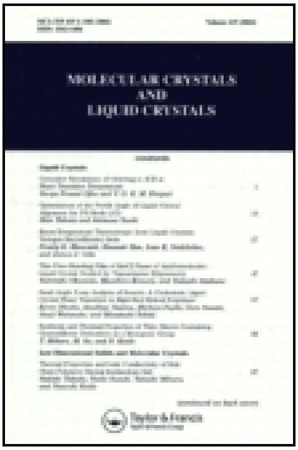

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A Liquid Crystal Broad Band Stokes-Meter

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A Liquid Crystal Broad Band Stokes-meter

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A device for the determination of the complete polarization state of light in a broad spectral interval is presented. Two tunable achromatic phase retarders with planar aligned nematic liquid crystals are used to modulate the polarization without moving components.

Keywords: liquid crystal; broad band polarimetry; achromatic phase retarder

INTRODUCTION

A Stokes-meter[1] is a device that allows to measure the complete polarization state of light including linear and circular polarization. The Stokes vector[2] $\mathbf{s} = (I, Q, U, V)$ is related to the polarization ellipse as follows.

$$\begin{aligned} Q &= P\,I \cos 2\alpha \cos 2\omega \\ U &= P\,I \sin 2\alpha \cos 2\omega \\ V &= P\,I \sin 2\omega \end{aligned} \tag{1}$$

P is the degree of polarization, I the total light intensity and α the position angle of the long axis of the polarization ellipse. The light is righthanded polarized for $V, \omega > 0$ and the ellipticity is $e = \tan|\omega|$.

The effect of an optical device on the polarization state is described by a 4 x 4 Mueller matrix **M** that is multiplied with the incoming Stokes vector[2].

$$\mathbf{s}' = \mathbf{M} \bullet \mathbf{s} \tag{2}$$

The detector measures only the total intensity I' of the resulting Stokes vector **s'**. For a complete determination of **s** it is necessary to create four different states $\mathbf{M_i}$ of the device with linear independent first rows (a_i,b_i,c_i,d_i). The measured intensities I_i' are :

$$I_i' = a_i\, I + b_i\, Q + c_i\, U + d_i\, V \quad ; \qquad i = 1,2,3,4 \tag{3}$$

If the 16 constants are known the Stokes vector **s** can be calculated from the measured intensities. Subsequently the parameters of the polarization ellipse can be found using Eq. (1).

An effective way to create the required states is to use tunable phase retarders and an analyzer. A high efficiency on both linear and circular polarization is achieved by combining halfwave and quarterwave retarders[1]. The halfwave retarder modulates linear polarization while the quarterwave retarder converts circular to linear polarization that can be measured with the analyzer. Liquid crystal (LC) retarders allow to create the four required states by switching both retarders between full and zero retardance using the electrooptic effect. If a broad spectral range is considered achromatic phase retarders[3] with retardance insensitive to wavelength are needed.

DEVICE CONSTRUCTION AND CALIBRATION

Achromatic LC phase retarders were realized using standard LC cells with x=4μm or 10μm cell gaps and 5x5mm² ITO electrodes. The LC's were chosen from a set with previously measured optical properties[4]. The 4μm cells were filled with 5CB which has a high dispersion of birefringence Δn with wavelength. The 10μm cells were filled with cyclohexane-phenyl mixtures having a low dispersion of Δn. The retardance of one 4μm cell is subtracted from that of a 10μm cell by crossing their fast axes. Due to the different dispersions of Δn the wanted retardance can be obtained for two different wavelengths and the total retardance δ (Eq. (4)) becomes insensitive to wavelength in this spectral interval[5].

$$\delta = (\Delta n_1\, x_1 - \Delta n_2\, x_2\,) \,/\, \lambda \tag{4}$$

In Fig. 1 the described quarterwave retarder is compared with a single layer retarder using 5CB that is quarterwave at 650nm (x=0.85μm). The double layer design strongly reduces dispersion. The halfwave retarder uses two 10μm cells in order to achieve the required LC layer thickness x_1.

