Observation of the Faraday effect via beam deflection in a longitudinal magnetic field

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We report the observation of the magnetic field induced circular differential deflection of light at the interface of a Faraday medium. The difference in the angles of refraction or reflection between the two circular polarization components is a function of the magnetic field strength and the Verdet constant. The reported phenomena permit the observation of the Faraday effect not via polarization rotation in transmission, but via changes in the propagation direction in refraction or in reflection. An unpolarized light beam is predicted to split into its two circular polarization components. The light deflection arises within a few wavelengths at the interface and is therefore independent of pathlength.

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Well established magneto-optical phenomena are the Faraday, Cotton-Mouton-Voigt and the magneto-optical Kerr (MOKE) effects, as well as magnetic circular dichroism. These are described by changes in the azimuth (optical rotation) or the ellipticity of an electromagnetic wave. Apart from changes in these Stokes parameters, a magnetic field may also influence the propagation direction of light.

The deflection of a light beam in isotropic media subject to a homogenous transverse magnetic field has been reported by Rikken and Tiggelen who observed the deflection in scattering as well as in transmission, and by Blasberg and Suter who showed that angular momentum conservation causes a small lateral displacement near resonance in an atomic vapor. Transverse magnetic field induced refraction at the cesium vapor/glass interface has been reported by Schlesser and Weis. However, their observed deflection appears to be nonlinear in the strength of the magnetic field and nonlinear in the light intensity. A complete explanation for this effect has not yet been provided.

Here, we show that it is also possible to observe magneto-optical deflection at an interface in the presence of a longitudinal magnetic field. In particular, we show that longitudinal magnetic field induced refraction and reflection at an interface gives rise to a circular differential beam deflection, and that this is an alternate means to determine Verdet constants.

A magnetic field renders any medium (isotropic or oriented) optically active. In particular, any isotropic medium becomes uniaxial in the presence of a magnetic field, and its refractive indices for right- (+) and left- (−) circularly polarized light are unequal, such that the plane of polarization of a linearly polarized electromagnetic wave rotates as the wave propagates along the direction of the field. The Faraday rotation in radians developed by an electromagnetic wave at the wavelength λ traversing a distance l is given by:

$$α = VB l = \frac{\pi l}{\lambda} \left(n^-(+) - n^+(-)\right)$$

FIG. 1: a) Double refraction at the boundary of a Faraday medium (shaded) and a medium with negligible Verdet constant characterized by the scalar refractive index $n_0$. The direction of the transmitted beam is different for left- and right-circularly polarized waves. An unpolarized or a linearly polarized beam will thus split into two. b) Reflection inside a Faraday medium. The incident beam is subject to circular birefringence $n^{(\pm)}$ such that the left- and right- circular components have different angles of reflection.

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where $V$ is the frequency-dependent Verdet constant, and $B$ is the magnetic field strength. Magneto-optical activity should, however, not only manifest itself through Faraday rotation in transmission, but should also be observable as a deflection of the light beam in reflection and in refraction at an interface. We have recently reported the observation of related phenomena in the case of natural optical activity (chirality).

If one considers the refraction of an electromagnetic wave at a boundary formed by a Faraday medium and a medium with a negligible Verdet constant, as shown in Fig. 1a, then the left- and the right-circularly polarized waves or wave-components must independently obey Snell’s law. Circularly polarized waves that propagate along the optical axis in the Faraday medium, will
It follows that magneto-optical double refraction \( \theta \), where the Verdet constant is the strength of an applied magnetic field: and hence Verdet constants, or in the case of a known interface can be used to determine circular birefringences, thus refract in the medium characterized by the polarization independent refractive index \( n_0 \) with angles of refraction \( \theta^{(-)} \) and \( \theta^{(+)} \), depending on whether they are, respectively, left- or right-circularly polarized. Similarly, if an unpolarized or linearly polarized wave is incident from the Faraday medium with angle of incidence \( \theta_i \), then it will split into two beams, one left- and the other right-circularly polarized. The angular divergence \( \delta = \theta^{(+)} - \theta^{(-)} \) between the two refracted circular polarization components in Fig. 1a is

\[
\delta \approx \frac{(n^{(+)} - n^{(-)})}{n_0} \sin \theta_i \frac{\sin \theta}{\cos \theta}, \tag{2}
\]

where \( \theta \) is the average of the two angles of refraction. It follows that \( B \)-field induced deflection of light at an interface can be used to determine circular birefringences, and hence Verdet constants, or in the case of a known Verdet constant the strength of an applied magnetic field:

\[
\delta \approx -\frac{\lambda}{\pi n_0 \cos \theta} V B. \tag{3}
\]

It is interesting to note that unlike Faraday rotation (Eq. (1)), which is a function of the light path through the medium, magneto-optical double refraction arises within a few wavelengths at the interface. This could for instance be of use in the study of ultrathin transparent samples.

