

Direct naked-eye detection of chiral and Faraday effects in white light

G. ROPARS^{1(a)}, A. LE FLOCH^{1,2}, J. ENOCH³ and V. LAKSHMINARAYANAN^{4,5,6,7}

¹ *Laboratoire de Physique des Lasers, Université de Rennes 1, URU 435 - 35042 Rennes cedex, France, EU*

² *Laboratoire de Chimie et Photonique Moléculaires, unité CNRS 6510, Université de Rennes 1 35042 Rennes cedex, France, EU*

³ *School of Optometry, University of California - Berkeley, CA 94720, USA*

⁴ *School of Optometry, University of Waterloo - Waterloo, Ontario, Canada N2L 3G1*

⁵ *Department of Electrical and Computer Engineering, University of Waterloo - Waterloo, Ontario, Canada N2L 3G1*

⁶ *Department of Physics and Astronomy, University of Waterloo - Waterloo, Ontario, Canada N2L 3G1*

⁷ *Michigan Center for Theoretical Physics, University of Michigan - Ann Arbor, MI 48109, USA*

received 28 September 2011; accepted 13 February 2012

published online 15 March 2012

PACS 42.25.Ja – Polarization

PACS 87.19.1t – Sensory systems: visual, auditory, tactile, taste, and olfaction

PACS 42.66.Lc – Vision: light detection adaptation, and discrimination

Abstract – We demonstrate that the human eye is able to detect the optical activity of chiral molecules and the Faraday effect, even under white-light viewing conditions, without the help of any polarizer. Indeed, we show that our eye acts as a differential analyzer and isolates the response in the blue part of the visible spectrum, thus avoiding the difficulties related to the inherent chromatic dispersion encountered in usual experiments performed under white-light conditions. Moreover the human eye enables to clearly distinguish between the fundamental reciprocal and non-reciprocal characteristics of the optical activity and the Faraday effect, respectively. Furthermore the human eye, without any specific optical dichroic axis in the retina, enables us to read, with the naked eye, hidden information encoded via different states of polarization, and suggests the possibility of direct detection of quantum entanglement effects.

Copyright © EPLA, 2012

The transverse vectorial nature of light is a powerful tool to investigate birefringences and dichroisms of different gaseous, liquid and solid media [1–3]. Polarimetry is widely used in physics, chemistry and biology. Recently circular dichroism and spectropolarimetry have brought observational evidence to solve astrophysical problems like the dissipation of angular momentum from accretion disks [4,5]. Moreover, astronomers have also recently succeeded in detecting and monitoring for the first time the blue polarized light scattered in the atmosphere of an exoplanet [6]. However, most of the experiments require monochromatic or narrow-band light sources to avoid dispersion effects. Arago himself observing the sunlight passing through a quartz crystal placed between crossed polarizers [7], discovered the optical activity but was surprised to see a complex superposition of different colors. The optical rotations of linearly polarized light, both in

the case of optical activity and Faraday effect, vary with the different wavelengths and obscure the measurements in white light. Moreover, since the experiments of von Frisch with bees [8], many animals have shown to be directly sensitive to the polarized Rayleigh scattered UV and blue light of the sky [9] and use the spatially polarized light of their surroundings for navigation, signalization. Although a universal master gene has been identified [10,11], many fundamental differences remain between the structures and functions of the various complex eyes. For instance, to the best of our knowledge, detecting fundamental effects with the naked eye is considered as out of reach for humans, although Haidinger earlier showed [12] the existence of polarization patterns on the retina. One may wonder if it is possible to completely avoid the chromatic dispersion effects, so as to perform polarimetry in the polarized surrounding white light and detect directly, with the naked eye, fundamental effects such as the optical activity of chiral molecules, the Faraday effect, or even to read hidden polarized information.

