"Aether Drag" and Moving Images

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We contrast the two situations in which either a light beam is incident on a moving medium or a moving optical image is incident on a stationary medium. The principle of relativity suggests that the effects on the light of propagating through the medium should be similar. We find, however, that there are subtle differences which we can understand in terms of the relative alignment of the Poynting and wave vectors. Our analysis and experiments investigate both translational motion and rotation.

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For many purposes, it suffices to describe the propagation of light in terms of a simple (scalar) refractive index. There are more subtle effects, however, in which the full vector nature of the field and its governing Maxwell equations has to be incorporated. In each of these, the key fact is that the wave vector and Poynting's vector need not be parallel [1]. Important examples include the influences of magnetic [2,3] and gravitational fields [4,5], each of which can result in transverse displacement of a light ray and, of course, the birefringence and optical activity encountered in crystal optics [1]. Common to all these phenomena is the influence of a magnetic field, irrespective of whether the field has been applied externally or appears as a consequence of transformation between motional frames [6].

To this list, we can add the behavior of light in moving media and the celebrated aether drag of Fresnel [7], whereby the motion of the medium drags the light with it. This effect was demonstrated in the 1970s by Jones [8,9] who showed that a light beam normally incident on a transversely moving medium was laterally displaced by a small amount, Δx_J, given by

$$\Delta x_J = \frac{v_m}{c} L(n_g - n_\phi^{-1}). \tag{1}$$

Here, v_m is the transverse velocity of the medium, c is the speed of light, L is the thickness of the medium, n_g is the group refractive index, and n_ϕ is the phase refractive index. By using a highly dispersive glass, Jones was able to confirm the identification of the group and phase indices, confirming the concurrent theoretical analyses of Player and Rogers [10,11].

In a separate, but similar, set of experiments, Jones showed that when transmitted along the axis of rotation, the linear polarization state was rotated through a small angle $\Delta\theta_p$ [12],

$$\Delta\theta_p = \frac{\Omega_m}{c} L(n_g - n_\phi^{-1}) \tag{2}$$

where Ω_m is the angular velocity of the medium. These experiments were again supported by a theoretical analysis by Player [13], and the phenomenon has since been referred to as the mechanical Faraday effect [14]. This is, indeed, an example of the magnetic field associated with a moving medium [6].

We have recently reasoned that, in addition to rotating the polarization state, the spinning medium should also rotate the transmitted image through the same angle [15] and that this is a manifestation of the equivalence of spin and orbital angular momentum [16]. That analysis treated the rotation of an image as simply a collection of rays each of which was displaced in accordance to Eq. (1); this obtained the equivalent of Eq. (2), but for images,

$$\Delta\theta_i = \frac{\Omega_m}{c} L(n_g - n_\phi^{-1}). \tag{3}$$

Subsequently, in an approach similar to [13], we used a modified wave equation to predict the phase acquired by beams carrying orbital angular momentum on propagation through a spinning medium [17]. It is useful to consider two Laguerre-Gaussian modes which have a helical phase structure [18] with opposite handedness, that interfere to produce a "petal" intensity pattern [19]. On transmission through a rotating medium, the acquired phase change between the beams results in a rotation of the petal interference pattern through the angle predicted by Eq. (3) [20]. As the Laguerre-Gaussian modes form a complete basis set, any arbitrary image can be formed by an appropriately weighted superposition of these modes, and this rotation extends to arbitrary images.

The beautifully engineered experiments of Jones were already at the limit of their precision; an extension to measurement of image shifts and rotations is likely to run into additional problems associated with stress induced lensing in the moving media. A possible alternative to translating or rotating the medium is to translate, or rotate the light, keeping the medium stationary. While the transverse velocity of the disc in Jones's experiment was only a few 10 s of ms^{-1}, it is possible to produce a translating interference pattern or translating image many orders of magnitude faster than this.