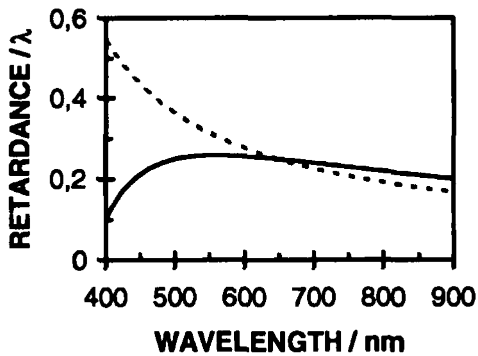
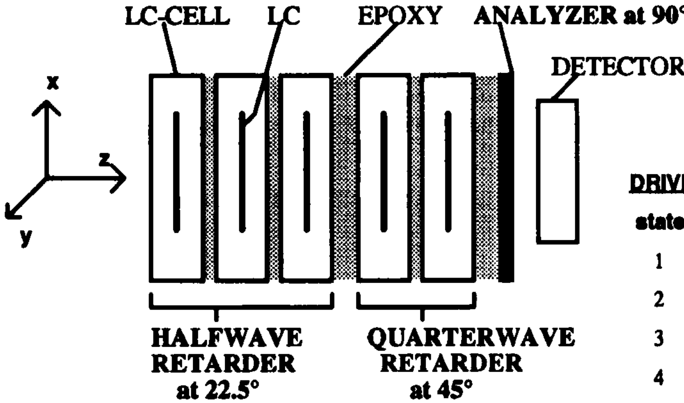


FIGURE 1 Dispersion of retardance for double cell quarterwave retarder and single layer retarder using 5CB (dotted line). T=20°C.

A sheet polarizer (extinction ratio > 10^3 for 400...750nm and 12.5 for 800nm) serves as the analyzer. With a μ-controller 2 kHz square wave driving voltages are supplied to the LC layers. The four required states are created by switching both retarders between full (planar alignment of LC) and zero (homeotropic alignment) retardance. The device is sketched in Fig. 2.

The position angles of the retarders and the transmission direction of the analyzer are chosen to give especially simple constants (a_i,b_i,c_i,d_i) in Eq. (3). However this is for ideal retarders and analyzers. In reality absorption and reflections at the material interfaces degrade transmission and modify the polarization state. The retardances change with wavelength although the achromatic design reduces this effect and the extinction ratio of the analyzer is limited. Finally alignment errors of about 1° for the individual LC cells are expected during fabrication. Thus it is necessary to calibrate the device with light of known polarization states.



DRIVING SCHEME

state	retarders	
1	λ/2	λ/4
2	λ/2	0
3	0	λ/4
4	0	0

FIGURE 2 Liquid crystal Stokes-meter. The fast axes of the retarders and the analyzer are in the x-y plane at the given angles with respect to the x-axis. Light enters from the left side.

The calibration was done with a diode line spectrometer used as detector, a Glan type polarizing prism and a LC phase retarder with known transmission and retardance smaller than halfwave for the wavelengths of interest. From collimated light of a tungsten lamp the Stokes vectors (1,1,0,0), (1,0,1,0) and (1,-1,0,0) were created with the polarizing prism set at angles $\alpha=0°$, 45° and 90°. With the measured intensities I_i' the constants a_i, b_i and c_i were calculated with Eq. (3). In order to determine the values d_i the polarizing prism was set at 0° followed by the calibration retarder at 45° giving a Stokes vector with strong circular polarization ($V,\omega\neq0$). With the known transmission and retardance of the retarder its Mueller matrix[2], the Stokes vector produced by the combination and the constants d_i were calculated.

DEVICE PERFORMANCE

The quality and reproducibility of polarization measurements was tested in 6 test runs over a period of three weeks. The device was mounted anew for each test and conditions varied due to scattered light from other laboratory activities. Fig. 3 shows the result of a spectral measurement for a linearly polarized light beam from the polarizing prism set at a position angle of 60°.