^(a)E-mail: guy.ropars@univ-rennes1.fr

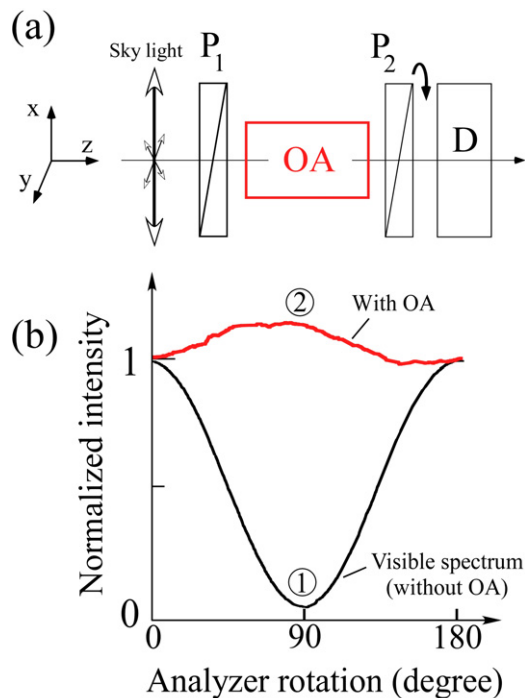


Fig. 1: (Colour online) Basic white-light polarimetry. (a) Experimental set-up using the light of the sky. Polarizer P_1 and analyzer P_2 are HN22 polaroids, OA corresponds to the optical activity of the sucrose solution contained in a cell, D is a visible spectrum detector. (b) Experimental sky white-light intensity transmitted when the polarizer P_2 is rotated. Black line 1: without the sucrose cell, the degree of polarization reaches 0.9. Red line 2: with a 50 cm long sucrose cell filled with a concentration of 0.4 g/ml, the minimum is smoothed, due to the dispersion effect, preventing any optical activity measurement.

To investigate this possibility let us first try to test chirality, *i.e.*, to perform a measurement of the optical activity of a sucrose cell using white light and a standard detector. The usual polarimetric experiment is schematized in fig. 1(a). In a first step, without the cell, the light coming from the sky for instance, is detected through polarizers P_1 and P_2 , where P_2 is rotated from 0° to 180° . When using HN22 polaroids the degree of polarization of light after passing through the crossed polarizers, defined as $\rho = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$, where I_{\max} and I_{\min} are the maximum and minimum intensities, respectively, reaches $\rho = 0.9$ (curve 1 in fig. 1(b)). If, in a second step we try to measure the optical activity of a solution of dextrogyre sucrose contained in a 50 cm long cell filled with a concentration of $C_0 = 0.4$ g/ml and located between the two polarizers, we obtain the curve 2 of fig. 1(b). The experimental chromatic dispersion of the optical activity of the sucrose reaching more than 90° for our cell between the blue and red edges of the visible spectrum [13], smooths the minimum and forbids any measurement in white light. We observe successive different colors but we are unable to measure the optical activity of sucrose in this experiment. Surprisingly if now we try to measure the optical

activity of sucrose with the naked eye, in the absence of any analyzer, the observation is then direct.

Before realizing the experiment, let us recall the main properties of the polarization sense in the human eye [12,14], necessary to carry out naked-eye polarimetry. The typical Haidinger's pattern appears as an image centered on the fovea. The blue brush of the pattern is parallel to the E -vector of the linearly polarized light entering the pupil, while the yellow brush is perpendicular to the E -vector. Using colored filters, one can readily show that only the blue light (below 500 nm) falling on the blue cones can induce patterns subtending a visual angle of about 3° , centered on a 1 mm^2 disk, at the center of the fovea. Recently, as these patterns cannot be photographed, they have been calculated, simulated and experimentally mimicked [14] taking into account the distribution of the blue cones in the fovea [15,16]. An estimation of the contrast of the polarization pattern is about 3% [14], clearly above the threshold of the sensitivity of the human eye to a contrast, which is of about 1% [17,18]. Hence the naked eye can behave like a monochromator, selecting only the blue part of the spectrum. Moreover when the polarization of the light is rapidly switched in front of the eye, the patterns are rapidly reactivated and a short 0.1 s recovering time can be measured [14]. This provides us with the opportunity to use here this short time opportunity to differentially compare two successive polarization states so as to detect chiral and Faraday effects.

