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Wave Propagation in Moving Chiral Media: The Fizeau Experiment Revisited

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ABSTRACT

The Fizeau experiment is discussed as a concrete example for investigating wave propagation in isotropic chiral media. Exact special relativistic formalism is used throughout, first order approximations are developed from the exact forms. To measure the velocity effects from the interference fringes one has to adequately modify the construction of the original Fizeau experiment. A relativistically exact model for first order in velocity was developed giving a relatively simple formalism and enabling an easy solution to propagation and scattering of electromagnetic waves in the presence of moving chiral media.

1. INTRODUCTION

The expression for the speed of light first determined in transparent moving media wned by Fresnel [1] and experimentally verified by Fizeau's experiment. The effect of media's velocity was measured by means of an interferometric method. In Fizeau's experiment moving fluid (water) was contained within stationary boundaries, therefore no Doppler frequency shifts occur to an observer in the laboratory frame of reference (Γ) where these boundaries are at rest. Consequently only phase shifts are measurable [1, 2]. On the other hand, from the point of view of an observer in the comoving frame of reference where the fluid is at rest (Γ'), a transformation from Γ to Γ' yields Doppler shifted frequency and wavelength. This in turn affects the propagation in terms of the dispersive properties of the medium in question. Fizeau's experiment and different explanations of its result including the dispersion properties of the moving media were carefully retested and reviewed by others [2, 3]. Recently research of wave propagation in chiral media became a prominent subject of interest [4, 5]. As far as the present authors are aware, Engheta et al. [6] were the first and only ones who linked electromagnetic theory and wave propagation in moving chiral media solving the problem of reflection of plane wave from a plane chiral interface uniformly moving at a constant velocity.

The statement of the Fizeau's experiment as a propagation and scattering problem is not simple even for the case of simple media: it involved moving media in stationary pipes, hence in the regions where the flow is injected and drained, the simple model of a uniform flow is inadequate. In order to reconcile this difficulty, a model has been proposed before [7], whereby the simplicity of the uniform flow is preserved, at the expense of violating the flow field continuity at the boundaries. This approach yields the correct Fresnel type formulas for the phases and also facilitates the discussion of reflection and refraction of waves at boundaries. This model is adopted for the present analysis as well. In any case, as far as these authors are aware, the analysis of a Fizeau-type experiment involving chiral media has not be attempted to date.

This is the subject of this paper, using the Fizeau experiment setup as a concrete example for investigating wave propagation in non-simple moving media. Exact special relativistic formalism is used throughout and first order approximations are developed from the exact forms. Using the simple configuration depicted in Fig. 1 we consider a linearly polarized plane wave, originating in a simple medium, say air, normally incident onto two slab regions containing chiral media moving with same speed in the opposite direction. Still considering the point of view of an observer in Γ, within each such slab region the incident wave splits into two- one right handed and the other left handed- circularly polarized plane waves. The two waves posses different wavelengths but retain the original frequency of the incident wave, because for the laboratory observer only boundaries at rest are involved. For these four circularly polarized waves the amplitudes are differently effected by the motion of the fluid. As a result, the waves emerging out of each slab region are rotated in respect to the incident wave. The result is therefore more complicated and requires deeper scrutiny.

2. FIZEAU'S EXPERIMENT

In Fig. 1 light incident from the left is split into two beams propagating through transparent pipes containing a uniformly moving chiral fluid. The emerging beams are redirected towards a screen or an eyepiece, where the ensuing interference fringes can be observed. The goal of the experiment is to inspect the drag effect produced by the motion of the fluid as manifested by the shifted interference fringes in the observer's field of vision. This effect is caused by the phase changes incurred by the beams propagating through the moving medium. It should be emphasized that the glass pipes are fixed in place and therefore no Doppler frequency shift occurs to an observer in Γ. Inasmuch as the fluid has to enter and leave the tubes, there are regions, usually at the edges of the pipes, where the uniformity of the flow cannot be maintained. For the ease of the theoretical analysis we neglect the behavior of the fluid near the edges and assume a time constant and uniform flow. Restricting the discussion to the upper pipe we first discuss a model of wave scattering from a slab region containing a moving chiral medium, bounded by two fixed parallel plane boundaries. The medium surrounding the pipes is characterized by ε_0, μ_0 and the glass envelope is considered infinitely thin and therefore does not feature in our analysis. The chiral medium is excited by a plane wave $\mathbf{E}_i = \hat{\mathbf{x}}E_0 e^{ik_o z - i\omega t}$ all parameters are considered in Γ. Since the boundaries are fixed, boundary conditions are applied in Γ. It follows that for an observer in Γ all waves, inside and outside chiral media, oscillate with the same frequency ω of the incident wave. In order to simplify the analysis we first consider a first order multiple reflection approximation, namely the internal reflections are ignored. This simplifies the analytical work involved, still highlighting the effects of moving media on the propagating waves. The same effects are apparent in the exact solution given below, which for chiral media at rest agree with the results derived by other methods [4] The wave equation for the chiral media at rest in Γ' is

