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Angle of View Polarization Characterization of Liquid Crystal Displays and Their Components

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Abstract

LCD performance is generally evaluated in terms of luminance and color versus viewing angle. In the present paper, we show that this type of display can be favorably characterized in terms of polarization. We show that ELDIM EZContrast instrument which is routinely used for viewing angle measurements can be upgrade for measuring the polarization state of the light at each incidence and azimuth angle. More precisely, the degree of polarization of light, its ellipticity and polarization direction can be measured at each incidence angle between 0 and 88° and for all the azimuth angles (from 0 to 360°). Important differences between the displays can be detected and related to their internal structures when luminance and color profiles are quite similar. The same setup can also be used to characterize optical components of the LCDs.

Keywords : Polarization, viewing angle, polarization degree, ellipticity

1. Introduction

LCD operation and optimization depends on the use of sophisticated polarization compensation. The objectives of these compensators are to optimize overall polarization state and consequently to obtain the highest contrast. This optimization is made for the highest large range of viewing angles to optimized appearance [1]. The entire LCD structure can be modeled to predict its polarization properties [2]. So the polarization state of light emitted by the display versus incidence and azimuth angles is important for measuring, in addition to the standard luminance and color information.

Fourier optics instruments first introduced by ELDIM in 1994 are now widely used for measuring viewing angle properties of LCDs. The well known EZContrast instrument proposed by Eldim is used to obtain luminance and color of the full viewing angle aperture in only one measurement. We present here a new option available with these EZContrast instruments which can measure the full polarization state of the light emitted by the displays in addition to luminance and color information.

2. Theory of the polarization of light

The electric field characterizing any light wave can be divided into two components:

$$E_t = E_{polarized} + E_{unpolarized} \qquad (1)$$

The polarized component can be defined by its elliptical coefficients (ellipticity ε and orientation α) as indicated in Fig. 1. Based on this representation, we are able to estimate the intensity of such a polarized light passing through a polarizer whose polarization angle is at angle θ by:

$$I(\theta) = \frac{A_0}{2}(1 + \cos 2\varepsilon \cos 2(\theta - \alpha)) \qquad (2)$$

