Enhancement of circular differential deflection of light in an optically active medium

Rajitha Papukutty Rajan and Ambarish Ghosh*
Centre for Nano Science and Engineering, Indian Institute of Science, Bangalore, 560012, India
*Corresponding author: ambarish@ece.iisc.ernet.in

Received January 4, 2012; accepted January 31, 2012; posted February 6, 2012 (Doc. ID 160767); published March 27, 2012

In this letter, we investigate the circular differential deflection of a light beam refracted at the interface of an optically active medium. We show that the difference between the angles of deviation of the two circularly polarized components of the transmitted beam is enhanced manifold near total internal reflection, which suggests a simple way of increasing the limit of detection of chiro-optical measurements. © 2012 Optical Society of America

OCIS codes: 160.1585, 260.0870, 120.5410, 120.5710, 260.1440, 120.3930.

Chiral molecules, molecules that are non-superimposable on their mirror images, form a medium with natural optical activity [1], such that the medium responds differentially to left and right circularly polarized states of light. Since most biologically relevant molecules are chiral, the measurement of optical activity is of great importance to the pharmaceutical industry. The standard way of detecting and estimating the concentration of chiral molecules is by measuring optical rotation, which refers to the rotation of the plane of polarization of a light beam when it is transmitted through a chiral medium. This technique, although well established, is not suited for miniaturization, since the sensitivity of the measurement decreases as the optical path length is reduced. Recently, a new method [2] of detecting optical activity in microfluidic volumes has been developed, where the angles of reflection, refraction, and diffraction were shown to be circularly differential at the interface between an achiral and a chiral medium, caused by the small difference in refractive indices for the two circularly polarized (CP) states of light in a chiral medium. Since refraction, reflection, and diffraction [3] are interface effects, the technique is well suited for miniaturization and possible implementation in lab-on-a-chip devices, and it is only limited by the minimum angle of deviation that can be measured accurately.

Very small beam deflections have been measured [4,5] by many groups with sophisticated interferometric setups, down to picoradians or so. Some of these schemes are inspired by quantum [6] “weak” measurements and were recently used for measuring small (~nanoradians) deflections of circularly polarized light beams at the interface of an optically active medium [7]. In this letter, we investigate a new way of improving the limit of detection of these measurements, where rather than making very sensitive measurements of small beam deflections, we investigate ways to increase the angular deflection. The essence of our method lies in the observation that the angular deflection of the beam depends very strongly on the angle of incidence, especially for beams incident at angles close to the critical angle for total internal reflection.

The system under study was not a collection of chiral molecules, but instead we used a glass (SF11) prism under the action of a magnetic field. Although natural optical activity is inherent to a collection of chiral molecules, it is also possible to induce optical activity in many materials by the application of an external magnetic field (Faraday effect). The application of a magnetic field of strength $B_{\text{eff}}$ parallel to the direction of propagation of a light beam of wavelength $\lambda$, makes a medium circularly birefringent, such that the difference of refractive indices between the two CP states of light is given by

$$n_{\text{LCP}} - n_{\text{RCP}} = \frac{VB_i}{\pi},$$

where $V$, the Verdet constant, depends on the material and the wavelength $\lambda$. Accordingly, for light refracting at an interface between two media of different Verdet constants, the angles of refraction have been observed [8] to depend on the CP states. The difference between the angles of refraction depends on the strength of the magnetic field, the Verdet constants of the media, and on the angles of incidence and the refractive indices of the two media. To estimate it quantitatively, let us consider a prism made of a material of Verdet constant, $V$, placed in a material of negligible Verdet constant, such as air (see Fig. 1).