$$\nabla'^2 \mathbf{E}' + k'^2 \mathbf{E}' + 2\omega' \mu\xi \nabla' \times \mathbf{E}' = 0 \tag{1}$$

where ξ is called the chirality factor. μ and ε have their usual meaning of electric permitivity and magnetic permeability respectively. Eq. 1 is satisfied by two plane waves of opposite circular polarization propagating in the positive z direction

$$\mathbf{E}'^{+}_{\substack{cw\\ccw}} = \mathbf{E}'^{+}_{\substack{cw0\\ccw0}} (\hat{\mathbf{x}} \pm i\hat{\mathbf{y}}) e^{ih'^{+}_{\substack{cw\\ccw}} z' - i\omega'^{+}_{\substack{cw\\ccw}} t'} \tag{2}$$

$\mathbf{E}'^{+}_{cw0}$ and $\mathbf{E}'^{+}_{ccw0}$ are the constant amplitudes. Superscripts +, - indicate propagation in the positive, negative z direction, while the subscripts cw, ccw stand for clockwise and counterclockwise circular polarization (assuming an observer looking in the direction of propagation) respectively. It should be noticed again that in Γ, $\omega = \omega^{+}_{cw} = \omega^{+}_{ccw}$. It is interesting to note that an observer comoving in the chiral medium measures now two circularly polarized waves possessing different frequencies $\omega^{+}_{cw}{}'$, $\omega^{+}_{ccw}{}'$ and two corresponding propagation vectors $\mathbf{h}'^{+}_{cw}$, $\mathbf{h}'^{+}_{ccw}$ respectively. In terms of an observer in Γ, the electric field in the upper tube is

$$\mathbf{E}^{+} = (\hat{\mathbf{x}} + i\hat{\mathbf{y}}) E^{+}_{cw0} e^{ih^{+}_{cw} z - i\omega t} + (\hat{\mathbf{x}} - i\hat{\mathbf{y}}) E^{+}_{ccw0} e^{ih^{+}_{ccw} z - i\omega t} \tag{3}$$

The relations between the propagation vector and frequency in Γ are given by:

$$h^{+}_{\substack{cw\\ccw}} = \frac{1 + vC_{\substack{cw\\ccw}} / c^2}{C_{\substack{cw\\ccw}} + v} \omega \tag{4}$$

and $C_{\substack{cw\\ccw}}$ are the phase velocities of the cw, ccw waves respectively. Using a successive multiple reflection model, the boundary conditions at z=0 determine the waves propagating in the positive z direction within the chiral medium. Those waves serve as excitation for the boundary at z=d. A general elliptical polarization is assumed for all waves involving the boundary equations. It is interesting to note that elliptical polarization for a reflected wave when the incident wave is linearly polarized can occur in isotropic media too. this effect exist for lossy media [8]. Relying on the basic properties of the chiral media, a cw polarized wave within the chiral medium is generated by a cw incident wave. while the proper reflected wave is ccw polarized. A similar argument applies to a ccw incident wave. Representing the linearly polarized incident wave as a sum of two oppositely rotating circularly polarized waves having the same amplitude enables us to exploit the principle of superposition, i.e., the solution is derived for the waves which rotate in the same sense. Solving the boundary equations at the boundary z=0 and then at z=d yields the complex amplitudes of the transmitted wave:

$$E_t = E_{to}\left(\hat{\mathbf{x}} \cos\left(\frac{h^{+}_{cw} - h^{+}_{ccw}}{2} d \right) + \hat{\mathbf{y}} \sin\left(\frac{h^{+}_{cw} - h^{+}_{ccw}}{2} d \right) \right) e^{ik_o(z-d) - i\omega t} \tag{5}$$

where

$$E_{to} = \frac{2\eta_o Z E_0}{(\eta_o + Z)^2} \tag{6}$$

The transmitted wave is linearly polarized but rotated in the x-y plane by an angle ψ

