OPTICAL REVIEW Vol. 21, No. 5 (2014) 642–650

# Modeling and Computer Design of Liquid Crystal Display Backlight with Light Polarization Film

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(Received March 31, 2014; Revised June 3, 2014; Accepted June 24, 2014)

The article is devoted to elaboration of the model of scattering polarization film like dual brightness enhancement film (DBEF). This model is used for computer design of backlighting system of liquid crystal display (LCD) where light polarization is important. The model elaboration required development of measurement methods and reconstruction of the parameters for the film polarization, development of the accurate computer model of the polarized light scattering on thin surface. The results of design of LCD backlight with polarization film are presented in the article as well. So it was demonstrated that design of backlight devices with DBEF is possible with help of elaborated software.


**Keywords:** polarization, DBEF, BRDF, BTDF, backlight, LCD, spectral scatterometer

## 1. Introduction

Illuminating systems of liquid crystal displays (LCD) require not only specially designed luminance distribution over the display surface but also specially designed state of polarization of light which illuminates the thin-film transistor (TFT) matrix. To obtain required light polarization state the illumination systems use specific polarization films placed just under the TFT matrix. The main disadvantage of most of films is low efficiency caused by absorption of the part (usually 40–45%) of light which polarization does not coincide with the polarization the film produces. Therefore, the efficiency of the backlight illumination system is reduced by about two times.[1)]

The solution which allows not reducing efficiency of backlight illumination system can be found if to use special polarization dual brightness enhancement film (DBEF).[2)] The film is practically free from the absorption effect and reflects the light with polarization out of film transmittance instead of its absorption. As a result, the light with polarization state not coinciding with DBEF transmittance returns to the backlight system where it continues propagation in the backlight unit. An important specific of the backlight unit construction is an application of the special structures to depolarize light reflected from the DBEF and going back to the backlight unit. Without the depolarization the light reflected from DBEF cannot pass through the DBEF finally, and an efficiency of the backlight unit will be not improved. Usually the multiple reflections from the backlight microstructure and special diffuse films allow destroying reflected light polarization that DBEF produces. All these effects have to be taken into account for the accurate computer model of the light propagation in backlight with DBEF.

The main problem of the construction of the physically accurate computational model of backlight unit is very complex model of the DBEF. The film not only polarizes light but also scatters passed and reflected light. This DBEF behavior is convenient for LCD output which usually has to provide emission in wide view angle but complicates DBEF model. Moreover manufacturers hide internal film structure that makes almost impossible elaboration of accurate mathematical model of the film. Another solution is direct measuring of polarized bi-direction scattering distribution functions (polarized BSDF). However measurements of Mueller matrix are hardly feasible at all. Therefore it seems the possible solution lies in semi-empirical model of the polarized light scattering based on measurements of polarized BSDF of the polarized film. The article shows results of measurements and reconstruction of polarized bi-direction reflection and transmittance distribution functions (BRDF and BTDF) of DBEF. Elaboration of the model of the backlight unit with DBEF and its application to the design of the backlight LCD display is also presented.

## 2. Model of the Polarized BSDF

Physically accurate light simulation with DBEF films is possible if we can construct physically correct computer model of the polarized BSDF of the film. There are two ways to elaborate the model: the first way is to solve wave equation on the film microstructure and the second way is to measure parameters of polarized light scattering. Unfortunately the first way is impossible due to lack of accurate information of the film structure. So the only possible solution is to measure the polarized BSDF.

BSDF without polarization is a luminance factor providing transformation of the surface illuminance to the surface luminance. As the transformation depends on incident and output angles and light spectrum this luminance factor is 5D

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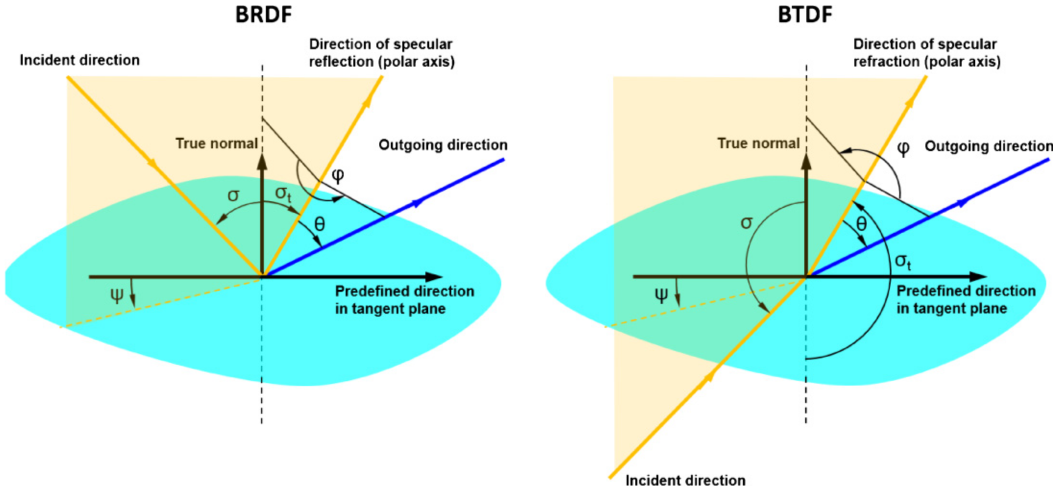


Fig. 1. (Color online) Coordinate systems of BRDF and BTDF.

function of wavelength and angles of observation and illumination:

$$L(\psi,\sigma,\varphi,\theta,\lambda) = BSDF(\psi,\sigma,\varphi,\theta,\lambda)\cdot E(\psi,\sigma,\lambda), \quad (1)$$

where $L$ is a surface luminance, $E$ is a surface illuminance, $\lambda$ is a wavelength of illumination and observation, $\psi$ is the azimuth of light incidence in the plane of the local surface normal, $\sigma$ is the polar angle of light incidence from the local surface normal, $\varphi$ is the azimuth of observation in the plane of the "specularly" reflected (transmitted) axis, and $\theta$ is the polar angle of observation from the "specularly" reflected (transmitted) axis.