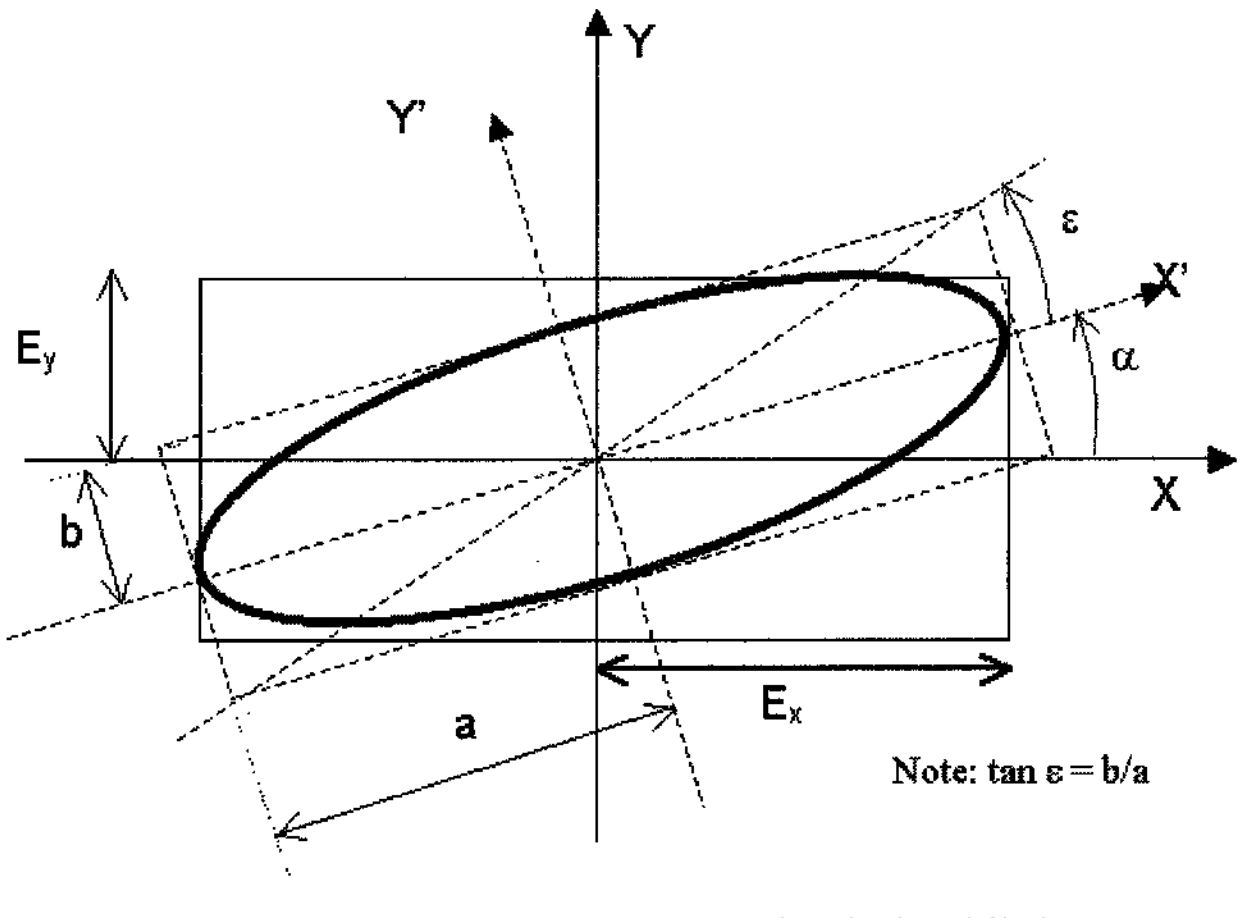

Fig. 1. Definition of elliptic parameters of polarized light.

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Unpolarized light component is only defined by the degree of polarization ρ given by the ratio of intensity due to polarized component over the total light intensity. In case of perfectly polarized light, ρ=1 and in case of complete unpolarized light ρ=0.

$$\rho = \frac{I_{\text{polarized}}}{I_{\text{total}}} \tag{3}$$

In order to be able to completely describe light polarization state, we thus need three parameters, the polarization orientation α, the polarization ellipticity ε and the degree of polarization ρ.

3. Stokes vector and Mueller formalism

These three previous parameters can be combined to a fourth one (light intensity) in order to provide Stokes vector [3]. Using the previous notations, the four Stokes parameters can be defined as:

$$S = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = I.\begin{bmatrix} 1 \\ \rho.\cos 2\varepsilon.\cos 2\alpha \\ \rho.\cos 2\varepsilon.\sin 2\alpha \\ \rho.\sin 2\varepsilon \end{bmatrix} \tag{4}$$

Mueller matrix can handle propagation of partially polarized light through optical systems. It transforms Stokes vector by successive multiplications with 4x4 matrices belonging to individual optical elements. Using this formalism, we can compute the effect of a single polarizer and combination of polarizer and a wave-plate on this Stokes vector. When measuring a Stokes vector S_e by using one polarizer whose orientation is θ, Stokes vector becomes S given by:

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta & -\sin 2\theta & 0 \\ 0 & \sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{Rotation } -\theta} . \underbrace{\begin{bmatrix} 1/2 & 1/2 & 0 & 0 \\ 1/2 & 1/2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}}_{\text{Perfect polarizer}} . \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta & \sin 2\theta & 0 \\ 0 & -\sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{Rotation } \theta} . \begin{bmatrix} I_e \\ Q_e \\ U_e \\ V_e \end{bmatrix} \tag{5}$$

Adding a wave-plate with phase rotation φ and orientation β between polarizer and light source will lead to modification of the Stokes vector as follows:

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta & -\sin 2\theta & 0 \\ 0 & \sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{Rotation } -\theta} . \underbrace{\begin{bmatrix} 1/2 & 1/2 & 0 & 0 \\ 1/2 & 1/2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}}_{\text{Perfect polarizer}} . \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta & \sin 2\theta & 0 \\ 0 & -\sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{Rotation } \theta} . \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\beta & -\sin 2\beta & 0 \\ 0 & \sin 2\beta & \cos 2\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{Rotation } -\beta} .. \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\varphi & \sin\varphi \\ 0 & 0 & -\sin\varphi & \cos\varphi \end{bmatrix}}_{\text{waveplate } \varphi \text{ phase}} . \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\beta & \sin 2\beta & 0 \\ 0 & -\sin 2\beta & \cos 2\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{Rotation } \beta} . \begin{bmatrix} I_e \\ Q_e \\ U_e \\ V_e \end{bmatrix} \tag{6}$$

