Optics Communications 285 (2012) 1669–1674

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Concurrent measurement of linear birefringence and dichroism in ferrofluids using rotating-wave-plate Stokes polarimeter

Jing-Fung Lin *, Meng-Zhe Lee

Graduate School of Computer Application Engineering, Far East University No.49, Zhonghua Rd., Xinshi Dist., Tainan, Taiwan, ROC

ARTICLE INFO

Article history:
Received 25 August 2011
Received in revised form 30 November 2011
Accepted 5 December 2011
Available online 15 December 2011

Keywords:
Birefringence
Dichroism
Ferrofluid
Retardance
Stokes polarimeter

ABSTRACT

In this study, an optical scheme based on Stokes–Mueller Formalism and rotating-wave-plate Stokes polarimeter is successfully developed for obtaining concurrent measurements of the linear birefringence and dichroism. For a quarter-wave plate sample, the measured values of the principal axis angle and retardance are found to have average absolute and normalized errors of 0.0859° and 0.76%, respectively, while the measured dichroism of the quarter-wave plate has an average value of 0.0203. When analyzing ferrofluid film samples with concentrations ranging from 2 to 6%, it was found that for a given concentration of ferrofluid, retardance increases with applied magnetic fields and tends to saturate at high levels. Additionally, under the condition of the same magnetic field, the experimental results show that retardance is proportional to the concentration; the higher concentration will result in more retardance and absorption. Consequently, the derived algorithm for concurrent measurements of the linear birefringence and dichroism is feasible, and the relation between the concentration and magneto-optical effect was successfully investigated.

1. Introduction

It is known that linear birefringence (LB) is caused by the different phase retardation (retardance) of two linearly polarized eigenstates of light passing through the material. It has been known that many crystals such as quartz exhibit the optical property of linear birefringence. The linearly birefringent wave plate needs to have a precise value of retardance to ensure the polarization of light and the success operation in different applications. It is noted that the LB measurement done by modulation technique was outlined in Refs. [1–6]. In addition to linear birefringence, linear dichroism (LD) is the differential absorption between two orthogonal components of linearly polarized light [7]. This phenomenon occurs with certain natural crystals, with stretched polymers and with other non-isotropic samples. When light propagates through a dichromatic material, the difference in absorption coefficients between orthogonal components changes the polarization state of light.

One of the optically anisotropic materials is ferrofluid (magnetic fluids, MFs). MFs are very stable colloidal suspensions of ultrafine single domain magnetic particles (about 10 nm in size) in a suitable carrier liquid. These magnetic liquids typically consist of metallic (Fe, Ni, or Co) cubic spinel oxidic single domain ferro- or ferrimagnetic nanoparticles, suspended in polar or non-polar solvents using suitable surfactants. They have an increasing number of commercial and industrial applications, which are a result of their unusual physical and magnetic properties. Magnetic fluids are used in mechanical devices, such as seals, bearings and dampers, and also in electromechanical devices such as loudspeakers, stepper motors, and sensors [8–9].

Of the recent interest are the magneto-optical effects, which are of use to characterize magnetic particles in suspension, and which may provide a basis for numerous device applications. The earliest investigations on magneto-optical effects in colloidal suspensions were made by Kerr (1901), Majorana (1903), and Cotton-Mouton (1907). There had been little further development in this field until stable magnetic colloidal suspensions became available in the 1960s. Since then, linear dichroism and birefringence have been the main optical effects studied in magnetic fluids [8]. Magnetic fluids as plain materials in magnetics get renewed interests in optics recently with the development of optical communications and booming of nanoscience and technology. As optically functional materials, magnetic fluids can be used to design many new-style photonic devices, for instance, optical-fiber modulator, tunable grating, wavelength-division multiplexer, optical switch, and light modulator [10].

The simultaneous measurement of two optical anisotropic properties, i.e. linear birefringence and linear dichroism, is important when both exist together in a number of situations. For the linear birefringence and linear dichroism measurements in magnetic fluids, for example in 1983, Taketomi [11] proposed a simple experimental setup for the study of birefringence in a magnetic fluid thin film. To substitute four parameters' values including the two absorption coefficients of magnetic fluids with respect to the ordinary ray and extraordinary ray

* Corresponding author. Tel.: +886 6 5979566 5364; fax: +886 6 5977510.
E-mail address: jacklin@cc.feu.edu.tw (J.-F. Lin).

0030-4018/$ – see front matter
doi:10.1016/j.optcom.2011.12.032

and the maximum and minimum transmitted intensities when rotating the analyzer, the birefringence (the difference between the refractive indices for extraordinary and ordinary light, respectively) can be easily obtained by this experimental setup and method. In 1986, an apparatus for measuring the linear birefringence and linear dichroism induced in liquids or dispersions by an applied magnetic field was proposed by Batchelor et al. [12]. On the condition that the principal axis angle is known as 45° and modulation is driven by a sinusoidal waveform, to derive the algorithm and have the disadvantages as the inability to simultaneous measurement and easier calibration.

In 1995, Gerligand et al. proposed a Mueller matrix polarimeter with the rotating polarizing element (quarter-wave plate and polarizer) and detected the intensity by a CCD camera [13]. The 16 matrix elements are obtained and the derived algorithm is used to determine the principal axis, retardance, and verify the dichroism in two ionic ferrofluids as Fe_2CoO_4 and γFe_2O_3. This paper also discussed the temperature effect and estimated the measurement error. In 2006, Kooij et al. demonstrated the versatility of spectroscopic ellipsometry in transmission mode for simultaneously measuring the linear magneto-optical quantities with high accuracy [9]. The relations between the ellipsometric quantities Ψ and Δ on one hand and the birefringence and dichroism on the other hand, are derived.