Figure 1 demonstrates coordinate systems of BRDF and BTDF.

For accurate simulation of backlight like devices the most optimal solution is storing results of BSDF measurements as 5D table of Mueller matrix. Muller matrix provides correct transformation of light ray polarization when effects of the coherence are not important. That is in the case of light polarization the luminance and illuminance from (1) are represented as Stokes vectors while luminance factor is present as Mueller matrix:

$$\begin{pmatrix} L_1(\psi,\sigma,\varphi,\theta,\lambda) \\ L_2(\psi,\sigma,\varphi,\theta,\lambda) \\ L_3(\psi,\sigma,\varphi,\theta,\lambda) \\ L_4(\psi,\sigma,\varphi,\theta,\lambda) \end{pmatrix} = \begin{pmatrix} BSDF_{11}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{12}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{13}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{14}(\psi,\sigma,\varphi,\theta,\lambda) \\ BSDF_{21}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{22}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{23}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{24}(\psi,\sigma,\varphi,\theta,\lambda) \\ BSDF_{31}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{32}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{33}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{34}(\psi,\sigma,\varphi,\theta,\lambda) \\ BSDF_{41}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{42}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{43}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{44}(\psi,\sigma,\varphi,\theta,\lambda) \end{pmatrix} \times \begin{pmatrix} E_1(\psi,\sigma,\lambda) \\ E_2(\psi,\sigma,\lambda) \\ E_3(\psi,\sigma,\lambda) \\ E_4(\psi,\sigma,\lambda) \end{pmatrix}. \quad (2)$$

The first component of the Stokes vector corresponds to full light intensity (luminance or illuminance). Other components of the Stokes vector describe state of light polarization (linear, circular and elliptic). Namely, the second component of the Stokes vector is an intensity difference between horizontal and vertical linearly polarized components, the third component is an intensity difference between linearly polarized components oriented at $\pm 45°$, and the last component is intensity difference between right and left circular polarized components.

To obtain all values of the polarized BSDF (2) we need to measure the various parameters of the polarization of the sample luminance ($L_1(\psi,\sigma,\varphi,\theta,\lambda), L_2(\psi,\sigma,\varphi,\theta,\lambda), L_3(\psi,\sigma,\varphi,\theta,\lambda), L_4(\psi,\sigma,\varphi,\theta,\lambda)$) for various parameters of the polarization of the sample illumination ($E_1(\psi,\sigma,\varphi,\theta,\lambda), E_2(\psi,\sigma,\varphi,\theta,\lambda), E_3(\psi,\sigma,\varphi,\theta,\lambda), E_4(\psi,\sigma,\varphi,\theta,\lambda)$) and then solve system of corresponding 16 linear equations deduced from (2). Taking into account that only light energy ($L_1(\psi,\sigma,\varphi,\theta,\lambda)$—the first component of the vector Stokes) can be directly measured we have to use special polarization filters with the defined Mueller matrices in the light channels of illumination and observation. Figure 2 shows general scheme of the measurements. As a result, Eq. (2) is modified to the following:

$$L(\psi,\sigma,\varphi,\theta,\lambda) = F^o(\psi,\sigma,\varphi,\theta,\lambda)\cdot BSDF(\psi,\sigma,\varphi,\theta,\lambda) \cdot F^i(\psi,\sigma,\varphi,\theta,\lambda)\cdot E(\psi,\sigma,\varphi,\theta,\lambda), \quad (3)$$

where

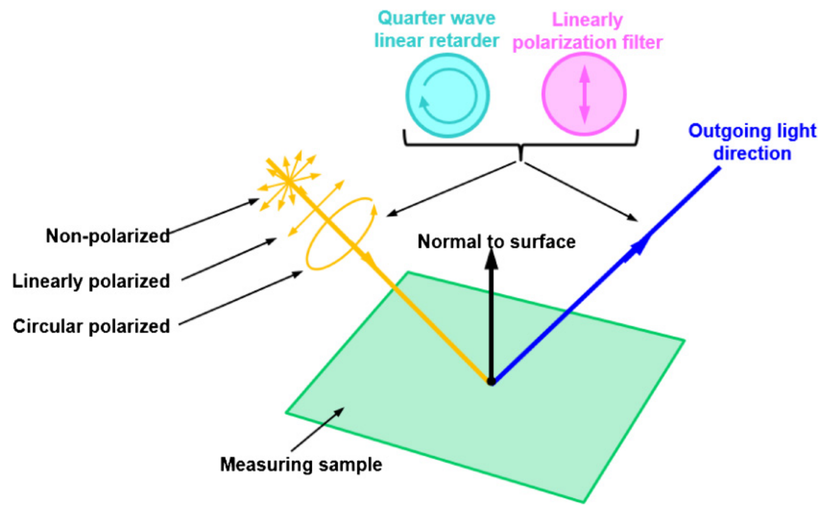


Fig. 2. (Color online) General scheme of polarized BRDF and BTDF measurements.