To estimate the circular birefringence of the prism in presence of a magnetic field $B$, parallel to the incident light beam, we note that the average angle of refraction at the first interface, $\alpha$, is related to the average refractive index, $n_0$, of the prism (material SF11, $n_0 = 1.77862$ at $\lambda = 632.8$ nm), such that

$$\sin(\alpha) = \sin\left(\frac{\alpha_1 + \alpha_R}{2}\right) = \frac{\sin(i)}{n_0}.$$  \hspace{1cm} (2)

Accordingly, the magnetic field component parallel to the direction of propagation of the light beam inside the prism is given by

$$B_{\text{eff}} = B \cos(\alpha - i),$$  \hspace{1cm} (3)

which in turn causes an effective circular birefringence,

$$n_{\text{LCP}} - n_{\text{RCP}} = \frac{VB_{\text{eff}}\lambda}{\pi},$$  \hspace{1cm} (4)
which is estimated to be around $10^{-7}$ at normal incidence ($i = 0$) for magnetic fields of around 300 gauss (assuming $V = 20 \text{ rad T}^{-1} \text{ m}^{-1}$ at $\lambda = 632.8 \text{ nm}$). By applying Snell’s law at the second interface for the two CP beams, one can estimate the difference of deviation angles, $\delta$, between the two outgoing beams as a function of the angle of incidence.

The experimental setup to study the effect of variation in the angle of incidence is shown schematically in Fig. 2. Monochromatic light of wavelength 632.8 nm from a He-Ne laser (5 mW) is transmitted through a polarization modulation system, and then through a prism made of SF11 glass. We have tried various types of polarization modulation schemes, such as Pockels cells, photoelastic modulators (PEM), and liquid crystals, etc., and the overall characteristics of the results have been the same for all the systems. The prism was mounted on a manual rotation stage and was placed at the center of a Helmholtz coil, capable of producing a field up to 260 gauss. The position of the beam is measured synchronously with a position-sensitive detector and lock-in amplifiers. To ensure that the deflection measurements were indeed due to the Faraday effect, we measured $\delta$ as a function of the magnetic field $B$, and found a linear dependence. Please note that the experimental setup was not sensitive towards any linear birefringence effects arising due to the quadratic Cotton-Mouton-Voigt effect. Upon insertion of a half-wave plate before the prism, the sign of $\delta$ was reversed (as expected). Note that the polarization of the CP beams are expected to become somewhat elliptical at each refracting interface, due to the difference of Fresnel transmission coefficients between that of the $s$ and the $p$ beams, which is probably why the estimated ($\sim 0.1 \mu \text{rad}$) and the measured ($\sim 0.05 \mu \text{rad}$) values of $\delta$

for a given magnetic field (260 gauss) are different by an approximate factor of 2.

The dependence of $\delta$ on the angle of incidence, $i$, was observed to have a marked increase near the critical angle for total internal reflection at the second interface. We define an enhancement factor (EF) as $\delta(i)/\delta(0)$, which provided an estimate of the increase of the deflection angle at a particular angle of incidence compared to the deflection at normal incidence. The experimental results, along with estimates based on the simple theory described before, are shown in Fig. 3. A small constant offset (along the $x$ axis) between the measured and the predicted data, noticeable clearly at the incidence angles close to the critical angle, is probably due to the error in our estimate of the angle of normal incidence. The signal to noise (S/N) ratio of the measured deflection angles rises by an order of magnitude compared to the measurements at normal incidence, except very close to the critical angle, where the circular differential deflection of the beam becomes very sensitive to the angles of incidence, resulting in higher measurement errors for $\delta$. As shown in the inset of Fig. 3, the measurement errors (for typical data acquisition time of few seconds) become high very close to the critical angle (within 0.05°), which
is due to inherent beam pointing instabilities of the laser (expected to be around 0.002° for a measurement window of 15 minutes, as specified by the manufacturer).

In summary, we demonstrate how the difference between the angles of refraction for the two circularly polarized states of light are enhanced near critical angle for total internal reflection at the interface of an optically active medium. This effect may be useful in improving the limit of detection of chiro-optical measurements, especially those based on circular differential deflection measurements in microfluidic devices.

We thank DST Fast Track Scheme, DBT, and ADA (NPMASS) for funding this work. Loan of the polarization modulator from Applied Photonics Initiative, IISc is gratefully acknowledged.

References