$$\psi = \frac{h^{+}_{cw} - h^{+}_{ccw}}{2} d = \frac{\omega d}{2} \frac{\left(\frac{1}{C_{cw}} - \frac{1}{C_{ccw}} \right)\left(1 - \frac{v^2}{c^2} \right)}{\left(1 + \frac{v}{C_{cw}} \right)\left(1 + \frac{v}{C_{ccw}} \right)} \tag{7}$$

which for low velocities becomes

$$\psi \approx \frac{\omega d}{2} \left(\frac{1}{C_{cw}} - \frac{1}{C_{ccw}} \right)\left(1 - \left(\frac{1}{C_{cw}} + \frac{1}{C_{ccw}} \right) v \right) \tag{8}$$

In addition to the constant term in ψ (i.e. the effect caused by the optical activity of chiral medium at rest) there is a change in the rotation angle due to velocity effects. In the lower tube this velocity effect is obtained by replacing v with -v.

The expressions for the emerging waves are used to analyze Fizeau's experiment with moving chiral media. Eq. 5 is used directly to obtain the results for the upper tube. For the lower tube Eq. 5 applies for the appropriate parameters, including the opposite sign for the velocity. Denoting waves at the lower tube by an upper bar sign, the amplitudes of the emerging cw and ccw waves, expressed in terms of the waves at the upper tube are given by

$$\overline{E}_{\substack{cw\\ccw}} = E_{to} \exp[-i(h^{-}_{\substack{cw\\ccw}} + k_o)d] \quad (9)$$

Clearly, interference patterns cannot be created by circularly polarized waves possessing opposite sense of rotation . Comparison of Eq. 9 to Eq. 5 shows that the cw and ccw waves emerging from the tube posses a different phase. Therefore superimposed interference patterns will be produced, and this fuzzy pattern will not be easy to use for measurements. This suggests that a purely cw or ccw incident wave will lead to a single and therefore more distinct pattern. Consider the incident plane wave to be a cw wave only. The emerging waves are then $\mathbf{E}_{t_{cw}}$ and $\overline{\mathbf{E}}_{t_{cw}}$, as defined by Eqs. 5, 9. This results in interference term (as defined in Ref. 9, i.e., the cross intensity of the two waves)

$$J_{cw} = E^2_{to} \cos[\tfrac{1}{2}(h^{+}_{cw} + h^{-}_{cw})d] \quad (10)$$

The phase difference between $\mathbf{E}_{t_{cw}}$ and $\overline{\mathbf{E}}_{t_{cw}}$ shifts the interference fringes compared to their position for zero velocity. For low velocities ($v << C_{cw}$) the phase difference becomes

$$\tfrac{1}{2}(h^{+}_{cw} + h^{-}_{cw})d \approx -\omega d\left(\frac{1}{C^2_{cw}} - \frac{1}{c^2}\right)v \quad (11)$$

which is identical to the Fresnel formula for simple media. Similarly the interference of ccw waves gives the same expression Eq. 11 with cw replaced by ccw.

As mentioned earlier, the analysis given up to this point is not exact in the sense that the full boundary conditions are not satisfied. The full analysis is more important for more complex configurations involving oblique incidence, for example. As far as the present subject is concerned the subsequent analysis will show that the amplitudes of the emerging waves have different forms. Here we assume the presence of four plane waves within the chiral media, all take part in the boundary equations at z=0 and z=d. As before we solve the boundary equations for the upper tube. The results for the lower tube are obtained by replacing v with -v. We assume that all waves inside and outside the chiral medium have elliptical polarization. Each wave is represented as a sum of ccw and cw waves. The amplitude of the cw emerging wave is

$$E_{t_{cw}} = E_0\left(\frac{2\eta_o Z e^{i(\delta^{+}_{cw} + \delta^{-}_{ccw} - \delta_o)}}{e^{i\delta^{-}_{ccw}}(\eta_o + Z)^2 - e^{i\delta^{+}_{cw}}(\eta_o - Z)^2}\right) \quad (12)$$

where $\delta^{+}_{\substack{cw\\ccw}} = h^{+}_{\substack{cw\\ccw}} d$, $\delta^{-}_{\substack{cw\\ccw}} = h^{-}_{\substack{cw\\ccw}} d$, $\delta_o = k_o d$.
Similarly the amplitude of the ccw wave gives the same expression as Eq. 12 with cw replaced by ccw and vise versa. Comparison of Eq. 12 to Eq. 5 shows additional terms that result from the full solution. The same expressions hold for the lower tube with the replacement of v with -v. The complex amplitudes of the cw and ccw waves emerging out of the lower tube expressed with the parameters of the upper tube are

$$\overline{E}_{t_{\substack{cw\\ccw}}} = E_{t_{\substack{ccw\\cw}}} e^{-i(\delta^{+}_{\substack{ccw\\cw}} + \delta^{-}_{\substack{cw\\ccw}})} \quad (13)$$