On the two equations above, Ie, Qe, Ue and Ve stand for the 4 Stokes parameters of the source that we are trying to identify, and I, Q, U and V stand for the 4 Stokes parameters of the source associated to the different polarizer/retarder wave-plate used. As we only need to measure the intensity, we need to deal with only the I component of these two equations. We will need to take three measurements with a single polarizer to extract Qe and Ue. If M(θ) is the intensity measured with a polarizer orientated with an angle θ, it can be shown that:

$$\frac{M(\theta) - M(\theta + \pi/2)}{M(\theta) + M(\theta + \pi/2)} = \frac{Q_e}{I_e} \tag{7}$$

$$\frac{2M(\theta + \pi/4) - M(\theta) - M(\theta + \pi/2)}{M(\theta) + M(\theta + \pi/2)} = \frac{U_e}{I_e} \tag{8}$$

Three additional measurements combining polarizer and wave-plate orientations need to be taken in order to get information on the degree of polarization. Please note that in order to eliminate all unnecessary component of the equation, θ and β should satisfy $|\theta - \beta| = \pi/4$. In the same way, if M(θ,β) is the intensity measured with a polariser at an angle θ and wave plate at an angle β we can show that:

$$\frac{M(\theta, \beta + \pi/2) - M(\theta, \beta)}{M(\theta, \beta) + M(\theta + \pi/2, \beta)} = \frac{V_e}{I_e}\sin\varphi \tag{9}$$

$$\frac{M(\theta, \beta + \pi/2) - M(\theta + \pi/2, \beta)}{M(\theta, \beta) + M(\theta + \pi/2, \beta)} = \frac{Q_e}{I_e}\cos\varphi \tag{10}$$

We can see from equations (9) and (10) that the retardation phase of the wave-plate φ can be deduced from the measurement. A perfect quarter wave plate is then not necessary and a variation of the retardation versus wavelength can be admitted.

4. Calibration measurements

ELDIM EZContrast was modified in order to be able to achieve various measurements necessary to extract the different Stokes coefficients. Traditionally, polarizers oriented at 0°, 45° and 90° are already present in the equipment. Two wave-plates oriented at -45° and 45° were added to this existing configuration. Measurements were performed on an opal diffuser illuminated by monochromatic light coming from an integrating sphere. We thus consider that light coming from this source is totally unpolarized. Wavelength of the source was controlled through a monochromator.

First, the results reported in Fig. 2 show a non uniformity of the degree of polarization of the sample especially at high angles. This actually comes from the inner polarization of the optics of the EZContrast. This parasitic polarization should be taken into account when unknown samples are measured. It is part of the calibration and system dependant. We also analyze the evolution of the phase shift of the wave-plate as a function of the viewing angle and the wavelength of the source. As expected, phase shift is almost independent of the viewing angle (cf. Fig. 2). Comparisons between phase shift measured at normal incidence with this method and theoretical values or ellipsometric measurements show very similar results (cf. Fig. 3).

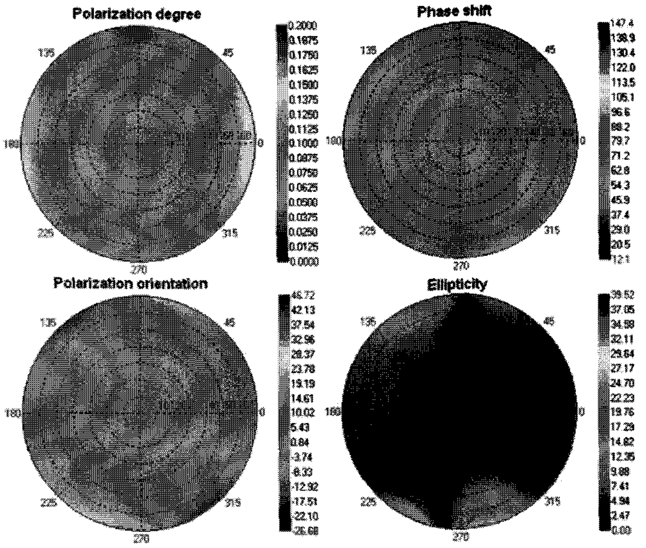


Fig. 2. Measured polarization state of an unpolarized source at 550nm. Parasitic polarization effects appear only at high incidence angles