The naked-eye polarimetric experiment is realized either by using the partially polarized sky light or an artificial polarized light source (fig. 2(a)). The polarized white-light source is here provided by a simple liquid-crystal display screen of a desktop computer giving a linearly polarized light. Let us for instance look at the screen alternatively through the sucrose cell and without the cell by shifting rapidly the cell laterally (fig. 2(a)), so as to use the 0.1 s time. We then observe successively polarization patterns on the foveal pit similar to those simulated in figs. 2(b), (c) for different cell lengths. For dextrogyre sucrose solutions ($C_0 = 0.4$ g/ml) in a 10 cm long cell, we observe a $55^\circ \pm 5^\circ$ optical rotation (fig. 2(b)). For a 20 cm long cell, the optical rotation reaches $110^\circ \pm 5^\circ$ (fig. 2(c)). The observations through the sucrose cells are no more obscured by dispersion effects associated with the presence of the long and medium wavelengths of the incident white light. When we vary the sucrose concentration we observe the increasing value of the rotation of the polarization pattern represented in fig. 3(a). Note that as no preferential axis exists for the polarization sense in the human eye, all the directions are equally detected with the same precision giving constant error bars. The blue, green and red curves are theoretical curves deduced from the Drude formula [19] which takes into account the dispersion variations for the sucrose [13], where the specific rotation $[\alpha]$ of the electric field is given by

$$[\alpha] = \sum_i \frac{A_i}{\lambda^2 - \lambda_i^2}, \quad (1)$$

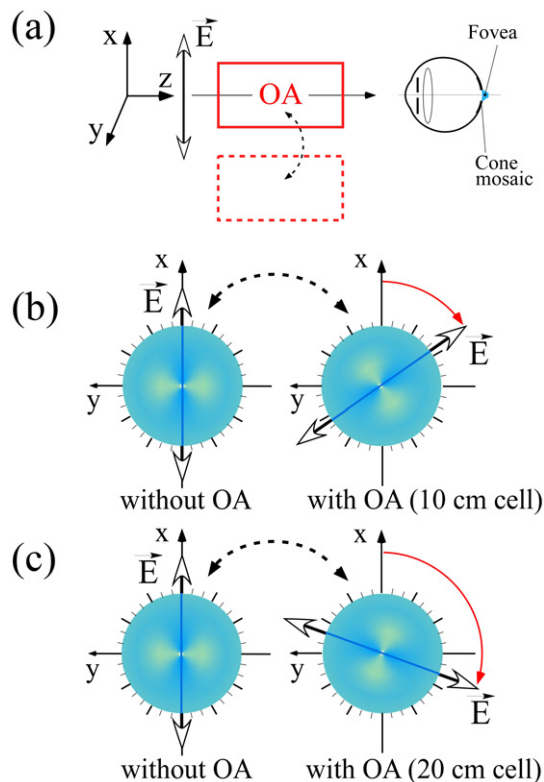


Fig. 2: (Color online) Direct naked-eye polarimetry. (a) Direct observations of a polarized light from a computer screen, alternatively with and without the sucrose cell. The polarizers are removed and the naked eye alone is used as detector. (b) Naked eye: observed and simulated polarization patterns [14], in the absence and in the presence of a 10 cm sucrose cell length filled with a concentration $C_0 = 0.4$ g/ml. Here the angular graduations are drawn on the computer screen. With the 10 cm cell, the experimental value of the polarization rotation is $55^\circ \pm 5^\circ$. The precision is deduced statistically from the different values obtained by successive measurements and from values obtained by different observers. (c) Same as in (b), but with a 20 cm sucrose cell length. The experimental value of the polarization rotation is then $110^\circ \pm 5^\circ$.

where A_i are constants associated to the visible or near ultraviolet absorption bands λ_i . The three curves correspond to the three cone pigments of the retina, having absorption maxima in the blue part of the spectrum ($\lambda_{\max} = 420$ nm), the green part ($\lambda_{\max} = 531$ nm) and the red part ($\lambda_{\max} = 588$ nm) [15,16]. Note that the naked-eye measurements are in agreement with only the theoretical curve corresponding to the blue part of the spectrum (fig. 3(a)). This constitutes an indirect confirmation of the crucial role played by the blue cones alone in the polarization sensitivity of the human eye.