The form of equation Eq. 13 enables an easier examination of the interference between the wave emerging out of the tubes. In order to measure the effects of the velocity on the waves, the construction of figure 1 is used again. The shift of the fringes resulting from the interference between the cw waves alone and between the ccw waves alone. The change of the light intensity resulting from the interference of the cw waves (namely the interference term) is

$$J_{cw} = |E_{t_{cw}}||E_{t_{ccw}}|\cos(\phi_{cw} - \phi_{ccw} + \delta^{+}_{cw} + \delta^{-}_{ccw}) \quad (14)$$

where

$$\phi_{cw} = -tg^{-1}\left(\frac{(\eta_o + Z)^2 \sin\delta^{-}_{ccw} - (\eta_o - Z)^2 \sin\delta^{+}_{cw}}{(\eta_o + Z)^2 \cos\delta^{-}_{ccw} - (\eta_o - Z)^2 \cos\delta^{+}_{cw}}\right) - \delta_o \quad (15)$$

The interference term and the phase ϕ_{ccw} of the ccw waves is obtained by exchanging the cw and ccw indices in Eqs. 14, 15. Since the additional terms ϕ_{cw}, ϕ_{ccw} have a complicated dependence in the velocity, a simple analysis of the interference fringes is not available. The elimination of ϕ_{cw}, ϕ_{ccw} results with a slight modification to the construction of Fig. 1. Let us consider the case where the interference is limited to the x components of the cw wave emerging out of the upper tube and the ccw wave emerging out of the lower tube only. In this case the interference term is of the form

$$J_x = |E_{t_{cw}}|^2 (1 + \cos(\delta^{+}_{cw} + \delta^{-}_{ccw})) \quad (16)$$

Similar expressions result from the interference of the y components. One can discuss the interference between the x (or y) components of the other two emerging waves. In this case the interference term is of the form of equation Eq. 16 exchanging the cw and ccw indices. Eq. 16 is much more simple to analyze. One can achieve the result of Eq. 16 with the aid of two polarizators positioned at the end of each tube allowing the transmission of the x components only. The upper tube is to be excited with a cw circularly polarized wave and the lower tube with a ccw circularly polarized wave (the practical arrangements of the Fizeau experiment are not discussed in this article). The shift of the interference fringes (relative to the case of zero velocity) is proportional to the sum of $\delta^{+}_{cw} + \delta^{-}_{ccw}$ which give for the first order in velocity

$$\omega d\left[\left(\frac{1}{C_{cw}} - \frac{1}{C_{ccw}}\right) + \left(\frac{1}{c^2} - \frac{1}{C^2_{cw}} - \frac{1}{C^2_{ccw}}\right)v\right] \quad (17)$$

3. VELOCITY FIRST ORDER MODEL

A relativistically exact model for first order in velocity was developed before for moving simple media [10]. This model gives a relatively simple formalism enabling an easy solution to propagation and scattering of electromagnetic waves in the presence of moving simple media. A similar model is developed in the sequel for homogenous isotropic chiral media, which will be used to obtain the results of Fizeau's experiment more easily. During the development of this model we assume that the waves are circularly polarized with a fixed sense of rotation (i.e., cw and ccw polarization are analyzed separately).

Let us assume that an isotropic chiral medium is moving with velocity $\mathbf{v}$ relative to Γ. Minkowski's equations for isotropic chiral media, correct for the first order in velocity are given by

$$\begin{bmatrix}\mathbf{D}\\ \mathbf{B}\end{bmatrix} = [A]\begin{bmatrix}\mathbf{E}\\ \mathbf{H}\end{bmatrix} + \mathbf{v}\times[A_v]\begin{bmatrix}\mathbf{E}\\ \mathbf{H}\end{bmatrix} \quad (18)$$

where

$$[A] = \begin{bmatrix}\varepsilon+\mu\xi^2 & i\mu\xi\\ -i\mu\xi & \mu\end{bmatrix}$$

$$[A_v] = \begin{bmatrix}-2i\mu\xi(\varepsilon+\mu\xi^2) & \mu\varepsilon+2\mu^2\xi^2-1/c^2\\ -(\mu\varepsilon+2\mu^2\xi^2-1/c^2) & -2i\mu^2\xi\end{bmatrix}$$