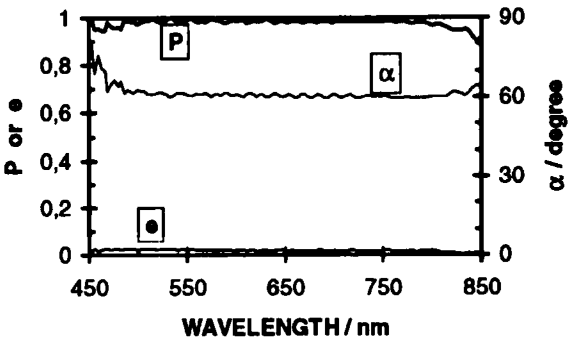


FIGURE 3 Measured degree of polarization P, ellipticity e (left scale) and position angle α of the polarization ellipse (right scale) for linearly polarized light with position angle 60°.

The device works with high efficiency in the wavelength region 500...800nm. With averaged constants (a_i,b_i,c_i,d_i) for this spectral interval we get P=0.982, e=0.018 and α=60°.58. The expected shape of the polarization ellipse (P=1,e=0,α=60°) is reproduced well. Below 500nm uncertainties arise from low light levels and beyond 800nm the extinction of the analyzer is too bad.

In Table I the results of the tests with linear polarization at position angles varying from 0° to 180° are summarized. The spectral interval is 500...800nm. The calibration was done with test 1.

TABLE I Statistics of linear polarization measurements. Number **n** of measurements, degree of polarization **P**, ellipticity **e**, error in position angle **δα** and laboratory temperature are given.

Test	n	P	e	δα	T / °C
1	3	0.988 ± 0.008	0.019 ± 0.006	± 0°.99	24.0
2	7	1.000 ± 0.000	0.034 ± 0.018	± 1°.65	24.2
3	3	0.972 ± 0.038	0.011 ± 0.008	± 1°.55	24.4
4	5	0.969 ± 0.042	0.047 ± 0.035	± 1°.58	24.5
5	4	0.958 ± 0.048	0.018 ± 0.004	± 2°.95	24.6
6	2	0.947 ± 0.031	0.020 ± 0.006	± 0°.24	25.3
total	24	0.977 ± 0.037	0.028 ± 0.023	± 1°.67	

The device measures linear polarization with high efficiency, an error in position angle below 2° and linear to circular conversion smaller than 3%. The decrease in P is due to the low clearing temperature of the biphenyl (35°C) leading to a high temperature dependence of retardance. With a double layer phase retarder using two LC's with high and equal clearing temperatures we already achieved a temperature drift below 0.05%/K compared to 2%/K for the halfwave plate used here.

The influence of oblique incidence of light was investigated with test 2. For these measurements the device was tilted arround an axis perpendicular to the transmission direction of the analyzer. The incoming collimated light beam was polarized either parallel or perpendicular to the transmission direction of the analyzer. In Fig. 4 the measured polarization P, ellipticity e and deviation $\Delta\alpha$ of position angle from the normal incidence measurement are shown.

