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Simple spectral technique to identify the ordinary and extraordinary axes of a liquid crystal retarder

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ABSTRACT

We present a very simple method to distinguish between ordinary and extraordinary axes in an optical retarder. The method is based on inserting the retarder in between two crossed linear polarizers, oriented at 45° to the neutral axes. By tilting the retarder to obtain oblique-incidence illumination, a different behavior is observed depending on the orientation of the ordinary/extraordinary axes relative to the tilt direction. Simply using white light illumination from a tungsten lamp and spectral analysis by means of a portable spectrometer, it is possible to differentiate between ordinary and extraordinary axes. Theoretical analysis is provided, as well as the experimental verification with a liquid crystal variable retarder (LCR). A significant difference of the LCR retardance variation is obtained for different orientation of the LC director relative to the tilt direction.

1. Introduction

Linear wave-plates (or linear retarders) are key elements in most optical systems requiring control of the state of polarization (SOP) [1]. They are made of anisotropic uniaxial material where the optical axis lies in the plate plane. Two parameters must be known for their proper use: the retardance ϕ they introduce between ordinary and extraordinary waves for the operating wavelength (λ), and the orientation of the principal optical axis relative to the laboratory reference frame.

Under the common assumption of a linear retarder (i.e., devoid of depolarization or diattenuation), the neutral axes can be found by simply inserting the retarder between crossed polarizers. Since retarders are usually mounted on in-plane rotatable mounts, their neutral axes are found by rotating the retarder and searching for the angles where a null transmission between the crossed polarizers is retained. However, this simple method does not resolve the ambiguity among the ordinary and extraordinary neutral axis.

In addition, different methods have been developed to measure the waveplates' retardance [2]. Those based on heterodyne interferometry provide very precise measurements [3,4], but they are limited to use monochromatic light with specific wavelength and require complex systems. Other techniques use spectral measurements. When the wave-plate is inserted between crossed polarizers, and the system is illuminated with a continuous broadband light source, the transmitted light exhibits an oscillating spectrum due to the approximated λ^{-1} dependence of the spectral retardance $\phi(\lambda)$ [5–8]. However, again, these methods do not distinguish between ordinary and extraordinary axes.

Therefore, different techniques have been developed to distinguish between fast and slow axes. They are usually based in precise phase measurements for orthogonal polarization components using the heterodyne interference technique [9–12]. In Ref. [12] an oblique incidence on the wave-plate was selected. Another technique requires a prism retarder as a reference, so the combination of the test wave-plate with the prism reveals the relative orientation of their neutral axes [13]. The technique in Ref. [14] is based on measuring the intensity reflected on a metallic surface as a function of the angle of incidence when the incident light first traverses the wave-plate.

The distinction between ordinary and extraordinary axes can be especially relevant in liquid crystal variable retarders (LCR), where the orientation of the optical axis changes with applied voltage. In ferroelectric LCRs, the optical axis switches between two stable positions within the wave-plate plane [15], while in nematic LCRs it tilts towards the direction of light propagation,

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eventually canceling the effective retardance [16,17]. The spectral characterization method described above has been usually employed to determine the retardance wavelength and voltage dependence in LCR devices [18,19], properties that are useful to develop tunable wavelength filters [20]. In all these works, normal incidence was carefully selected in order to measure the retardance, since non-normal incidence might significantly affect the measurements. Using a three position configuration of the polarizers it is possible to also deduce the optic axis orientation [21].

The extraordinary axis of a nematic LCR can be distinguished if the device is inserted in an interferometer [22]. Since the applied voltage affects the effective extraordinary index, a variation is detected for light polarized along this axis, while no variation is observed when it is polarized along the ordinary axis. If the reflections at the LC layer are non-negligible, a Fabry–Perot multiple beam interference is produced, and the voltage dependent variations are directly observed in transmission measurements [23,24]. However, these effects do not occur if the device includes antireflective coatings.

Therefore, the goal of this work is to present a general and simple method to distinguish between the ordinary and extraordinary axes of a linear wave-plate. Our method is based on the different effective retardance obtained when the retarder is illuminated under oblique incidence. This different behavior is very easily observed with a spectral characterization method. The transmitted spectrum looks significantly different when the optical axis lies parallel or perpendicular to the wave-plate plane of rotation relative to the incident light. We present experimental results that validate the method using a nematic LCR.