$$L(\psi,\sigma,\varphi,\theta,\lambda)=\begin{pmatrix}L_1(\psi,\sigma,\varphi,\theta,\lambda)\\L_2(\psi,\sigma,\varphi,\theta,\lambda)\\L_3(\psi,\sigma,\varphi,\theta,\lambda)\\L_4(\psi,\sigma,\varphi,\theta,\lambda)\end{pmatrix},\qquad E(\psi,\sigma,\varphi,\theta,\lambda)=\begin{pmatrix}E_1(\psi,\sigma,\lambda)\\E_2(\psi,\sigma,\lambda)\\E_3(\psi,\sigma,\lambda)\\E_4(\psi,\sigma,\lambda)\end{pmatrix},$$

$$BSDF(\psi,\sigma,\varphi,\theta,\lambda)=\begin{pmatrix}BSDF_{11}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{12}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{13}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{14}(\psi,\sigma,\varphi,\theta,\lambda)\\BSDF_{21}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{22}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{23}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{24}(\psi,\sigma,\varphi,\theta,\lambda)\\BSDF_{31}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{32}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{33}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{34}(\psi,\sigma,\varphi,\theta,\lambda)\\BSDF_{41}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{42}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{43}(\psi,\sigma,\varphi,\theta,\lambda) & BSDF_{44}(\psi,\sigma,\varphi,\theta,\lambda)\end{pmatrix},$$

$F^o(\psi,\sigma,\varphi,\theta,\lambda)$ is the Mueller matrix of polarization filter in light channel of the observation, $F^i(\psi,\sigma,\varphi,\theta,\lambda)$ is the Mueller matrix of polarization filter in light channel of the illumination.

Applying different polarization filters (filters of linear polarization, filters of circular polarization or excluding filters at all) in the light channels of illumination and observation it is possible to fulfill 16 independent measurements of sample luminance and wholly reconstruct polarized BSDF.

To reduce number of measurements we investigated character of the polarization of the light scattered on DBEF sample. In investigation we used the limited numbers of wavelengths and directions of illumination and observation. Our investigation proved linear character of light polarization[3–5] scattered with DBEF sample that allowed reducing number of measurements to four independent ones done for different orientations of filter of linear polarization in illumination channel only. In this case, using unpolarized light source and unpolarized light detector (3) is reduced to

$$L_1(\psi,\sigma,\varphi,\theta,\lambda)=BSDF_F(\psi,\sigma,\varphi,\theta,\lambda)\cdot E_1(\psi,\sigma,\varphi,\theta,\lambda),$$
$$BSDF_F(\psi,\sigma,\varphi,\theta,\lambda)=\begin{pmatrix}BSDF_{11}(\psi,\sigma,\varphi,\theta,\lambda)\cdot F^i_{11}(\psi,\sigma,\varphi,\theta,\lambda)+\\BSDF_{12}(\psi,\sigma,\varphi,\theta,\lambda)\cdot F^i_{21}(\psi,\sigma,\varphi,\theta,\lambda)+\\BSDF_{13}(\psi,\sigma,\varphi,\theta,\lambda)\cdot F^i_{31}(\psi,\sigma,\varphi,\theta,\lambda)+\\BSDF_{14}(\psi,\sigma,\varphi,\theta,\lambda)\cdot F^i_{41}(\psi,\sigma,\varphi,\theta,\lambda)\end{pmatrix}, \tag{4}$$

where $BSDF_F(\psi,\sigma,\varphi,\theta,\lambda)$ is an "unpolarized" BSDF which can be measured on goniospectrophotometer when polarization filter was added to the illumination channel.

Finally, solving (4) for different parameters of the polarization filter the Mueller matrix of BSDF for the fixed wavelength and directions of observation and illumination has the following:

$$BSDF=\frac{1}{2}\begin{pmatrix}\tau_{\max}+\tau_{\min} & \cos(2\delta)(\tau_{\min}-\tau_{\max}) & \sin(2\delta)(\tau_{\min}-\tau_{\max}) & 0\\\tau_{\min}-\tau_{\max} & \cos(2\delta)(\tau_{\min}+\tau_{\max}) & \sin(2\delta)(\tau_{\min}+\tau_{\max}) & 0\\0 & -2\sin(2\delta)\sqrt{\tau_{\min}} & 2\cos(2\delta)\sqrt{\tau_{\min}} & 0\\0 & 0 & 0 & 2\sqrt{\tau_{\min}}\end{pmatrix}. \tag{5}$$

Parameters $\tau_{\min}$, $\tau_{\max}$, and $\delta$ of the matrix are calculated on the base of BSDF measurements done for orientations 0, 90, 45, and 135° of linear polarization filter in the illumination channel. The following dependence of the measured scalar values of the luminance factor allows reconstructing $\tau_{\min}$, $\tau_{\max}$, and $\delta$ coefficients:

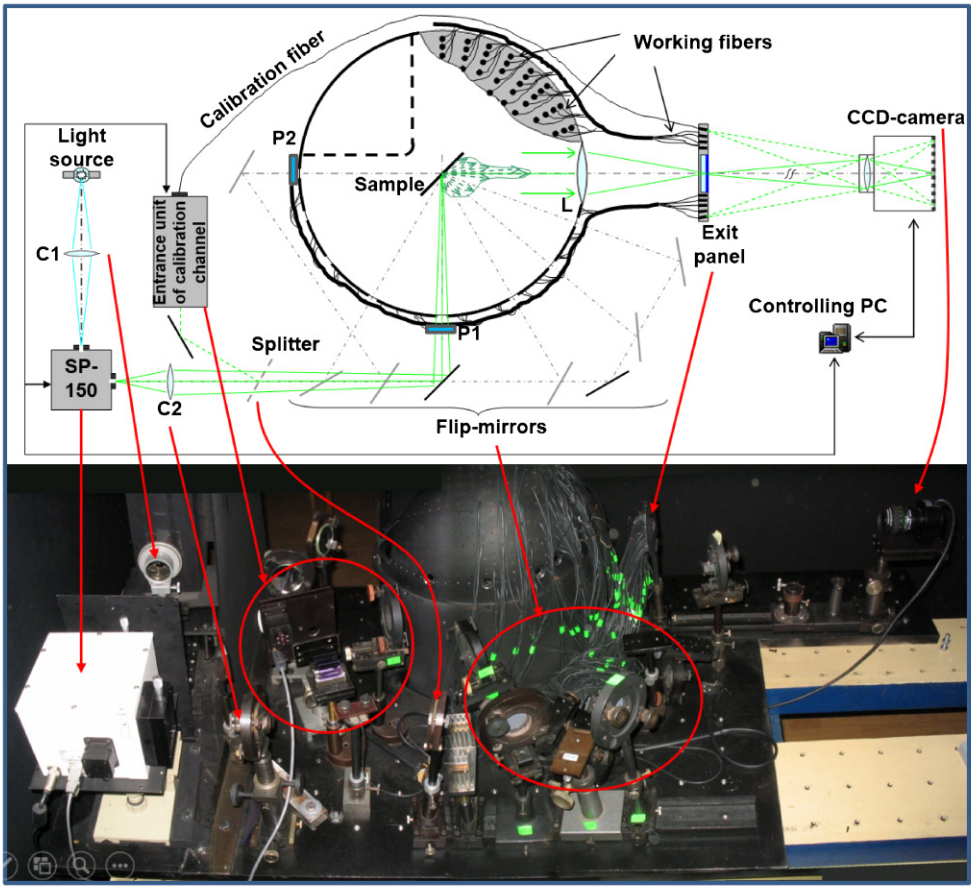


Fig. 3. (Color online) General scheme of measurement installation.

$$
\begin{aligned}
&(\tau_{\min} + \tau_{\max}) = BSDF_0 + BSDF_{90},\\
&(\tau_{\min} + \tau_{\max}) = BSDF_{45} + BSDF_{135},\\
&(\tau_{\min} - \tau_{\max}) = -\frac{1}{2}\sqrt{(BSDF_{90} - BSDF_0)^2 + (BSDF_{45} - BSDF_{135})^2},\\
&\delta = \frac{1}{2}\arccos\left(2\frac{BSDF_0 - BSDF_{90}}{\sqrt{(BSDF_{90} - BSDF_0)^2 + (BSDF_{45} - BSDF_{135})^2}}\right) - \psi,\\
&\delta = \frac{1}{2}\arcsin\left(2\frac{BSDF_{135} - BSDF_{45}}{\sqrt{(BSDF_{90} - BSDF_0)^2 + (BSDF_{45} - BSDF_{135})^2}}\right) - \psi,
\end{aligned}
\tag{6}
$$

where $BSDF_0$, $BSDF_{45}$, $BSDF_{90}$, and $BSDF_{135}$ are BSDF measured with filters of linear polarization in the illumination channel which orientations are 0, 90, 45, and 135° with respect to the plane of polarization of DBEF correspondingly.

## 3. Construction of the Polarized BSDF on the Base of Direct Measurements

Measurements of unpolarized BSDF is standard procedure now. It can be fulfilled on specialized goniospectrometers like NIST[6] or GSP-10x (commercial goniospectrometer produced by Murakami). Main disadvantage of these goniospectrometers is very long measurement process. The measurement of DBEF sample requires many measurements of the luminance factors of the sample. Number of measurements is about two orders of magnitude more than number of measurements necessary for isotropic sample. So the polarized measurements of DBEF sample were performed using an advanced technological base — Integra's spectral scatterometer.[7] Figure 3 shows scheme and photo of the Integra's spectral scatterometer. Main advance of this spectral scatterometer is possibility to measure full BSDF for one direction and polarization of light incidence in one-step that speedups measurement process in order of magnitude. Below are details of the Integra's spectral scatterometer.

The monochromator (SP-150) with a computer control of a wavelength selects a narrow wavelength interval from the lamp light so that the light emitted from its exit slit is nearly monochromatic. The optical system of condenser 2 (together

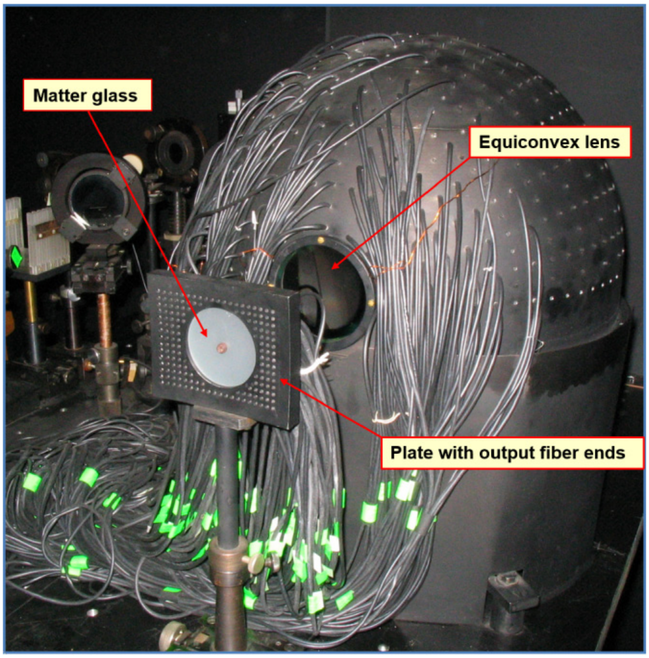


Fig. 4. (Color online) Face view to opal glass of measurement device.

with a number of mirrors) forms the beam illuminating a sample being measured.

A number of auxiliary flip-mirrors allow illuminating the DBEF sample under fixed set of incidence directions (angles for BRDF measurement). The top scheme of Fig. 3 corresponds to incidence angle 45°. After reflection from an auxiliary mirror the light is polarized by passing through the polarizer. In case of BTDF measurement the angle of incidence is controlled by rotation of the sample holder. The orientation of the plane of polarization for light incident on the sample is provided by corresponding rotation of filter of linear polarization P1 (BRDF measurement) or P2 (BTDF measurement).

The sample itself is placed in the center of metallic hemisphere with holes in which the entrance ends of working fibers are fixed. The output ends of fibers are combined in the exit panel.