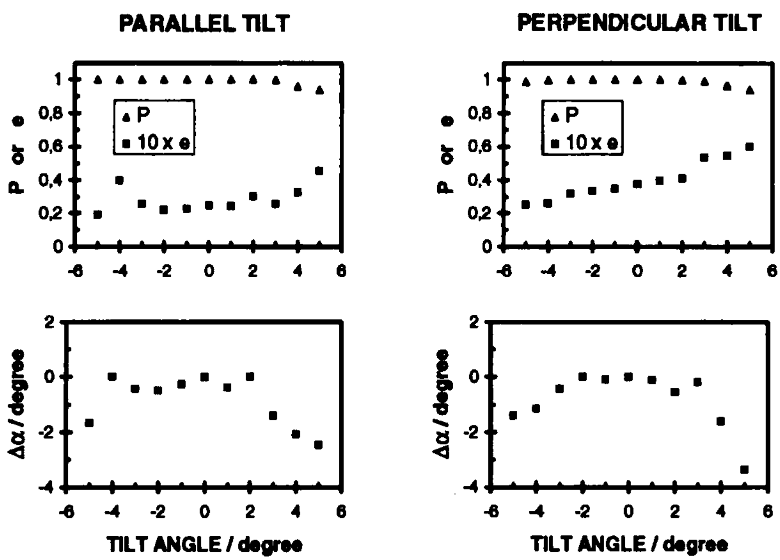


FIGURE 4 Effect of oblique incidence of light. Note that the ellipticity has been multiplied with ten.

For tilt angles between -5° and 3° the measured position angle changes less than 2°, the efficieny is 98% or better and ellipticity remains within the statistical error (Table I). Thus the device is quite insensitive to oblique incidence of light. With an acceptance angle of at least 8° it can be used in convergent light beams with a focal ratio of f/7 and in imaging applications.

In order to test the efficiency of circular polarization measurements a LC phase retarder with known properties was mounted in front of the device. The retardance is 1, 5/4,3/2 and 7/4 wavelengths for the wavelengths 770, 630, 540 and 470nm. The phase retarder at a position angle of 25° was illuminated with white light polarized linearly at a position angle of -20°. The results of measurements are shown in Fig. 5.

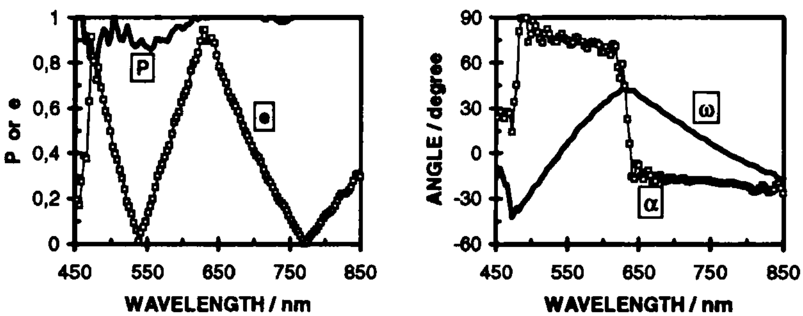


FIGURE 5 Measurement of a liquid crystal phase retarder with fast axis at 25°, illuminated with linearly polarized light at -20°.

At 770nm, where the retardance is fullwave, the incoming linear polarization remains unchanged with zero ellipticity, position angle -20° and no circular polarization (ω=0).

For 630nm the retarder acts as a first order quarterwave plate which is confirmed with an ellipticity near 1 (0.95 is measured) and ω=+45° indicating completely righthanded polarized light.

For 540nm we have a first order halfwave plate that rotates the incoming linear polarization (e=0,ω=0,α=-20°) through twice the angle between the position angles of polarizer and the retarder from -20° to +70°.

Finally at the wavelength 470nm the retarder behaves like the combination of a first order quarterwave plate with a halfwave plate. Thus the polarization state is changed like at 630nm except that the righthanded circular polarization is converted to lefthanded circular polarization ($\omega = -45°$).

It is seen that the device effectively measures the polarization state of light in a broad spectral interval including linear and circular polarization. The spectral interval can be extended in the long wavelength region with the use of a polarizing prism. The achromatism of the phase retarders can in principle be improved by combining more than two LC layers. However this is not a practical task because the ITO coating of each LC cell yields a loss in transmission of about 10%.

CONCLUSION

A device for the determination of linear and circular polarization in a broad spectral interval (500...800nm) has been demonstrated. The use of achromatic and switchable liquid crystal phase retarders ensures a compact design without moving parts. Although inexpensive float glass cells were used both linear and circular polarization are determined with high accuracy and reproducibility.

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