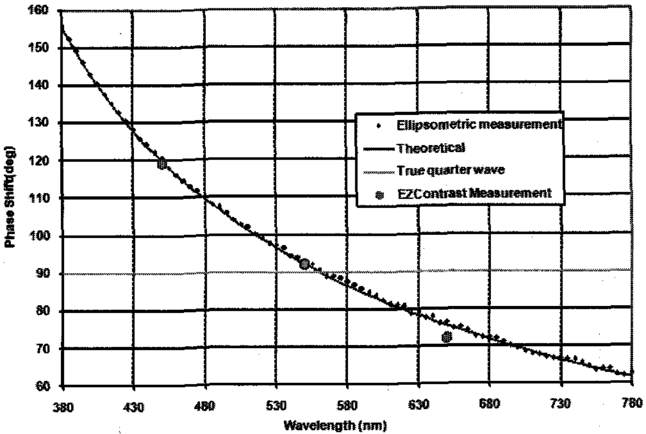


Fig. 3. Comparisons of wave-plate phase shift as a function of wavelength

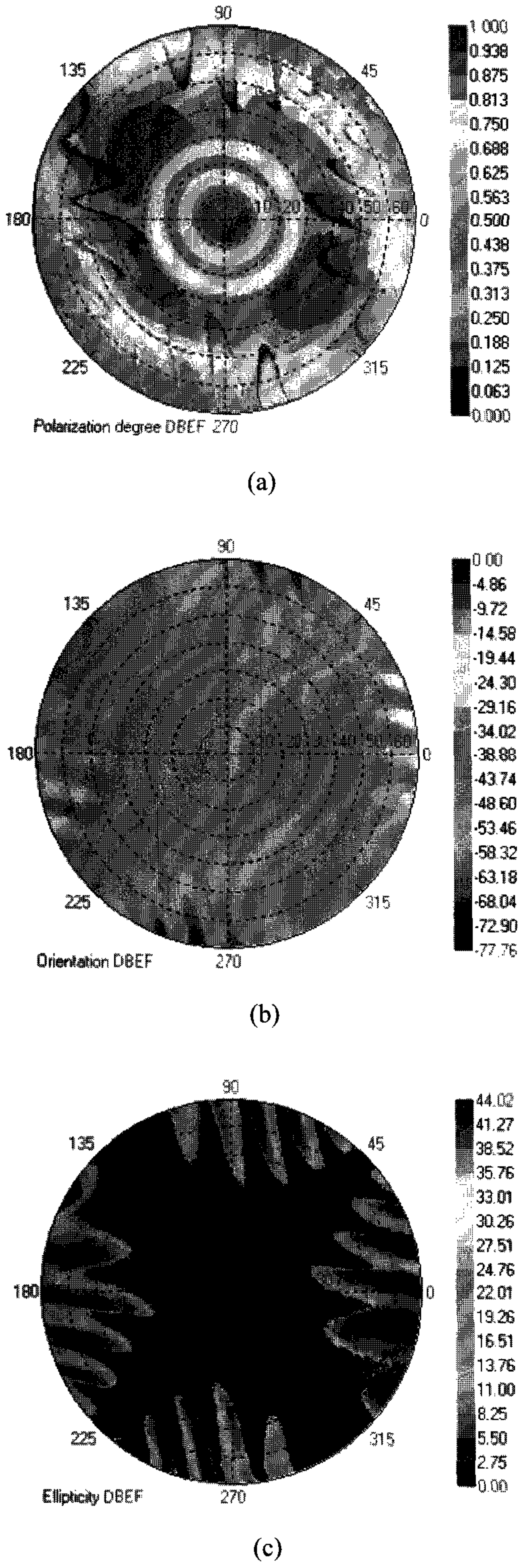
5. Measurements on DBEF and LCD

We present successively some measurements on one Dual Brightness Enhancement Film (DBEF) and one on liquid crystal display (LCD).