Equiconvex lens L gathers light diffusely reflected from the sample within 10° from the specular direction and focuses the light on the matte screen of the glass plate (Fig. 4). The latter is positioned in the focal plane of the lens. So the lens transforms angular distribution of light emitted from the sample into spatial distribution on the matte glass plate (the angle is transformed into radius). This means that rays emitted from any point on the sample at the same direction are focused in the same point on matte glass. Thus the lens forms detailed image of angular distribution of scattered light near the direction of specular reflection (transmission) where BSDF varies very fast.

The opal glass screen is matted from the side of equiconvex lens. It is mounted in common panel together with output ends of the fibers like as shown on Fig. 4. The plate side directed to the camera is a part of sphere having its center in the entrance pupil of CCD-camera lens. So the exit ends of all fibers are directed to the CCD-camera entrance pupil. CCD-camera forms the image of the panel with the matte glass and the fiber ends.

The splitter derives a part of illuminating beam and directs it (with the auxiliary mirror) to the entrance unit of the calibration channel. The output end of the calibration fiber is mounted on the panel together with the exit ends of the working fibers. So the calibration fiber participates in forming of the CCD-camera image. Thus the controlling PC can get information about flux of the illuminating beam.

The measurements of BSDF of the DBEF sample are carried out separately for a number of fixed orientations of entrance linear polarizer placed at 0, 45, 90, and 135° and for the following angles of illumination: $\psi = 0$, 45, 90, and 135° and $\sigma = 0$, 10, 20, 30, 45, and 60° (see Fig. 1). Due to specifics of construction of the Integra's spectral scatterometer the luminance factors values for all angles of observation: $\varphi = 0$, 45, 90, 135, 180, 225, 270, and 315°, and $\theta = 0$, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, 50, and 70° (see Fig. 1), were measured in one step (see Fig. 3). Trial spectral measurements fulfilled for the range 390–730 nm with step 10 nm showed very low spectral dependence of polarized BSDF on wavelength that allows fulfilling all measurements for 550 nm wavelength only. Figure 5 shows dependence of measured BSDF values of DBEF sample for four orientations of polarization filter (0, 45, 90, and 135°) on $\theta$ observation angle (all graphs are represented for fixed values of $\psi$, $\sigma$ and $\varphi$ angles). Finally, using (4)–(6), all measured BSDF values of DBEF sample were recalculated to the polarized BSDF of DBEF.

To check correctness of the measurements and reconstruction of polarized BSDF we fulfilled a number of measurements of the luminance of DBEF sample illuminated with natural light and light with different polarizations and compared the measured values with simulated ones based on reconstructed polarized BSDF. Figure 6 demonstrates scheme of the measurements. DBEF was illuminated with lamp 12V75WA (with nominal luminous flux: 1327 lm). Luminance of reflected and transmitted light was measured with SpectorRadiometer for six observation angles $\theta = 10$, 20, 30, 40, 50, and 60°. Three variants of DBEF rotation were examined (for rotation angles $\psi = 0$, 45, and 90°). Four cases of illumination are considered: the first one was natural (non polarized) illumination and other cases were linear polarized illumination with different angle rotation of polarization plane ($\alpha = 0$, 45, and 90°). To create linear polarization a filter (LPF: linear polarization filter) was placed between lamp and DBEF. Tables 1 and 2 demonstrate results of DBEF sample measurements and DBEF model simulations. The tests show good agreement of measured and simulated results. RMS of relative deviations between simulated and measured results of DBEF are 4.6% for light reflectance and 7.7% for light transmittance.