Recently, in 2009, Pu et al. developed a simple optical configuration based on a polarizer and derived the analytical expression of the transmitted elliptically polarized light [10]. From the rotation angle of the principal axis of the ellipse and the degree of polarization of the elliptically polarized light after magnetic fluids, the magnetic-field-induced linear birefringence and dichroism are investigated by numerical simulation. The results indicate that it is usually improper to ignore the linear dichroism for some applications.

The aim of the present study is to develop a simple metrology system for obtaining concurrent measurements of the linear birefringence and dichroism. Three probed lights are linearly polarized orientated at 0°, 45°, and circularly polarized, respectively, and a rotating-wave-plate Stokes polarimeter are utilized. The validity of the proposed approach is demonstrated experimentally using two samples, namely a quarter-wave plate and ferrofluids with different volume concentrations. Finally, the algorithm was successfully derived and the relation between the concentration and magneto-optic effect was investigated.

2. Methodology

2.1. Optical configuration

The optical configuration for the measurement of linear birefringence and dichroism is illustrated in Fig. 1. The measurement system consists of a light source, polarizer, quarter-wave plate, sample, and a Stokes polarimeter. A He–Ne laser with wavelength 632.8 nm is employed as the light source. Two probing linearly polarized light at 0° and 45° direction, respectively and another right-handed circularly polarized light are incident on the sample sequentially. The change in the polarization condition of the transmitted beam from the sample is monitored by measuring the Stokes parameters with a rotating-wave-plate Stokes polarimeter (Thorlabs, PA510). Subsequently, the principal axis angle, retardance, and dichroism are estimated by substituting the observed Stokes parameters of three output lights into the derived algorithm.

2.2. Principle

The polarization state of light can be completely described by a Stokes vector $S=\{S_0,\ S_1,\ S_2,\ S_3\}^T$ (where T denotes transposition). We can write the four Stokes components as

$$S=\begin{bmatrix}S_0\\S_1\\S_2\\S_3\end{bmatrix}=\begin{bmatrix}I_x+I_y\\I_x-I_y\\I_{45^\circ}-I_{-45^\circ}\\I_R-I_L\end{bmatrix}, \quad (1)$$

where S_0 is the total light intensity, S_1 represents the intensity difference between horizontal and vertical linearly polarized components, S_2 represents the intensity difference between linearly polarized components oriented at $\pm 45°$ angle, and S_3 represents the intensity difference between right and left circular components. A polarizer oriented horizontally (x), vertically (y), or at $\pm 45°$ would let light pass through with intensity $I_{x/y}$ or $I_{45^\circ/-45^\circ}$, whereas a quarter-wave plate followed by a polarizer oriented at $\pm 45°$ with respect to the slow axis of the wave plate would transmit $I_{R/L}$ as the intensity of left and right components of circular polarization.

An optic that changes the polarization state of light is modeled by a Mueller matrix (4×4) such that the inner product of the Stokes vector that models the polarization state of incident light $\hat{S}$ with the Muller matrix that models that optics M results in a Stokes vector that represents the polarization state of light exiting the optic S. According to the Stokes–Mueller formalism, the output light S is calculated by

$$S=\begin{bmatrix}S_0\\S_1\\S_2\\S_3\end{bmatrix}=\begin{bmatrix}m_{11}&m_{12}&m_{13}&m_{14}\\m_{21}&m_{22}&m_{23}&m_{24}\\m_{31}&m_{32}&m_{33}&m_{34}\\m_{41}&m_{42}&m_{43}&m_{44}\end{bmatrix}\begin{bmatrix}\hat{S}_0\\\hat{S}_1\\\hat{S}_2\\\hat{S}_3\end{bmatrix}=M\hat{S}. \quad (2)$$

The Mueller matrix M for a linearly birefringent dichroic medium, with its principal axis angle and retardance, α and β, and dichroism A is expressed as Eq. (3) [13].

$$M=\begin{bmatrix}1&AC&AS&0\\AC&C^2+S^2B\cos\beta&CS(1-B\cos\beta)&-BS\sin\beta\\AS&CS(1-B\cos\beta)&S^2+C^2B\cos\beta&BC\sin\beta\\0&BS\sin\beta&-BC\sin\beta&B\cos\beta\end{bmatrix}, \quad (3)$$

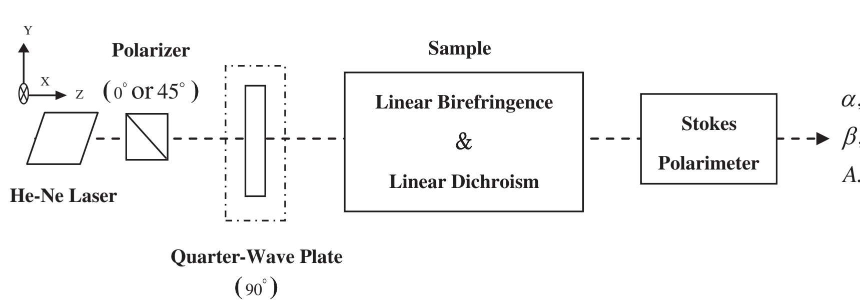

Fig. 1. Experimental setup for measuring the linear birefringence and dichroism.