In case of DBEF, peculiar constitution of the film itself produces some unexpected effects. The degree of polarization evolves regularly and symmetrically due to regular structure of film (cf. Fig. 4(a)). Ellipticity remains very low and orientation is quite constant for every viewing angle (cf. Fig. 4(b)). An additional phenomenon disturbs this polarization for some wide angles introducing shift in the orientation and increase of the ellipticity (cf. Fig. 4(c)).

The same analysis can be performed on the light emitted by any LCD. In white state, the measured polarization degree remains higher than 0.9 even for wide angles (cf. Fig. 5(a)) since LCD is a polarization device. We also observe a slight distortion of the orientation of the polarization as a function of the incidence angle inherent to liquid crystal properties and polarizer imperfections (cf. Fig. 5(b)). Comparisons between polarization orientation and luminance measurement of the sample show some links between the different observed behaviors (e.g. the azimuth along which luminance remains important corresponds to the azimuth where orientation shift is the slowest, cf. Fig. 6).

It is interesting to note that the polarization analysis of the light emitted by the same LCD display in Off state. In the case the liquid crystal cell is supposed to be in cross configuration and the residual light is representative of the different imperfections. In particular, the unpolarized light contribution generally drives the contrast since this light

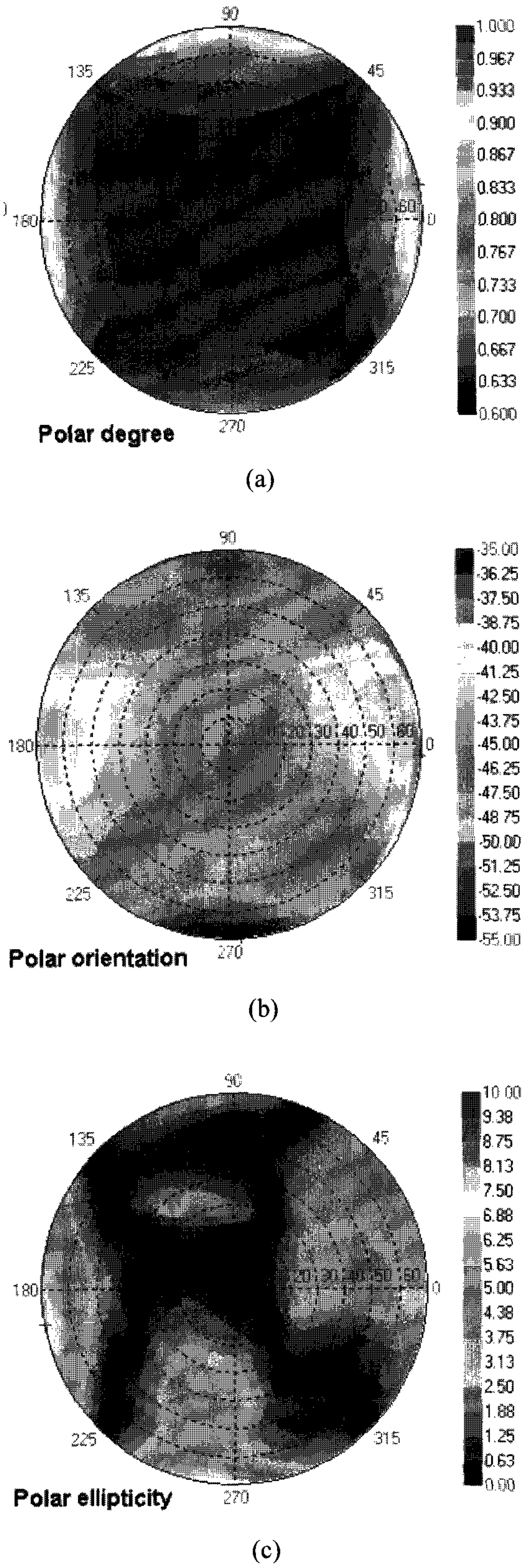


(a)

(b)

(c)

Fig. 4. Measured degree of polarization (a), polarization orientation (b) and ellipticity (c) of light after DBEF transmission.



(a)

(b)

(c)

Fig. 5. Measured degree of polarization (a), polarization orientation (b) and ellipticity (c) of light emitted by a LCD in On state.

