragging light with a low-dispersive medium. The enhancement observed in this Letter is in fact a manifestation of the Doppler shift and can also be called the enhanced Doppler effect. Therefore, a highly dispersive medium moving in an interferometer provides a sensitive method to detect linear motions.

With the technique of electromagnetically induced transparency (EIT), group indices as large as 10^7 are achievable [18]. Therefore, one can enhance the observed effect by an even larger factor, which could enable accurate detection of extremely slow speeds [24]. Note, however, that for very large group indices one has to keep higher-order corrections in Eq. (3), which cause the effect to saturate for large speeds.

In summary, we investigated the change in phase velocity of light propagating through a moving slow-light medium. We moved a warm Rb cell at speed 1 m/s and observed a maximum change of 330 m/s in the phase velocity of light. The enhancement observed in the Fresnel light-drag effect is proportional to the group index of the moving medium. This enhancement is due to the large group index of a Rb vapor and can be understood by means of the Doppler effect. By using techniques such as EIT, one can achieve very large group indices. Then, this immensely enhanced effect could be employed to increase the sensitivity of devices that work based on the Doppler effect.

The authors would like to thank Peter Milonni for useful discussions. A. S., I. D. L., and R. W. B. acknowledge the support of the Canada Excellence Research Chairs program, and M. M., O. S. M. L., and R. W. B. acknowledge the support of the U.S. Defense Threat Reduction Agency.

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