One may wonder if Faraday could have observed the so-called Faraday rotation [20] demonstrating that light responds to magnetic forces through diamagnetic or paramagnetic media, with the naked eye. Let us look at the polarized source through a Faraday optical rotator and then dropping it rapidly like for the sucrose cell. In our

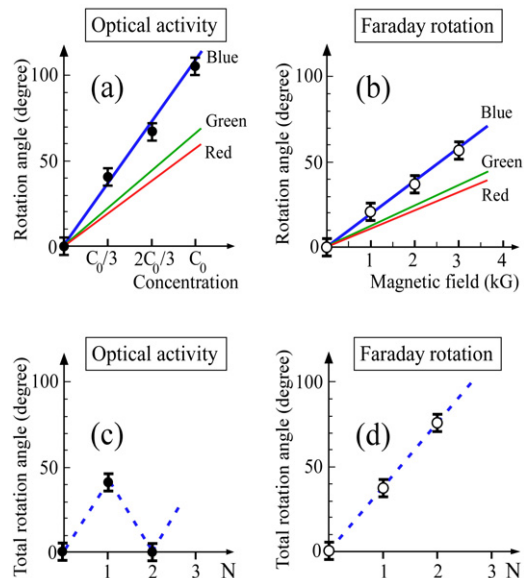


Fig. 3: (Color online) Rotation angle of the polarization measured with the naked eye through different types of circular birefringences. (a) Optical activity: rotation angle of the polarization *vs.* different sucrose concentrations with a 20 cm cell length. The filled-in circles are experimental measurements. The blue, green and red curves are the theoretical curves taking into account the sucrose dispersion in the blue, green and red parts of the spectrum [13] corresponding to the absorption maxima of the three cone pigments at 420 nm, 531 nm and 588 nm respectively. (b) Faraday rotation: rotation angle of the polarization *vs.* the magnetic-field strength. The open circles correspond to experimental measurements. The blue, green and red curves are the theoretical curves taking into account the dispersion of the Yb^{3+} -doped glass [21]. (c) Total optical activity rotation *vs.* the number of forward and backward passes through a 20 cm long sucrose cell ($C_0/3$ sucrose concentration). After one round trip the polarization rotation is cancelled. The optical activity is a reciprocal effect. (d) Faraday rotation *vs.* forward and backward passes, for a magnetic field of 2 kG. After one round trip the polarization rotation is multiplied by a factor 2. The Faraday effect is a non-reciprocal effect.

case we use a 19.5 mm long piece of glass doped with Yb^{3+} with its permanent magnet [21]. The 5 mm diameter Faraday rod can be adjusted inside the magnet to vary the effective magnetic field applied to the Faraday glass. The rotations of the polarization patterns with the naked eye for different values of the effective magnetic field are reported in fig. 3(b) and compared to the theoretical curves taking into account the dispersion of the Verdet constant for the doped glass [21]. Here too the polarization pattern rotations are also in agreement only with the theoretical predictions in the blue. The dispersion effects are again avoided.