## 4. Simulation of Illuminating System of LCD Backlight with DBEF

To check correctness of our approach and to show the

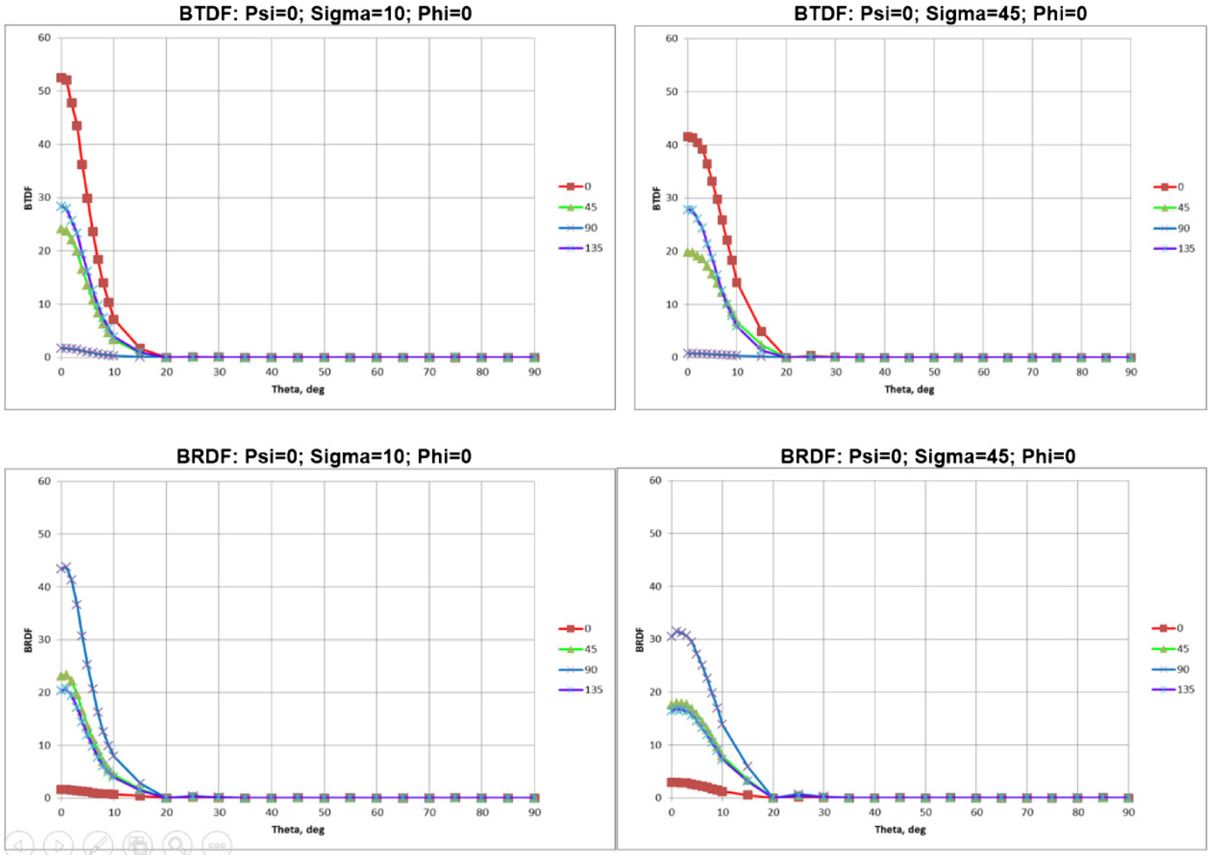


Fig. 5. (Color online) Dependence of measured DBEF BSDF values on $\theta$ observation angle. Data are provided for four orientations of polarization filter (0, 45, 90, and 135°).

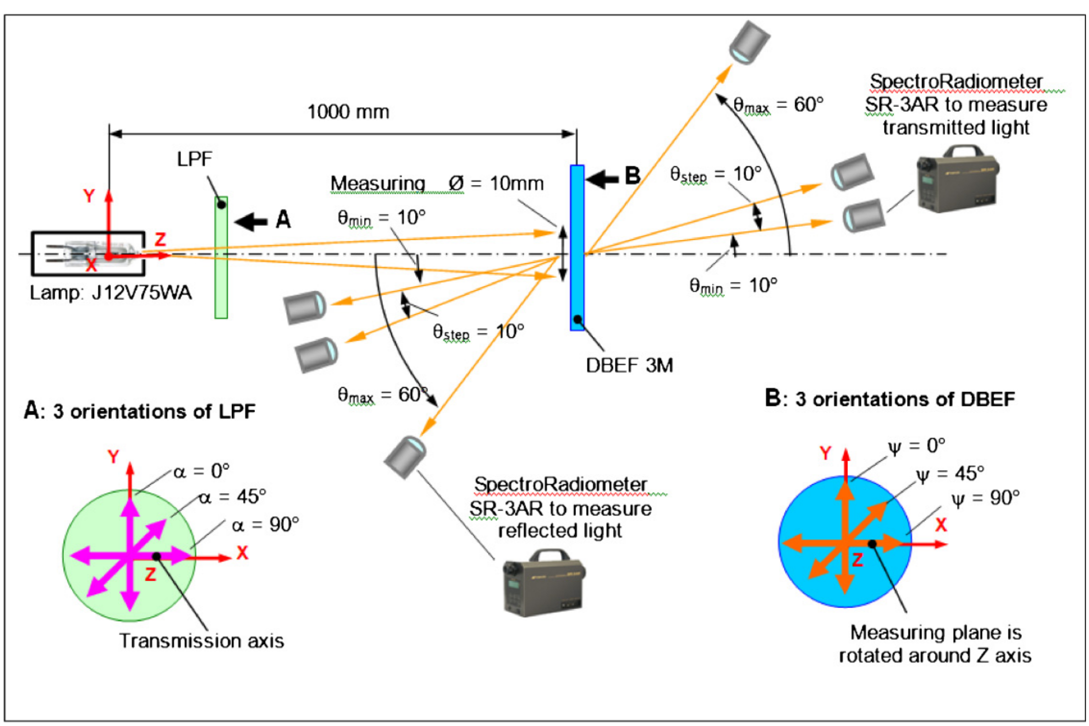


Fig. 6. (Color online) Test scheme of the model to check correctness of the measurements and reconstruction of polarized BSDF of DBEF sample.

Table 1. Measured and simulated luminance of the light reflected from the DBEF sample.

| Angle of DBEF rotation $\psi = 0°$ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Measured luminance (cd/m$^2$) | | | | Simulated luminance (cd/m$^2$) | | | |
| $\theta°$ | Natural | Angle of LPF rotation | | | Natural | Angle of LPF rotation | | |
| | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ |
| 10 | 380.0 | 23.8 | 170.5 | 316.4 | 423.0 | 27.2 | 199.1 | 341.1 |
| 20 | 58.2 | 8.5 | 24.8 | 33.6 | 65.9 | 10.0 | 26.8 | 36.5 |
| 30 | 15.5 | 5.6 | 6.9 | 7.3 | 19.3 | 6.7 | 7.0 | 7.1 |
| 40 | 5.3 | 2.3 | 3.0 | 3.3 | 7.1 | 2.6 | 2.9 | 3.1 |
| 50 | 3.8 | 1.4 | 1.5 | 2.1 | 4.6 | 1.5 | 1.9 | 2.0 |
| 60 | 2.7 | 1.3 | 1.7 | 1.9 | 3.2 | 1.2 | 1.8 | 1.9 |
| Angle of DBEF rotation $\psi = 45°$ | | | | | | | | |
| $\theta°$ | Natural | Angle of LPF rotation | | | Natural | Angle of LPF rotation | | |
| | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ |
| 10 | 530.3 | 224.7 | 32.0 | 241.2 | 549.1 | 238.3 | 42.4 | 255.6 |
| 20 | 53.0 | 24.0 | 14.7 | 26.1 | 60.0 | 27.2 | 16.7 | 27.3 |
| 30 | 14.0 | 6.3 | 5.0 | 6.5 | 15.6 | 7.0 | 6.8 | 7.0 |
| 40 | 5.9 | 2.9 | 2.7 | 2.5 | 6.1 | 3.2 | 3.0 | 2.9 |
| 50 | 3.1 | 1.7 | 1.1 | 1.7 | 3.3 | 1.8 | 1.3 | 1.9 |
| 60 | 1.7 | 1.2 | 0.4 | 1.6 | 2.2 | 1.3 | 0.7 | 1.5 |
| Angle of DBEF rotation $\psi = 90°$ | | | | | | | | |
| $\theta°$ | Natural | Angle of LPF rotation | | | Natural | Angle of LPF rotation | | |
| | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ |
| 10 | 898.0 | 750.0 | 367.0 | 45.4 | 929.0 | 786.1 | 396.8 | 49.6 |
| 20 | 67.0 | 40.3 | 29.8 | 14.5 | 70.9 | 46.5 | 31.7 | 17.8 |
| 30 | 15.3 | 7.4 | 6.0 | 5.9 | 17.7 | 8.2 | 8.0 | 7.7 |
| 40 | 6.2 | 3.2 | 3.0 | 2.7 | 7.6 | 3.5 | 3.5 | 3.5 |
| 50 | 3.7 | 2.0 | 1.6 | 1.4 | 4.2 | 2.4 | 1.9 | 2.3 |
| 60 | 2.4 | 1.6 | 1.0 | 0.7 | 3.1 | 1.6 | 1.5 | 1.2 |