One may also consider the components of an electromagnetic wave that reflect inside the Faraday medium. Because a circularly polarized wave reverses its circularity upon reflection, the incident and the reflected waves are necessarily associated with different refractive indices. Hence, in an optically active medium the angle of reflection of a circularly polarized wave will in general not equal the angle of incidence. An unpolarized or linearly polarized wave can therefore split into its two circularly polarized components upon reflection. The theoretical description of magnetic double reflection is complicated by the fact that the reflected wave no longer propagates along the optic axis of the system. The reflected beam is thus potentially subject to circular birefringence (Faraday effect) as well as the birefringence due to a transverse magnetic field. To simplify the discussion we will consider a reflected beam that propagates in a direction perpendicular to the magnetic field as shown in Fig 1b, such that it experiences no birefringence due to the longitudinal component of the magnetic field. Furthermore, we neglect any transverse \( B \)-field induced birefringence and assume that the reflected waves are only subject to an average refractive index \( n = \frac{n^{(-)} + n^{(+)}]}{2} \). The angular divergence \( \delta' \) is then given by

\[
\delta' \approx -\frac{\lambda \tan \theta_i}{\pi n} V B. \tag{4}
\]

Depending on the Fresnel reflection coefficients for a given interface, the circular components may not fully reverse their circularity upon reflection and become elliptically polarized. This can be accounted for by including the appropriate Fresnel coefficients.

We have observed the magnetic field induced double refraction and reflection phenomena in an experimental arrangement schematically depicted in Fig 2a. In the reflection measurements light from a 532 nm diode laser was modulated between left- and right-circular polarized with a Hinds photoelastic modulator (PEM) at ~50 kHz and then passed through a transparent glass (SF11) prism mounted between the pole pieces of an electromagnet (Walker HV7). The position of the beam was recorded with a position sensitive diode and a lockin amplifier. The difference in the angles of refraction for the two circular polarization components is shown in Fig. 2b as a function of the applied magnetic field strength. From a linear fit to the data and using Eqn. (3) a Verdet constant of \( 29.37 \pm 0.96 \text{ T rad}^{-1} \text{ m}^{-1} \) is obtained. This is in good agreement with the tabulated values of the Verdet constant for SF11 Schott glass, from which we extrapolate a Verdet constant of \( 30.44 \text{ T rad}^{-1} \text{ m}^{-1} \). Each data point in Fig. 2b is measured with an uncertainty that is approximately the size of the symbol. However, the photoelastic modulator itself gives rise to an angular deviation that fluctuates on the time scale of the measurement and causes the data points to deviate from a
The goodness of the straight-line fit is thus a more appropriate measure of the experimental error. The circular differential reflection in a longitudinal magnetic field was observed in a right-angle prismatic cuvette filled with carbon disulfide (CS$_2$). A mirror was mounted parallel to the hypotenuse on the inside of the liquid cuvette. The polarization modulated beam from a ∼473 nm diode pumped solid state laser travelled along the direction of the magnetic field in the liquid and upon reflection exited the liquid perpendicular to the magnetic field and normal to the window of the cuvette. From the detected angular divergence shown in Fig. 2c we deduce a Verdet constant of 23.7 ± 0.8 T rad$^{-1}$ m$^{-1}$. We suspect that the small difference with the reported constant of 0.0694 min G$^{-1}$ cm$^{-1}$ (20.2 T rad$^{-1}$ m$^{-1}$) at 476.5 nm [9] is due to ellipticity in the reflected beam, which has not been accounted for. We stress that even though the experimental geometry is chosen such that the medium is (approximately) uniaxial, the effects described here will in general be exhibited by any wave that refracts or reflects at the interface of a Faraday medium.

Similar effects are expected to arise in diffraction [10].

In summary, we have shown that the Faraday effect can be observed via double refraction or reflection at an interface in the presence of a longitudinal magnetic field. We have demonstrated that the difference in the propagation directions of the two refracted (or reflected) circular polarization components is an alternative means to determine Verdet constants or magnetic field strengths.

The effects reported here distinguish themselves in a number of ways from magneto-optical measurements reported hitherto. The magnetic double refraction and reflection phenomena may be observed both with polarized or with unpolarized electromagnetic waves. Further, the effects arise within a few wavelengths at the boundary, and may thus find application in the study of ultrathin samples. Finally, the phenomena do not suffer from the n-π ambiguity, which can plague Faraday rotation measurements in large magnetic fields [11], or in space astronomy. This prompts us to ask whether the deflection phenomena of this paper also manifest themselves in astrophysical observations.

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