As Maxwell's equations are invariant under transformation to a uniformly moving frame, one might expect the behavior in the two cases of the translating light and the translating medium to be equivalent. However, as the equations are not invariant to transformation to a rotating frame, the rotational case could be more complicated.

We create a lateral movement of straight line interference fringes by interfering two intersecting plane waves at an angle $\pm\alpha$ with a nominal wavelength λ_0. For small angles of intersection, the fringe period, Λ, is

$$\Lambda = \frac{\lambda_0}{2\alpha}. \tag{4}$$

If the two waves have a frequency difference $\delta\omega$, then the fringe pattern translates with a velocity

$$v_f = \frac{\delta\omega\lambda_0}{2\alpha}. \tag{5}$$

We generate the frequency shifts between the two beams using acousto optic modulators, which use an RF drive to create a moving grating within a crystal, such that the first order diffracted beam is frequency shifted. Typically operating at 100 MHz, such modulators can be tuned over 10 s of MHz; hence, two modulators driven at slightly different frequencies can produce beams with a relative frequency shift ranging from 0 to 10 s of MHz, which for a fringe spacing of a few millimeters corresponds to a maximum translational velocity of 10 s of kms^{-1}. As tuning the modulator also produces a slight angular shift of the beam, we operate them in a double-pass configuration, thus doubling the frequency shift and eliminating the angular shift, see Fig. 1.

A moving image requires a reference against which to measure its position. In our experiments, we use a Wollaston prism to duplicate the image; one image then passes through the glass medium and the other through free space. The medium is a quartz glass bar (Herasil 102, Spanoptic), 40 mm in diameter and 200 mm in length with a refractive index of 1.46. The relative displacement of the two images is measured from a single frame acquired from a time-gated, image-intensified CCD (iStar, Andor), with an effective shutter speed of around 10 ns. To ensure that the image is sufficiently bright, we use a 2-W, 532 nm laser as the optical source (Opus, Laser Quantum).

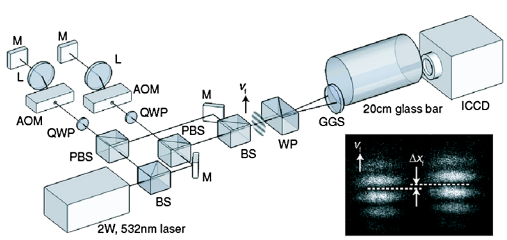

FIG. 1 (color online). Experimental configuration for producing a rapidly translating fringe pattern based on the inference between two frequency shifted plane waves. The inset shows the two interference patterns that are captured by the camera, one passing through the glass, the other through free space. BS, beam splitter; PBS, polarizing beam splitter; QWP, quarter wave plate; AOM, acousto-optic modulator; L, lens, M, mirror; WP, Wollaston prism; GGS, ground glass screen; ICCD, intensified camera.

Figure 2 shows the measured results for the case where the interference pattern is directly incident on the CCD. We find the measured displacement of the fringes is given by

$$\Delta x_f = \frac{v_f}{c} L(n-1) \tag{6}$$

where n is the refractive index (in our case, the glass is effectively non dispersive so the group index and the phase index are the same). It might have been expected that this would be identical to Δx_{J} given in Eq. (1). The obtained displacement Δx_f is readily identified, however, as that due to the difference in the transit time from source to CCD between the image passing through the glass with that through free space.

As a fringe pattern is delocalized in space, it perhaps should not be considered in the same way as one would an object or image. We overcome this concern by the insertion of a ground glass screen into the optical path prior to the medium so that the fringe patterns were localized, forming two adjacent, spatially incoherent images after the Wollaston prism. Both of these were then explicitly reimaged onto the plane of the CCD. We find that inserting the ground glass screen to localize the fringes and imaging them onto the camera does not change the observed results. In both cases, the interpretation of the shift as that associated with the temporal delay of the light transmitted through the medium suggests that the refractive index is that of the group velocity.

