Polarized back and frontlights for LCDs

Citation for published version (APA):

van Heesch, C., Jagt, H., Cornelissen, H., Broer, D. J., & Bastiaansen, C. (2004). Polarized back and frontlights for LCDs. *Proceedings of SPIE - The International Society for Optical Engineering*, 5289, 170-181.
<https://doi.org/10.1117/12.549463>

DOI:

[10.1117/12.549463](https://doi.org/10.1117/12.549463)

Document status and date:

Published: 01/12/2004

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

PROCEEDINGS OF SPIE

SPIDigitalLibrary.org/conference-proceedings-of-spie

Polarized back- and frontlights for LCDs

Van Heesch, Chris, Jagt, H., Cornelissen, Hugo, Broer, Dirk, Bastiaansen, Cees

Chris M. Van Heesch, H. Jagt, Hugo J. Cornelissen, Dirk J. Broer, Cees W. M. Bastiaansen, "Polarized back- and frontlights for LCDs," Proc. SPIE 5289, Liquid Crystal Materials, Devices, and Applications X and Projection Displays X, (28 May 2004); doi: 10.1117/12.549463

SPIE.

Event: Electronic Imaging 2004, 2004, San Jose, California, United States

Polarized back and frontlights for LCDs

C. Van Heesch¹, H. Jagt², H. Cornelissen², D.J. Broer^{1,2} and C. Bastiaansen¹

1.TU/e, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

2.Philips Research, Prof. Holstlaan 4, 5656 AA Eindhoven, The Netherlands

ABSTRACT

New designs are presented of backlight systems for transmissive and transfective LCD's based on stretched PET films with a well-defined micro-structure, which emit highly collimated or diffuse and linearly polarized light with a high efficiency. Moreover, edge-lit waveguide systems are discussed equipped slanted phase gratings which combine a range of desirable features such as a high transparency in direct view, a direct emission of light at normal angles to the plane of the waveguide and a purely unidirectional out-coupling of light towards the LCD-side. Moreover, these illumination systems emit colored, linearly polarized light which should contribute significantly to the energy efficiency of transmissive, transfective and reflective LCD displays.

Keywords: LCD, backlight, frontlight, anisotropic, micro-structure, holography, waveguide

1. INTRODUCTION

The energy and light economy of traditional transmissive LCDs is notoriously poor. In most LCDs less than 10 % of the generated light by the light source actually reaches the viewer. This poor efficiency is predominantly related to the use of absorption-based polarizers (light efficiency < 50 %). Nowadays, polarizers and color filters based on light reflection or light scattering are available which offer the opportunity to recycle the non-desired light components and which enhance the device efficiency. Simultaneously, for portable applications there is a demand for an increased use of ambient light in the illumination of LCDs. For instance, in so-called transfective and reflective LCDs, semi-transparent or full reflectors are employed that use ambient light to generate the image in a bright environment. An additional illumination means (a so-called backlight or frontlight) is used for operation under darker conditions.

Several new approaches are presented which have the potential to increase the energy efficiency or the display brightness of edge-lit LCDs by using non-absorbing optical mechanisms in the LCD-illumination system. The focus is directed towards increasing the efficiency of the lighting system and the first polariser. For this purpose, the polarizing function is integrated in the waveguide, in order to directly emit linearly polarised light. An efficiency gain can be achieved by internally recycling the unwanted polarisation direction. In contrast to the previously reported separate reflective and scattering sheet polarisers, the integration of the polarizing and recycling function in the waveguide, potentially reduces light loss, complexity, thickness, weight and cost. Additionally, it is attempted to enhance the LCD performance by achieving suitable (i.e. preferentially near normal) emission characteristics by the outcoupling mechanism. Three major approaches are used to achieve a linearly polarised light extraction from a waveguide system.

The first approach uses an anisotropically scattering polymeric layer in the waveguide to couple linearly polarised light out by scattering. This layer consists of an appropriate dispersion of a polymeric phase in an oriented polymeric matrix. In such use of an anisotropic scattering layer, the desired polarisation is the scattered one, whereas the undisturbed polarisation, which hence remains trapped in the waveguide, is to be recycled.

