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Light polarization states of a cholesteric liquid crystal probed with optical ellipsometry

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ABSTRACT

Herein a useful methodology to study optical properties of cholesteric liquid crystals (Ch-LC) is proposed by using the Fourier decomposition ellipsometry technique to calculate the Stokes parameters of transmitted and reflected light in the UV–Vis spectral range. Combining Bragg reflection and optical activity we were able to obtain ~100% of linear or circular light polarization from the Ch-LC sample using achromatic and non-polarized light source. The photonic bandgap and the polarization components can be controlled with the temperature as a result of alterations in the helix pitch of the cholesteric phase. Finally, it is demonstrated the correlation between the dissymmetry factor (g) calculated via the Stokes parameter S_3 and the reflection spectrum. The data revealed that the maximum value of S_3 is not coincident with the peak of maximum reflection. The reflected or transmitted light analysis via Stokes parameters obtained by ellipsometry showed an alternative and low cost method for optical characterization in Ch-LC.

1. Introduction

Cholesteric liquid crystals (Ch-LC) have been used as non-conventional optical elements in circularly polarized light sources, photonic effects (Bragg's reflection), and temperature probes due to the periodic and twist director vector around the cholesteric helical axis [1,2]. In particular, Ch-LC light reflection depends directly on the helical pitch, which can be controlled by the temperature of the sample. The classic plate-spring mnemonic model explains the temperature sensitivity of the molecular macrostructure, considering the planes of molecules being connected by springs [3]. When the Ch-LC is cooled down, the springs elongate and the sample reflects longer wavelengths (bathochromic shift). On the other hand, when the temperature increases, the springs are compressed and the reflected wavelengths are shorter (hypsochromic shift) [4,5]. Furthermore, these materials feature sufficient optical stability for many applications [6–9]. The main applications of chiral macrostructures include: bistable cholesteric reflective displays [10–14], optical filter for circularly polarized light in LCDs [15], electrically switchable mirrors [16], chiral pharmaceutical resolution [17], and photonic band gap materials [18,19].

The well-established dissymmetry factor (g) has been used to characterize the reflected or transmitted circular light polarization state of Ch-LC when circular polarized sources are used [3–5,12,18–24]. Alternative methods have been applied considering the emission ellipsometry technique in the Stokes theory scope for electromagnetic field [25–29]. According to the Stokes theory, it is possible to determine the light polarization states, emission, transmission or reflection measuring the light intensity and calculating the Stokes parameters S_0, S_1, S_2 and S_3. In addition, the anisotropy parameter (r) can also be calculated using the parameters S_0 and S_1 and linear polarized light [27].

In the present work the dissymmetry parameter g of a Ch-LC sample was calculated using a non-polarized UV–Vis source via the ellipsometry technique. It was found that more than 50% of the reflected light is circular polarized for non-polarized incident light and we observed that the polarization state of the reflected and transmitted light can be controlled by changing the helix pitch of the Ch-LC. We also demonstrate here that the dissymmetry factor (g) spectrum can be extracted from the Stokes parameters and

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the maximum efficiency of circularly polarized state is not coincident with the peak of the maximum reflectance spectrum.

2. Experimental

2.1. Ch-LC sample

In the present work, a helical molecular ordering is induced into a nematic phase by adding a chiral material with a proper anisometry. When the chiral dopant is mixed with a nematic host (N-host) the resulting helical pitch (p) is related to the chiral dopant by the relation: $1/p = \text{HTP} \times \text{Xc}$, where HTP and Xc are the dopant macroscopic helical twisting power and concentration, respectively [30]. HTP represents the capacity of the dopant to introduce a twist into the N phase giving rise to a cholesteric structure. Table 1 shows the main properties of the N-host (E180, Merck) and dopant (CB15, Merck) used in this work.

Herein, the Ch-LC sample was prepared by mixing E180/CB15 in 65/35 wt% proportion. The material was inserted by capillarity action in cells fabricated with two bare glass plates separated by 20 μm thick Mylar spacers. The filled cell was characterized by temperature-dependent polarized optical microscopy (POM) and UV–Vis spectrometry. Fig. 1 shows its respective transmission spectrum and POM images. The mixture reflects selectively mostly the green portion ($\lambda = 551$ nm) of the visible light spectrum, Fig. 1a. In fact, the selective reflected light is not a single wavelength but has a range of wavelengths where $\Delta\lambda = 59$ nm is product of the birefringence and the pitch of the Ch-sample. We estimated the pitch as $p = 0.43$ μm by using the relation above and considering HTP = +6.67 μm^{-1} for the chiral dopant CB15. When the Ch-sample was sandwiched between two glass-slides as described above the planar texture (or Grandjen) was observed under POM at 24.1 °C, this texture is quite stable [6–9] and we observed that the optical properties are still stable over more than one year. In Fig. 1b, the uniform area seen in transmissive mode POM is separated by several edges forming a network of disclinations. These disclinations in a texture where the helical axis is perpendicular to the substrate are called oily streaks and may be originated from inhomogeneities in cell spacing. However, the oily streaks are not visible in reflective mode POM. After, three heating/cooling cycles at 1 °C/min the following thermal behavior was determined for the Ch-sample: 23 Ch 43 I, where Ch = Cholesteric phase and I = Isotropic phase.