Table 2. Measured and simulated luminance of the light transmitted through the DBEF sample.

| Angle of DBEF rotation $\psi = 0°$ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Measured luminance (cd/m$^2$) | | | | Simulated luminance (cd/m$^2$) | | | |
| $\theta°$ | Natural | Angle of LPF rotation | | | Natural | Angle of LPF rotation | | |
| | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ |
| 10 | 672.0 | 563.0 | 267.0 | 34.8 | 693.1 | 585.8 | 286.1 | 40.0 |
| 20 | 30.1 | 22.4 | 13.1 | 4.2 | 35.5 | 27.5 | 14.8 | 4.3 |
| 30 | 3.0 | 1.9 | 1.0 | 0.9 | 3.5 | 2.5 | 1.6 | 0.9 |
| 40 | 2.1 | 1.0 | 0.7 | 0.5 | 1.2 | 0.7 | 0.6 | 0.5 |
| 50 | 1.2 | 0.7 | 0.4 | 0.3 | 1.0 | 0.5 | 0.4 | 0.3 |
| 60 | 1.1 | 0.7 | 0.2 | 0.2 | 1.0 | 0.4 | 0.2 | 0.1 |
| Angle of DBEF rotation $\psi = 45°$ | | | | | | | | |
| $\theta°$ | Natural | Angle of LPF rotation | | | Natural | Angle of LPF rotation | | |
| | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ |
| 10 | 685.5 | 330.2 | 564.3 | 270.0 | 704.8 | 346.4 | 595.1 | 288.6 |
| 20 | 35.2 | 16.2 | 27.0 | 15.0 | 38.1 | 18.0 | 29.9 | 16.2 |
| 30 | 4.7 | 3.0 | 3.2 | 1.1 | 3.4 | 3.7 | 7.0 | 2.0 |
| 40 | 2.0 | 1.4 | 1.9 | 0.6 | 1.3 | 1.0 | 2.0 | 0.6 |
| 50 | 1.5 | 1.0 | 1.4 | 0.5 | 1.0 | 0.9 | 1.2 | 0.5 |
| 60 | 1.2 | 0.7 | 1.0 | 0.3 | 0.9 | 0.7 | 1.0 | 0.4 |
| Angle of DBEF rotation $\psi = 90°$ | | | | | | | | |
| $\theta°$ | Natural | Angle of LPF rotation | | | Natural | Angle of LPF rotation | | |
| | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ | | $\alpha = 0°$ | $\alpha = 45°$ | $\alpha = 90°$ |
| 10 | 641.2 | 36.6 | 332.7 | 559.9 | 697.7 | 38.9 | 341.7 | 590.9 |
| 20 | 32.0 | 3.6 | 15.5 | 27.0 | 36.5 | 3.9 | 16.9 | 29.1 |
| 30 | 2.9 | 0.9 | 2.1 | 3.1 | 3.4 | 0.7 | 1.6 | 2.4 |
| 40 | 1.5 | 0.6 | 1.2 | 2.3 | 1.3 | 0.5 | 0.6 | 1.0 |
| 50 | 1.3 | 0.5 | 0.8 | 1.1 | 1.1 | 0.3 | 0.5 | 0.7 |
| 60 | 1.1 | 0.4 | 0.6 | 1.0 | 1.0 | 0.2 | 0.4 | 0.5 |

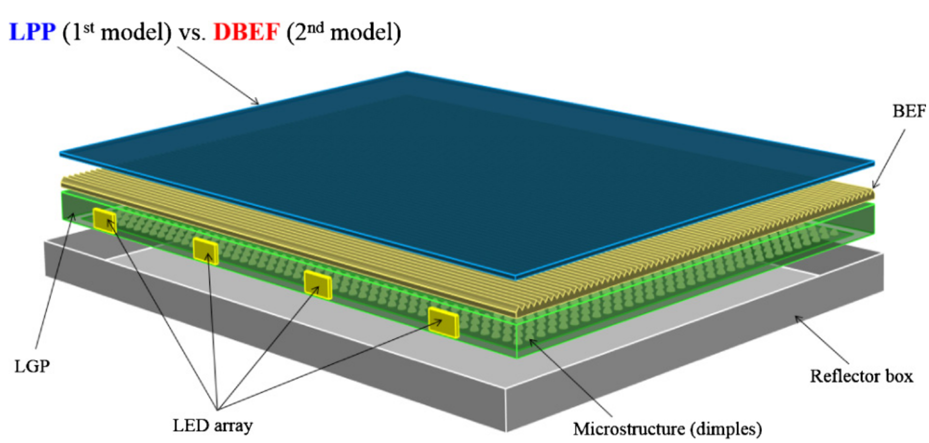


Fig. 7. (Color online) Scheme of typical backlight device.

advantages of DBEF application in the backlight systems of LCD displays two similar schemes of backlight units (with and without DBEF) were designed. The general scheme of the backlight device is shown in Fig. 7. For the simulation we used the optical simulation software system SPECTER.[8)] The system was extended with the model of the polarized BSDF.