The discrepancy between our results and the work of Jones is intriguing. For each configuration, either moving medium (Jones's experiment) or moving image (our experiment), the analysis of the phenomenon is explainable in either the rest frame of the medium or the frame in which the medium is moving, see Fig. 3. In the Jones experiment, the frame in which the medium is moving is the lab frame; both the Poynting vector, **S**, and wave vector, **k**, associated

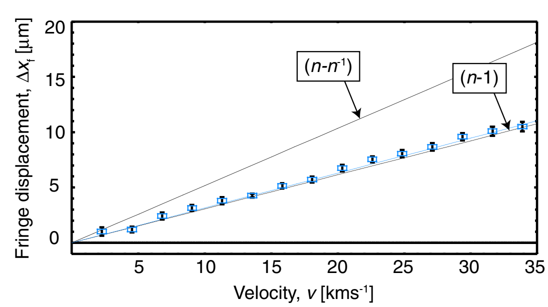

FIG. 2 (color online). The measured displacement of the nonlocalized interference fringes, after transmission through the medium, as a function of their translational velocity.

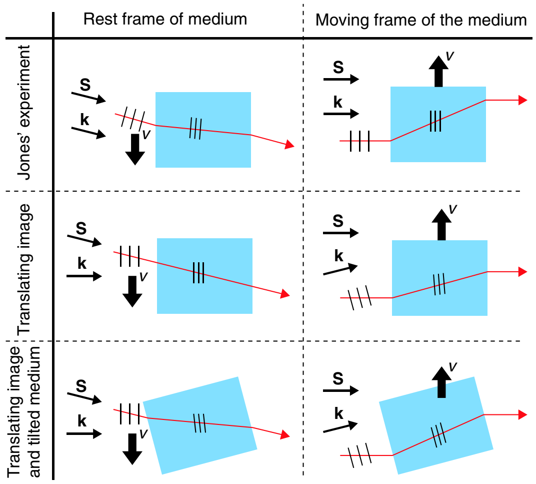

FIG. 3 (color online). The transverse photon drag phenomenon interpreted for the rest frame of the medium and the frame in which the medium is moving. The Poynting vector, **S**, is indicated by the arrow passing through the medium, and the wave vector, **k**, is normal to the parallel lines.

with the light are normally incident on the medium. The transverse displacement is due to aether drag. After transforming to the rest frame of the medium, the Poynting and wave vector of the light remain parallel but now have an incident angle on the medium given by $\beta = v/c$. In this frame of reference, the drag effect can be understood as the sum of two terms,

$$\Delta x_J = \Delta x_{\text{delay}} + \Delta x_{\text{refrac}}, \tag{7}$$

one associated with the optical delay as the light passes through the glass, Δx_{delay}, and one associated with refraction, Δx_{refrac} [10].

Our moving image experiment is an example in which the Poynting and wave vectors are no longer parallel [21]. In the rest frame of the medium (laboratory frame), the Poynting vector is incident at an angle β, but the wave vector is normally incident. It follows, therefore, that there is no refraction. The total shift, Δx_i, is only that of the optical delay,

$$\Delta x_i = \Delta x_f = \Delta x_{\text{delay}}. \tag{8}$$

In the frame in which the medium is moving, it is the wave vector that is incident at β, and the resulting refraction opposes the shift induced by the moving medium, leaving only a shift corresponding to the optical delay,

$$\Delta x_f = \Delta x_i = \Delta x_J - \Delta x_{\text{refrac}} = \Delta x_{\text{delay}}. \tag{9}$$

Consequently, to reproduce a shift of the magnitude of Jones for a moving image, it is necessary to tilt the stationary medium by the angle, β, such that the wave vector of the light strikes the surface at normal incidence.