Substituting Eq. 18 in Maxwell's equations in Γ yields

$$\nabla\times\begin{bmatrix}\mathbf{E}\\ -\mathbf{H}\end{bmatrix} = i\omega\left([A]\begin{bmatrix}\mathbf{E}\\ \mathbf{H}\end{bmatrix} + \mathbf{v}\times[A_v]\begin{bmatrix}\mathbf{E}\\ \mathbf{H}\end{bmatrix}\right) \quad (19)$$

with solution of the form

$$\mathbf{E} = \mathbf{E}_1 e^{i\omega\phi}; \qquad \mathbf{H} = \mathbf{H}_1 e^{i\omega\phi} \quad (20)$$

where only ϕ is velocity dependent (changes in amplitude are second order effects). From eqs. 19, 20

$$(\nabla + i\omega\nabla\phi)\times\begin{bmatrix}\mathbf{E}_1\\ -\mathbf{H}_1\end{bmatrix} = i\omega\left([A]\begin{bmatrix}\mathbf{E}_1\\ \mathbf{H}_1\end{bmatrix} + \mathbf{v}\times[A_v]\begin{bmatrix}\mathbf{E}_1\\ \mathbf{H}_1\end{bmatrix}\right) \quad (21)$$

Bohren's decomposition [5]) shows that for fields which are circularly polarized in one sense of rotation the fields $\mathbf{E}_1$, $\mp i\mathbf{H}_1$ coincides on the same circle (the discussion is restricted to circularly polarized waves with a certain sense of rotation). Therefore in the left hand side of Eq. 21 $\nabla\phi$ gives the dependency in velocity and is expressed by $\nabla\phi = \alpha\mathbf{v}$ (the model is restricted to irrotational motion only) with α

$$\alpha_{\substack{cw\\ccw}} = -\left(\frac{1}{C^2_{\substack{cw\\ccw}}} - \frac{1}{c^2}\right) \quad (22)$$

The results obtained so far are identical in form to the model for moving simple media. However the present model applies only to circularly polarized waves (or superposition of such waves). Each sense of rotation is affected differently as obviously seen by Eq. 22. Using Eq. 22 all terms containing $\mathbf{v}$ in Eq. 21 are canceled thus generating the form of Maxwell's equations for isotropic chiral media at rest for $\mathbf{E}_1, \mathbf{H}_1$ fields. Consequently $\mathbf{E}_1$, $\mathbf{H}_1$ satisfy the conventional vector wave equation of the isotropic chiral media, whose solutions for various coordinate system and problems are available. Let us apply the model on the first analysis of Fizeau's experiment (i.e. first order multiple reflection model). The waves within the chiral medium propagating towards the boundary z=d are calculated for zero velocity:

$$\mathbf{E}^{+}_{1} = \frac{Z}{\eta_o + Z}\left[(\hat{\mathbf{x}} + i\hat{\mathbf{y}})e^{ih^{+}_{cw}z} + (\hat{\mathbf{x}} - i\hat{\mathbf{y}})e^{ih^{+}_{ccw}z}\right]e^{i\omega t} \quad (23)$$

$h^{+}_{\substack{cw\\ccw}}$ are calculated for zero velocity. Next the fields are multiplied by the appropriate correcting factor $e^{i\omega\phi}$. Here $\mathbf{v} = \hat{\mathbf{z}}v$,

$$\phi_{\substack{cw\\ccw}} = -\left(\frac{1}{C^2_{\substack{cw\\ccw}}} - \frac{1}{c^2}\right)vz. \quad (24)$$

and the electric field within the upper tube is

$$\mathbf{E}^{+} = \frac{Z}{\eta_o + Z}\left[(\hat{\mathbf{x}} + i\hat{\mathbf{y}})e^{ih^{+}_{cw}z + i\omega\phi_{cw}} + (\hat{\mathbf{x}} - i\hat{\mathbf{y}})e^{ih^{+}_{ccw}z + i\omega\phi_{ccw}}\right]e^{-i\omega t} \quad (25)$$

and the wave transmitted out of the upper tube is

$$\mathbf{E}_t = \frac{2\eta_o Z}{(\eta_o + Z)^2}\left[(\hat{\mathbf{x}} + i\hat{\mathbf{y}})e^{ih^{+}_{cw}d + i\omega\phi_{cw}|_{z=d}} + (\hat{\mathbf{x}} - i\hat{\mathbf{y}})e^{ih^{+}_{ccw}d + i\omega\phi_{ccw}|_{z=d}}\right]e^{ik_o(z-d) - i\omega t} \quad (26)$$