Moreover, it is well known that the circular birefringences associated with the optical activity and the Faraday effect are fundamentally different. Lord Rayleigh [22] was the first to suggest the use of Faraday rotation for

optical isolation. He noted that the rotation should be in the same absolute direction whichever way the light may be travelling. If we neglect the interface losses, for transparent media both the optical activity and the Faraday effect can be represented by a 2×2 rotation matrix in the Jones formalism [3]. Let us call M_1 the propagation matrix for light travelling along the rotator and M_2 the corresponding matrix for light in the opposite direction. After a forward pass through the rod, a reflection and a backward trip through the rod, Jones calculus gives for a rotation θ of the electric field,

$$M_1(\theta_{\text{OA}})M_2(\theta_{\text{OA}}) = 1, \quad (2)$$

for an optical activity θ_{OA} , and

$$M_1(\theta_{\text{FR}})M_2(\theta_{\text{FR}}) = M(2\theta_{\text{FR}}), \quad (3)$$

for a Faraday rotation θ_{FR} . Optical activity appears as a reciprocal effect, while the Faraday effect appears as a non-reciprocal effect. Let us try to test this main difference with the naked eye for both cases but simply by using an extra mirror when looking at a computer screen so as to add forward and backward propagations through the two elements. The experimental results are shown in figs. 3(c), (d). Clearly the human naked eye is also able to observe directly this fundamental difference between the two types of circular birefringences.

One may also wonder if humans are able to perform multiaxis naked-eye polarimetry, *i.e.*, to read information encoded via hidden different axes of polarization of the light. In the presence of a perfectly constant intensity stimulus from a computer screen for instance and without the help of any polarizer, let us try to guess and measure the orientations of unknown successive polarized states, observed through an extra half-wave plate. Figure 4(a) shows typical successive flips of linearly polarization states selected by a first person. Figure 4(b) displays the corresponding response noted by a second observer using only his naked eye. The rapid 0.1 s creating and erasing time of the photoreceptor chromophores [14] allows the human eye to act as a differential analyzer and to follow the successive switches of the polarization states of a constant intensity light source.

To conclude, the naked-eye polarimetry provides a direct access to different fundamental effects. Note that the high sensitivity of the human eye to small contrasts, used here, has also recently allowed the detection of a single-atom layer with an opacity as low as 2.3% using the naked eye [23]. The naked-eye detection has also been suggested for “seeing” quantum entanglement without the help of man-made detectors [24–26]. The differential detection of amplified orthogonally polarized pulses could be identified without any polarizer thanks to the specific spatially distributed dichroism of the blue photoreceptors in the fovea if the pulses are emitted in the blue part of the spectrum. Moreover, note that, as shown in fig. 4, the eye

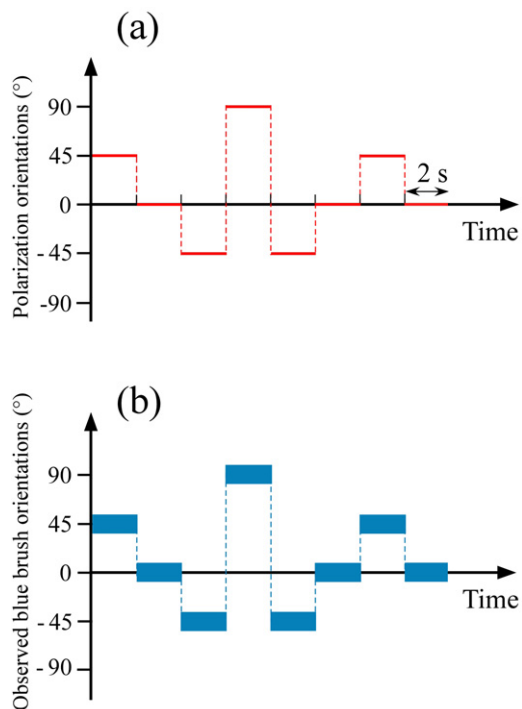


Fig. 4: (Color online) Typical naked-eye detection of multiaxis polarization flips. (a) The successive polarization orientations of the light emitted by a computer screen are switched randomly at 0° , 45° , $90^\circ \dots$ angles by a first person by using a half-wave plate. The light intensity reaching the eye remains strictly constant. (b) The successive corresponding blue brush orientations detected by a second person using only her naked eye. The thickness of the blue lines corresponds to the typical error bar ($\pm 5^\circ$).

should be able to discriminate between successive random polarization orientations of the pulses. This novel type of polarimetry with no defined transmission axis, may open opportunities in many areas including optics, information coding, retinal physiology [27,28] and evolutionary biology.