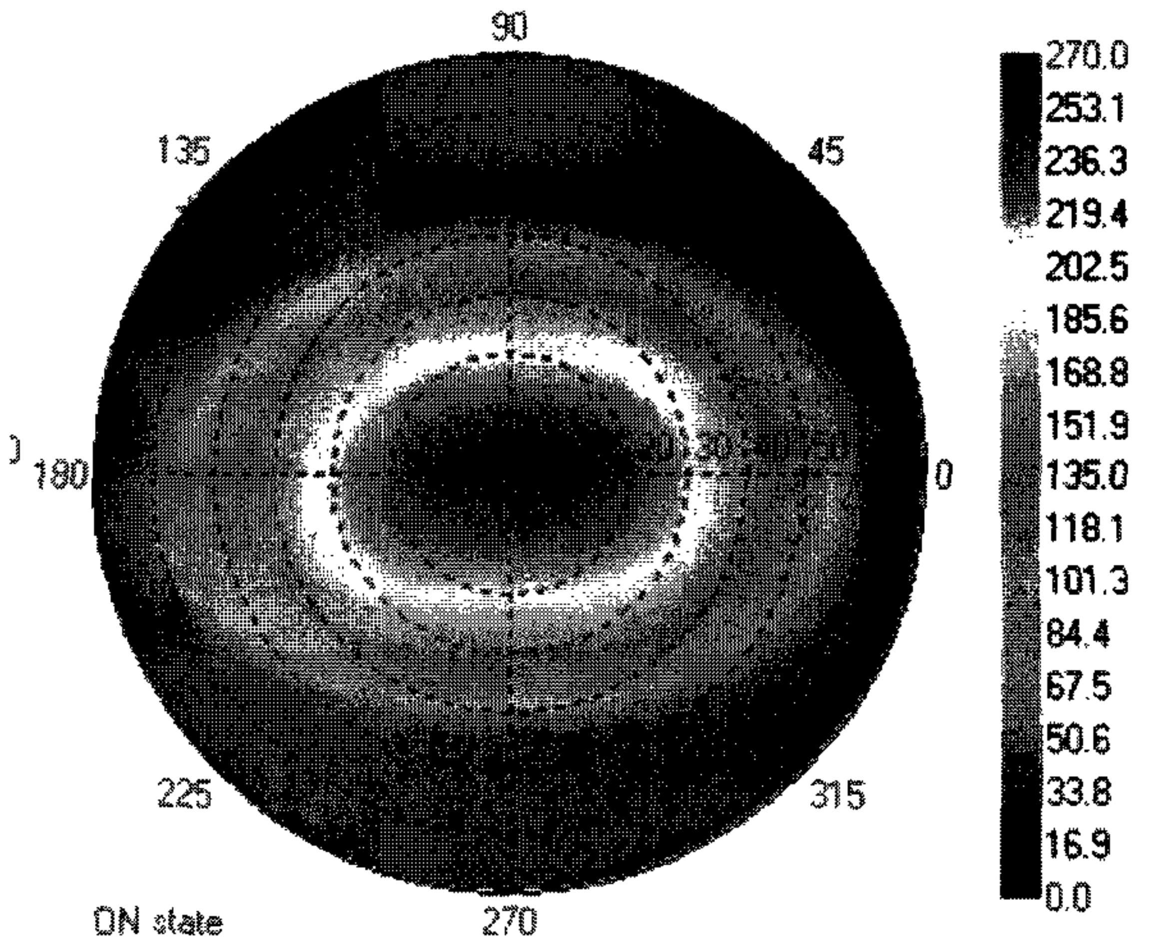
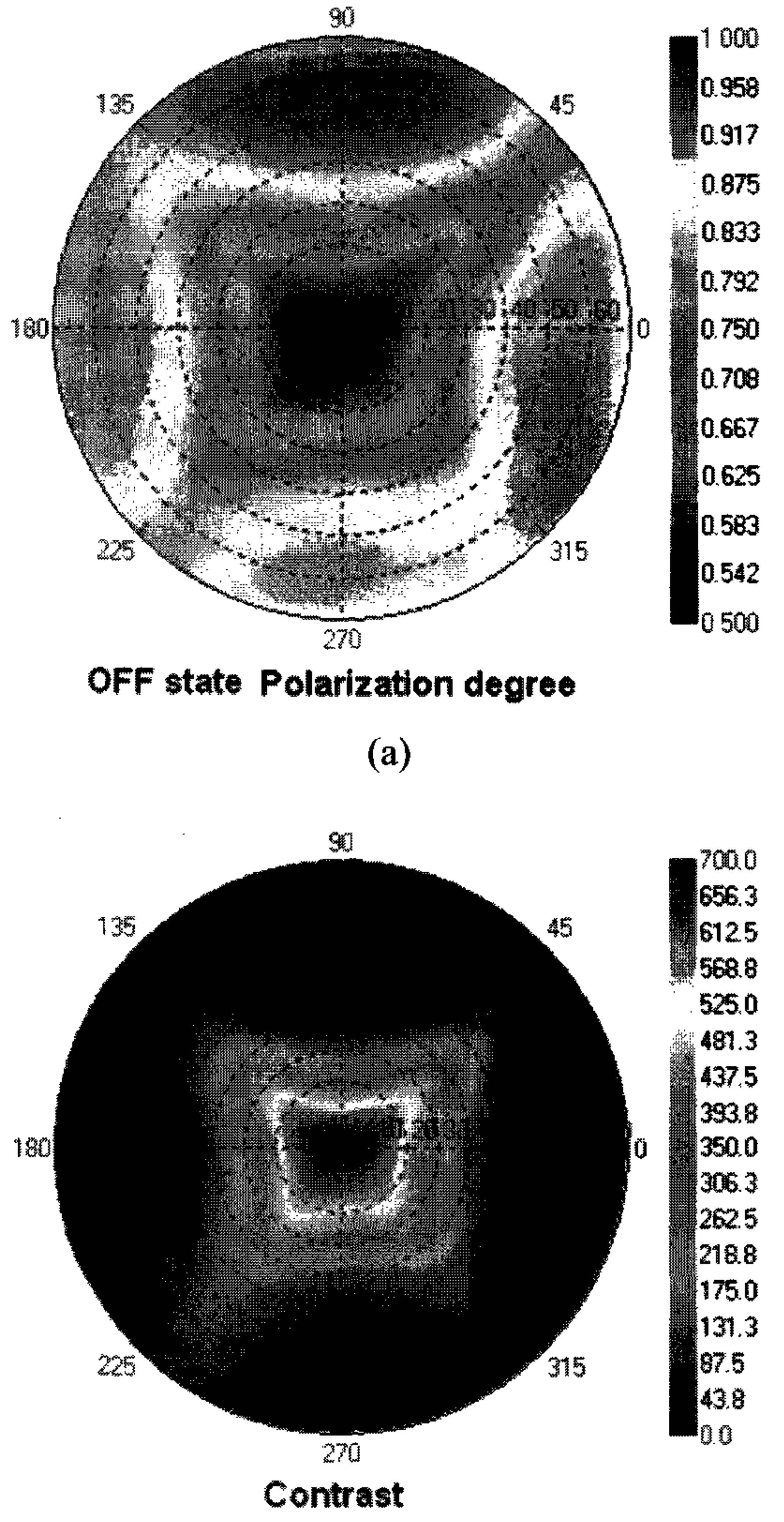


Fig. 6. Measured luminance of the LCD of Fig. 5.



(a)

(b)

Fig. 7. Measured polarization degree of Off state and comparison to luminance contrast of the LCD of figures 5 and 6

cannot be modulated by the liquid crystal cell. It is the case for the LCD discussed previously in Figs. 5 and 6. As shown in Fig. 7(a), the polarization degree in Off state is not high (about 0.5 in normal incidence). It means that half of the light detected in Off state is unpolarized and cannot be modulated by the LCD. The corresponding contrast (cf. Fig. 7(b)) is clearly limited by this parameter.

6. Conclusions

An assemblage of polarizers and wave-plates associated with Fourier optics made it possible to obtain a full viewing angle polarization characterization of any sample. By this mean, all key components of LCD can be characterized separately: from backlight and diffuser to brightness enhancement films or polarizers themselves. The polarization state of the light emitted by the LCD versus viewing angle is useful for a better understanding of the LCD behavior. In particular the polarization degree of the light detected in off state offers a good way to understand contrast limitations of LCDs.

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