The same steps are applied to the fields inside the lower tube replacing $\mathbf{v}$ with $-\mathbf{v}$. The interesting results are however the interference terms. For interference of the two cw waves, the interference term is

$$J_{cw} = 2\left[\frac{2\eta_o Z E_o}{(\eta_o + Z)^2}\right]^2 \cos\delta \quad (27)$$

where δ is the phase difference between the two cw polarized waves. Since the phases of both waves consist of identical zero velocity term and correcting factors of opposite sign

$$\delta = -\omega d\left(\frac{1}{C_{cw}^2} - \frac{1}{c^2}\right)v \tag{28}$$

which is identical to Eq. 11. The same procedure leads to the results for the ccw waves and to the interference terms obtained from the solution of the full scattering problem for first order in velocity.

4. SUMMARY AND CONCLUSIONS

Wave propagation in moving chiral media was discussed, using the classical Fizeau experiment as a concrete example. The motion affects the phase velocities of the electromagnetic waves within the chiral media. This in turn cause a change in the rotation angle of the transmitted waves and a shift of the interference fringes. The dependence of this shift is simplified with excitation of the tubes by circularly polarized waves instead of linear polarization in the case of the original Fizeau experiment. With the simplified model, the waves exciting both tubes rotate in the same direction (both cw or ccw) separating the effect of the different two phase velocities of the waves within the chiral media. For each excitation (cw or ccw) the Fresnel drag coefficient is obtained. In the full model the exciting waves are of opposite circular polarization and additional polarizators should be positioned at the end of each tube in order to ease the measurements. A relativistically exact model for first order in velocity was developed for the chiral medium. This model give a relatively simple formalism enabling an easy solution to propagation and scattering of electromagnetic waves in the presence of moving chiral media. The Fizeau's experiment was analyzed again using this model producing the Fresnel drag coefficients directly. This model will be used in the future to analyze electromagnetic wave propagation and scattering in more complicated configurations involving moving chiral isotropic chiral media.

6. REFERENCES

1 A. Sommerfeld, *Optics*. New York: Academic Press, 1964.

2 I. Lerche, "The Fizeau effect: Theory, Experiment, and Zeeman's measurements", *American Journal of physics*, vol. 45, December 1977.

3 F. Zernike, "The convection of Light Under Various Circumstances with Special Reference to Zeeman's Experiments", *Physica*, vol. 13

4 S. Bassiri , *Electromagnetic Waves in Chiral Media*, chap. 1 in *Recent Advances in Electromagnetic Theory*, Edited by Kritikos H. N., Jaggard D. L.

5 A. Lakhtakia, V. K. Varadan, V. V. Varadan, *Time-Harmonic Electromagnetic Fields in Chiral Media*, Berlin: Springer-Verlag, 1989.

6 N. Engheta, M. W. Kowarz, D. L. Jaggard, "Effect of chirality on the Doppler shift and aberration of light waves", *Journal of Applied Physics*, vol. 66, pp. 2274-2277, September 1989.

7 D. Censor "Scattering of a plane wave at a plane interface separating two moving media", *Radio Science*, vol. 4, pp. 1079-1088, November 1969.

8 J. A. Stratton, *Electromagnetic Theory* (page 506). New York: McGraw-Hill, 1941.

9 M. Born, E. Wolf, *Principles of Optics*, (pages 256 - 262).

10 D. Censor, First order propagation in moving media, *IEEE trans. Microwave Theory and techniques*, MTT-16, 1968, pp. 565-566.

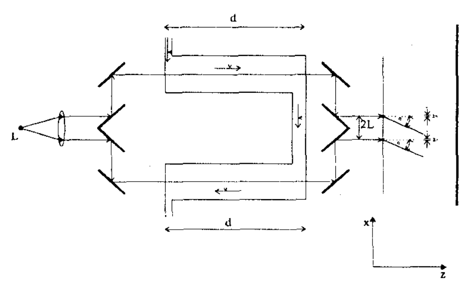

Figure 1 - General structure of Fizeau's experiment