We thank N. GISIN, D.-E. NILSSON and G. HORVÁTH for their suggestions, A. CARRÉ and L. FREIN for their technical assistance. This work was supported by the Contrat Plan Etat-Région PONANT.

REFERENCES

- [1] KAMINSKY W., *Rep. Prog. Phys.*, **63** (2000) 1575.
- [2] BARRON L. D., *Molecular Light Scattering and Optical Activity*, 2nd edition (Cambridge University Press, Cambridge, England) 2004.
- [3] HECHT E., *Optics* (Addison-Wesley, San Francisco) 2002.
- [4] CHRYSOSTOMOU A., LUCAS P. W. and HOUGH J. H., *Nature*, **450** (2007) 71.

- [5] YOUNG S., AXON D. J., ROBINSON, HOUGH J. H. and SMITH J. E., *Nature*, **450** (2007) 74.
- [6] BERDYUGINA S. V., BERDYUGINA A. V., FLURI D. M. and PIROLA V., *Astrophys. J. Lett.*, **673** (2008) L83.
- [7] ARAGO D. F., *J. Mém. Inst.*, **12** (1811) part 1, 93.
- [8] VON FRISCH K., *The Dance Language and Orientation of Bees* (Harvard University Press, Cambridge, Mass.) 1967.
- [9] HOEPPE G., *Why the Sky is Blue* (Princeton University Press, Princeton) 2007.
- [10] QUIRING R., WALLDORF U., KLOTER U. and GEHRING W. J., *Science*, **265** (1994) 785.
- [11] HALDER G., CALLAERTS P. and GEHRING W. J., *Science*, **267** (1995) 1788.
- [12] HAIDINGER H., *Ann. Phys. Chem.*, **63** (1844) 29.
- [13] BRUHAT G., *Optique*, 6th edition (Dunod, Paris) 2005.
- [14] LE FLOCH A., ROPARS G., ENOCH J. and LAKSHMINARAYANAN V., *Vision Res.*, **50** (2010) 2048.
- [15] RODIECK R. W., *The First Steps in Seeing* (Sinauer, Sunderland) 1998.
- [16] OYSTER C. W., *The Human Eye, Structure and Functions* (Sinauer, Sunderland) 1999.
- [17] HUBEL D. H., *Eye, Brain, and Vision* (Freeman, New York) 1988.
- [18] SHAPLEY R. and LAM D. M., *Contrast Sensitivity* (MIT Press, Cambridge, Mass.) 1993.
- [19] DRUDE P., *The Theory of Optics* (Longmans, Green; reprinted by Dover, New York) 1959.
- [20] FARADAY M., *Philos. Trans. R. Soc.*, **136** (1846) 1.
- [21] GAUTHIER D. J., NARUM P. and BOYD R. W., *Opt. Lett.*, **11** (1986) 623.
- [22] LORD RAYLEIGH, *Nature*, **64** (1901) 577.
- [23] NAIR R. R., BLAKE P., GRIGORENKO A. N., NOVOSELOV K. S., BOOTH T. J., STAUBER T., PERES N. M. R. and GEIM A. K., *Science*, **320** (2008) 1308.
- [24] BRUNNER N., BRANCIARD C. and GISIN N., *Phys. Rev. A*, **78** (2008) 052110.
- [25] DE MARTINI F., SCIARRINO F. and VITELLI C., *Phys. Rev. Lett.*, **100** (2008) 253601.
- [26] SEKATSKI P., BRUNNER N., BRANCIARD C., GISIN N. and SIMON C., *Phys. Rev. Lett.*, **103** (2009) 113601.
- [27] PERENIN M. T. and VADOT E., *Br. J. Ophthalmol.*, **65** (1981) 429.
- [28] CEPKO C., *Nat. Genet.*, **24** (2000) 99.