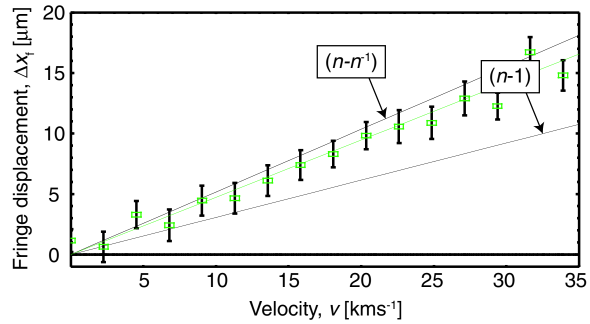

FIG. 4 (color online). The measured displacement of the nonlocalized interference fringes as a function of their translational velocity, where the angle of the medium is adjusted to account for the relativistic distortion.

This refractive term caused by the tilting of the glass bar can be introduced experimentally by mounting the end of the glass bar on a piezo actuated translation stage, controlled to set the relative angle of the bar to $\beta = v/c$. When we do this, we find that, as anticipated, the displacement of the moving image is increased, see Fig. 4, to a value scaling with $(n - n^{-1})$, equivalent to the Jones result.

Although we have established a self consistent interpretation for the two cases with respect to the translation of the medium or light, there remains a question over the rotational experiment. We created a translating image by the interference of two, frequency shifted, angled plane waves. In the same way, a rotating image can be created by interfering two frequency shifted helically phased beams [19]. As already discussed, the interference of helically phased beams results in a petal pattern. If the beams have a difference in frequency, $\delta\omega$, the pattern spins with an angular velocity $\Omega = \delta\omega/2l$. Figure 5 shows the measured rotational shift, which as with the linear case, scales with $(n - 1)$. Extension of the experiment to compensate the refractive term is not so straightforward; the adaptation would have to have a helical structure added to the end of the glass rod.

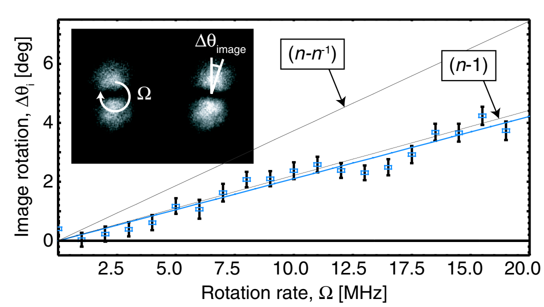

FIG. 5 (color online). The measured rotational shift of the petal interference pattern after transmission through the glass medium.

We have established that the phenomenon of aether drag can be analyzed in a consistent manner in either the rest frame of the medium or the frame in which the medium is moving. For both linear and rotary drag, in a moving medium, the shift of the transmitted image scales with $(n - n^{-1})$. However, for stationary media, the shift scales only with $(n - 1)$. This apparent dichotomy is resolved by consideration of the alignment of the Poynting and wave vectors of the incident light. The results relating to the rotational shift of a spinning image confirm that rotary drag is simply transverse drag acting at a radius vector, with the relevant velocity being the product of the radius and the angular rotation frequency. This result confirms that the action of a spinning medium on the rotation of a transmitted image is the same as for the polarization state, which may be understood as a further manifestation of the equivalence of spin and orbital angular momentum.

The work of Jones highlighted the different roles played by the phase and group indices in the phenomenon of aether drag. Today, it is possible to realize exotic optical media with values for these quantities that differ over many orders of magnitude, and the phase index can also take negative values [22]. The propagation of light through moving media of this form presents a rich variety of exotic phenomena [23–26]. Our work suggests that these phenomena, or at least analogous effects, might more readily be accessed by utilizing stationary media and rotating images.

The study of light in moving media may make a useful contribution to the famous Abraham-Minkowski dilemma, concerning the correct form of optical momentum in a dielectric [27]. The motion of the medium changes the constitutive relationships between the fields, **E**, **B**, **D**, and **H** [28], and introduces a concomitant birefringence and optical activity. It also modifies the momentum density so that, in particular, the quantities $\mathbf{D} \times \mathbf{B}$ and $\mathbf{E} \times \mathbf{H}/c^2$ (associated, respectively, with the Minkowski and Abraham momenta) are not only different in magnitude but also in direction. It is possible that this difference in direction might help us to investigate this long established problem.

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