Note that the proposed method is closely related to the crystal rotation technique, which can be used to measure pretilt angles in LC devices [25]. This pretilt angle makes the optical axis do not lie exactly in waveplate plane. And it induces a difference in the effective retardance with the angle of incidence that can be resolved the heterodyne methods. Our approach differs since we consider the optical axis in the waveplate plane. We use the spectral technique to easily visualize effective retardance changes, in order to easily identify the ordinary and extraordinary axes. The method is useful for static crystal waveplates as wells as for dynamic LCR devices.

The paper is organized as follows. A theoretical analysis based on the propagation of ordinary and extraordinary waves inside the LC layer is developed in Section 2. Then, in Section 3, the experimental arrangement is explained. It is rather simple since it only requires broadband white light illumination and spectral characterization with a spectrometer. Experimental results are included in Section 4. Finally Section 5 presents the conclusions of the work.

2. Retardance for non-normal incidence

It is well known that when a linear retarder is illuminated under normal incidence, the ordinary and extraordinary waves travel collinear. And the retardance introduced by a retarder composed of a single anisotropic layer at normal incidence is given by

$$\phi = \phi_e - \phi_o = \frac{2\pi d}{\lambda}(n_e - n_o), \tag{1}$$

where ϕ_e and ϕ_o stand for the phase gained by the extraordinary and ordinary waves, λ is the wavelength, n_e and n_o are the extraordinaty and ordinary refractive indices, and d denotes the width of the anisotropic layer.

However if the incidence is not normal, the calculation of the retardance requires an analysis in terms of the wave propagation inside an anisotropic media. The general analysis of the propagation of light in anisotropic crystals can be found in many texts [26,27], and specifically applied for liquid crystals for instance in [28]. General expressions for arbitrary general media can be found on [29,30].

For simplicity, we will concentrate here on the situation where the optical axis lies in the plate plane, and oblique incidence is considered. We ignore the amplitude variation caused by the difference in reflection and transmission coefficients for non-normal incidence. The effective retardance for the transmitted beam is calculated when the wave-plate is tilted, as schematized in Fig. 1.

The purpose of this section is to derive the expression of the retardance ϕ as a function of the angle of incidence θ. The general situation was analyzed in terms of Jones calculations in [31]. Here we briefly include the derivation of the effective retardance for the situation sketched in Fig. 1. Although the derivation is general, figures will consider the usual case for nematic liquid crystals, which are positive uniaxial materials, therefore with $n_e > n_o$. The

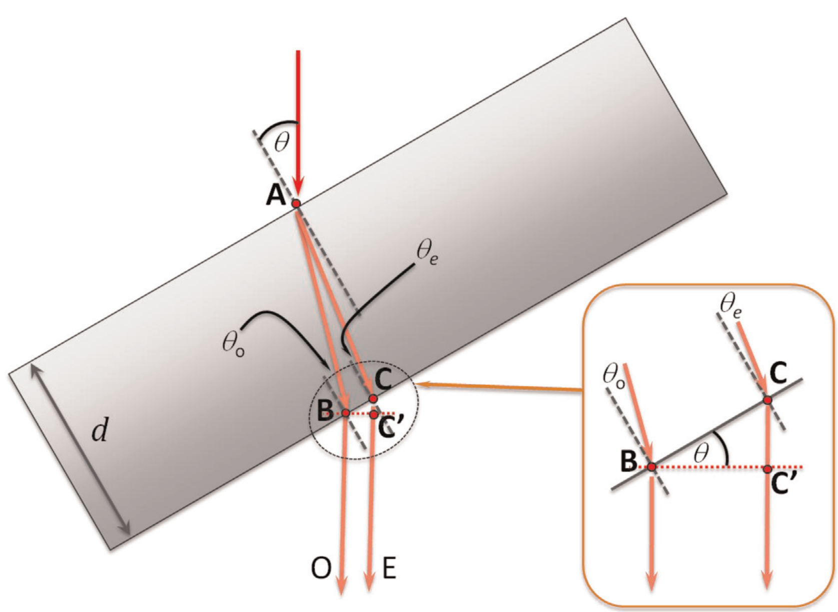

Fig. 1. Scheme of calculating the retardance with non-normal incidence.