In a second approach, linearly polarised light is coupled out of the waveguide at micro-structures which are patternable in order to obtain a homogeneous outcoupling. The approach is subdivided in two polarisation

separation mechanisms. In the first mechanism, polarisation separation is achieved by polarisation dependent Total Internal Reflection (T.I.R.) at an isotropic substrate-anisotropic layer interface. The corresponding refracted linear polarisation direction is coupled out of the waveguide by micro-structures consisting either of direct laser written surface relief/volume structures or micromachined surface relief structures in the anisotropic polymeric layer. In the second mechanism, polarisation separation and light outcoupling are simultaneously achieved at a micro-structured anisotropic-isotropic interface.

A third approach involves periodic holographic phase grating structures recorded in photopolymer mixtures, which couple waveguided light out by Bragg diffraction. In order to achieve a linearly polarised light emission, the polarisation dependence of the diffractive light outcoupling is investigated.

2. ANISOTROPICALLY SCATTERING POLARIZED WAVEGUIDES

2.1 Introduction

A ‘scattering polariser’ film is a special type of volume scatterer, as the film has an anisotropic scattering power.^{1,2,3} The scattering process is therefore referred to as ‘anisotropic scattering’. As a result, one linear polarisation direction of the incident light encounters a large scattering power in the film and is therefore selectively scattered in the bulk, whereas the orthogonal polarisation direction encounters a small scattering power (ideally zero) and is directly transmitted without significant scattering. The advantages of scattering polarisers over conventional absorbing sheet polarisers are significant, especially in Liquid Crystal Display (LCD) applications. The absence of light absorption enables a more efficient generation of polarised light by appropriate recycling of wrongly polarised light. The absence of light absorption also avoids heating and degradation of the polarisers in heavy-duty applications such as projection LCDs.^{1,2,3}

The scattering polarisers consist of a dispersion of a cross-linked or a thermoplastic polymer in an oriented and birefringent polymeric matrix (Figure 1).^{1,2,3} A refractive index match in a plane perpendicular to the orientation direction is generated between the continuous and dispersed phase, whereas a large mismatch in refractive index exists parallel to the orientation direction. Ordinary waves (light polarized perpendicularly to the plane of the propagation direction and the orientation direction) have no polarisation component parallel to the orientation direction. Therefore, they do not experience a mismatch in refractive index and are not scattered. Extraordinary waves (polarised in the plane of the propagation direction and the orientation direction) do have a component parallel to the orientation direction and thus experience a mismatch in refractive index between the continuous phase and the dispersed phase; hence they are scattered. As a consequence, light that has a polarisation component in the mismatching direction is scattered and the film has an opaque (white) appearance, whereas light polarised in the matching direction is directly transmitted, resulting in a transparent state. This enables a spatial separation of both linear polarisation directions.

Figure 1: Waveguide samples produced by lamination of an anisotropically scattering film onto a polymeric substrate.

2.2. Experimental

The matrix material used to produce the scattering polarisers, was Poly(ethylene terephthalate) (PET, Arnite D04 300) kindly supplied by AKZO Nobel (Arnhem, The Netherlands). As the dispersed phase rubbery Core-Shell (CS) particles (Rohm and Haas, Paraloid EXL 3647) were used. These spherical particles have a diameter of 200 nm and consist of a styrene-butadiene (S-BR) rubbery core and a Poly(methyl methacrylate) (PMMA) shell. Poly(carbonate) (PC) and PMMA sheets were purchased from Goodfellow. PC Compact Disc substrates, in the following referred to as PC (CD-grade) was supplied in 1 mm thick sheets by the Philips Research Laboratories (Eindhoven, The Netherlands). The monomers bisphenol A ethoxylated diacrylate, tripropyleneglycoldiacrylate (TPGDA), phenoxyethylacrylate (POEA), 9-vinylcarbazole and the UV-initiator 1-hydroxycyclohexylphenylketone were purchased from Aldrich.