Typical backlight devices contain standard elements: light guiding plate (LGP) with microstructure on bottom face, LED array, reflector box and brightness enhancement films (BEF). In the first scheme the simple filter of linear polarization (LPP: linearly photo-polymerizable polymer) produces linearly polarized emission on LGP output. In the second scheme advanced DBEF is used for the same goal. Simulation of LCD system requires advanced methods of calculation with support of all light polarization effects.

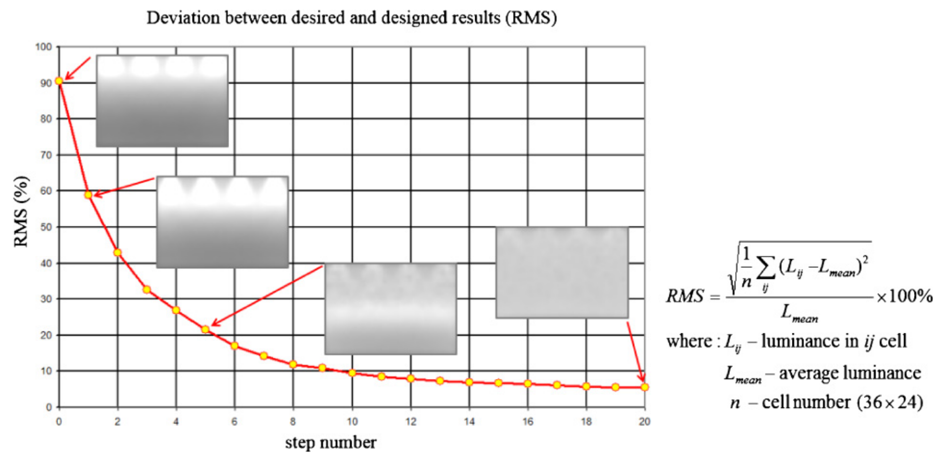


Fig. 8. (Color online) Auto-design of backlight device with DBEF.

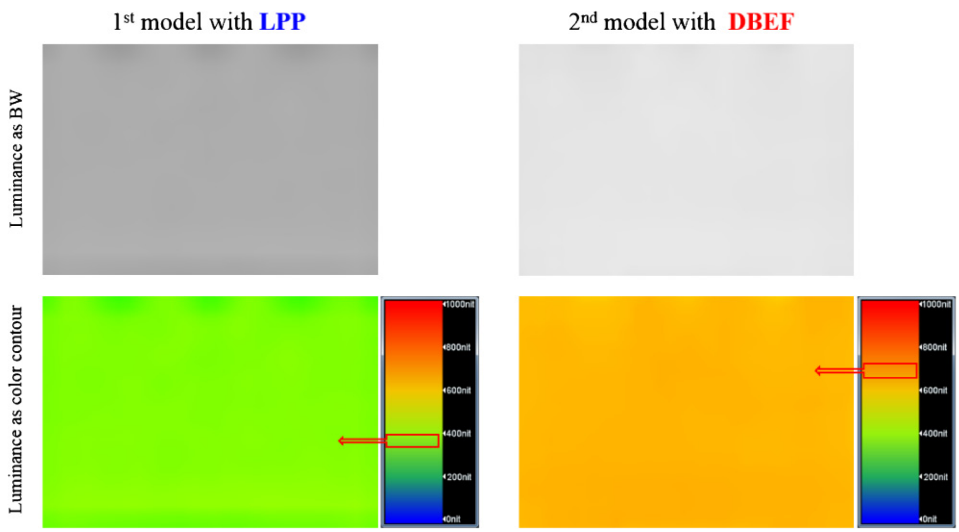


Fig. 9. (Color online) Output light distribution for models with filter of linear polarization and with DBEF.

The two main goals of LCD design are maximal efficiency and uniformity of light distribution. As a rule the design is executed with modification of microstructure density distribution. The calculation of similar systems usually takes a lot of time because the main method of simulation is a stochastic (Monte-Carlo) ray tracing which is time consuming. In current project we used auto-design tool described in the paper of Zhdanov et al.[9] The used auto-design tool supports thousands of design parameters and has very fast convergence. The graph in Fig. 8 presents dynamic of design convergence for backlight unit with DBEF. The graph presents dependence of root mean square (RMS) of output luminance distribution on design steps. Note that design of backlight unit without DBEF has similar divergence character.

Finally, the resultant outgoing luminance distribution for both LCD schemes is presented in Fig. 9. The luminance distribution is represented in pseudo-color where each color corresponds to particular luminance value. The results of design demonstrate advantage of DBEF usage for increasing of LCD efficiency. As we see the DBEF usage allows increasing of outgoing luminance almost in 1.5 times. These simulation results correspond to results of manufactured device measurements.

## 5. Conclusions

We elaborated the polarized BSDF model and demonstrated that computer simulation of backlight devices with DBEF is possible. The simulation results agree with experimental data. The elaborated software provides physically accurate simulation of polarized scattering phenomena in complex optical devices. Moreover, we demonstrated that not only simulation but also design of backlight devices with DBEF is possible with help of elaborated software.

**Acknowledgment**

The work was supported by RFBR, Grants No. 13-01-00454 and 12-01-00560.

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