2.2. Methods

UV–Vis spectroscopy was carried out by focusing white light beam on the sample, using a Deuterium–Tungsten lamp (Ocean Optics DTmini). The transmitted or reflected light was collected with a portable CCD spectrometer (Ocean Optics USB 2000). To obtain the polarized absorbance and the circular dichroism spectra an achromatic polarizer (Newport 10LP-VIS-B) and an achromatic quarter-wave-plate (Newport 10RP54-1) were inserted between the lamp and the sample. The Stokes parameters of transmitted or reflected light were obtained with the EE technique as previously reported [25,31]. Diffuse reflection of the sample was considered with normal incidence and reflection collected at 40°. A homemade heater system was used to control the sample temperature between 23 and 35 °C.

3. Results

Fig. 2a shows the absorbance, reflectance, and circular dichroism (CD) spectra of the Ch-LC sample at 23 °C. As the Ch-LC reflects circular polarized light, the CD spectra present left-handed helical twist. Theoretically, the light should be totally reflected and not giving rise to an absorption signal in the same helical twist direction. However, part of the absorption spectrum (photonic behavior) is due to the reflectance generated by Bragg's interference. This behavior is typical of liquid crystals in planar configuration [6] and it is related to a stable state with unique features. Fig. 2b displays the reflectance spectra for different sample temperatures ranging from 23 to 35 °C. The line shape in reflectance spectra indicates the presence of large and spaced oily streaks, corroborated with the transmittance spectrum. The blue shift, in relation to the highest and lowest temperature is 70 nm and the line shape does not change for reflectance spectra by increasing the temperature of the sample. The result agrees with the theoretical prediction of the spring compression model.

In order to investigate the polarization state of the transmitted or reflected light for the Ch-LC sample the EE technique was used. The state of polarization (linear, circular, and random) of the electromagnetic field can be experimentally determined through the Eq. (1) [5,25,26,31].

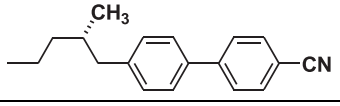
$$I(\theta) = \frac{1}{2}[A + B\sin(2\theta) + C\cos(4\theta) + D\sin(4\theta)] \quad (1)$$

where I is the field intensity, θ is the angle between the quarter wave plate and the fixed vertical linear polarizer, $A = S_0 - \frac{S_1}{2}$, $B = S_3$, $C = -\frac{S_1}{2}$, and $D = -\frac{S_2}{2}$) S_0, S_1, S_2, and S_3 are Stokes' observables: S_0 is assigned to the total intensity, S_1 is the amount of linearly polarized light at vertical or horizontal direction, S_2 is related to the amount of linearly polarized light rotated at +45° or −45° direction, and S_3 is the intensity of right- or left-handed circularly polarized light. The polarization degree (P) of the analyzed light can be calculated by [25,26,31]:

$$P = \frac{(S_1^2 + S_2^2 + S_3^2)^{1/2}}{S_0}. \quad (2)$$

Fig. 3a and b shows typical ellipsometry curves at 23 °C for the reflected and transmitted light, respectively. The black solid lines in Fig. 3 are the fittings using Eq. (1). The Ch-LC sample was probed with a non-polarized white light and the signal detected at the maximum of the reflectance spectrum ($\lambda_d = 545$ nm), see Fig. 2b. Table 2 lists the Stokes parameters S_1, S_2, and S_3 normalized by the arbitrary intensity S_0 at different sample temperatures using Eq. (1) (see all curves in Supporting information). The polarization degree P was calculated using Eq. (2) for the transmitted (T) and reflected (R) light. The parameter P and the normalized Stokes

Table 1
N-host and chiral dopant properties.

Material	Δε	Δn	HTP	Chemical composition	Thermal behavior (°C)[a]
E180 (N-host)	+3.7	0.1450	–	Mixture of ciano biphenyls and terphenyls	K > −30 N 61 I
CB15 (dopant)	–	–	+6.67		K 4 N (−30) I

[a] K = crystal; N = nematic; I = isotropic liquid.