A blend of 90% wt/wt PET and 10% wt/wt CS-particles was prepared on a co-rotating twin-screw extruder at a temperature of 280 °C.⁷ The blend was subsequently extruded into a film with varying thickness using a cast-film extruder at 280 °C. Similarly also a pure PET film was extruded. Tapes of varying initial length, initial width and initial thickness were cut from the extruded PET/CS and PET films and uniaxially stretched to draw ratios of 4 - 4.5 on a tensile tester at a temperature of 85 °C.⁷ This draw ratio was determined by measuring the displacements of ink marks on the film. The stretched PET/CS films were laminated onto PC or PMMA substrates of 1 or 2 mm thickness. The films were centrally positioned on the substrates but separated at least 10 mm from the side faces of the substrate. The side faces of the substrates were extensively polished. The films were laminated onto the substrates using acrylate monomers and subsequently cured with UV-light. Usually, bisphenol A ethoxylated diacrylate (+ 1 wt% UV-initiator) was used as the adhesive layer in case of a PC substrate and a 65.5 wt% Bisphenol A ethoxylated diacrylate + 33.5 wt% TPGDA + 1 wt% UV-initiator mixture in case of a PMMA substrate. In specific cases, a 82.5 wt% POEA + 16.5 wt% 9-vinylcarbazole + 1 wt% UV-initiator mixture was applied.

2.3. Results

The polarised backlights based on anisotropic scattering resulted in polarised contrasts (15-25), which are sufficient for backlight systems in e.g. cellular telephone applications. For more demanding LCD-applications, the conventional absorbing polariser will act as a clean-up polariser to enhance the contrast to the desired level, without much additional light loss. A predominant emission close to the normal direction could be achieved which is a highly desirable outcoupling characteristic. However, the emission across the sample was inhomogeneous (Figure 2). In the extrusion process in which the dispersed phase is distributed in the matrix material no possibilities exist to achieve a gradient in the concentration of the dispersed phase across

the film. Therefore, the possibilities for homogeneity control of the polarised light emission from the backlight are limited to the use of reflectors, edge-lighting from multiple sides, wedge shaped substrates or the use of additional micro-optic structures. However, an important parameter in optimizing the homogeneity of outcoupling is the scattering power of the anisotropic film. This scattering power should be tuned to the specific backlight size in order for an end face reflector to be effective. Collimated edge-lighting also improves the observed contrasts (when an appropriate substrate is used) and the homogeneity of light emission. However, the additional optical components to achieve such a collimated light input from a conventional lamp increase the backlight both in size and complexity. Such light collimation seems therefore only useful in large size backlight systems. Upon increasing the active area of the backlight it is expected that achieving a homogeneous light emission will become increasingly more difficult. Such larger area polarised backlights will need a relatively low scattering power of the top film, which results in a predominant light emission at large inclinations angles. Additional conventional prismatic Brightness Enhancement Foils (BEFs) are therefore likely to be needed in order to enhance the normal brightness but this adds to complexity, thickness and cost.⁴ An additional complication is the fact that such larger display types (e.g. notebook computer screens) use a polariser situated at 45° with respect to the primary directions. An additional retarding film will therefore be needed to rotate the emitted linearly s-polarised light to this 45° direction. Alternatively, the oriented film may be adhered at 45° to the substrate, but this is expected to yield a reduced polarised contrast and asymmetric luminance distribution. For these reasons, the polarised backlights seem to be the most promising for the smaller size backlights such as used in cellular telephone displays. In such applications, the emitted s-polarised light can directly be used in the LCD. However, a complication is the fact that such small area backlights conventionally use several LEDs instead of a CCFL, which hampers the achievement of a homogeneous emission. In a polarised frontlight it is essential that the waveguide emission is directed towards the LCD-panel rather than towards the viewer. The anisotropically scattering waveguides do not possess such a characteristic. There is however still an opportunity for use in a frontlight system by absorbing the s-polarised emission towards the viewer's side with a p-transmitting polariser. This has an additional advantage of viewing the LCD through the waveguide in its transparent state, which minimizes disturbances of the viewed image. The disadvantage of this approach is however the occurring contrast inversion when switching from frontlight to ambient light operation.

Figure 2: Photograph of the polarised emission by an anisotropically scattering polarised waveguide consisting of stretched 90wt% PET/10wt% CS (50*50 mm) adhered to a 2 mm thick PC substrate. Left side: p-polarised analysis, right side: s-polarised analysis. The uncollimated CCFL edge-lighting is incident from the top; a specular reflector is applied at the bottom. At the sides the corresponding polarised angular luminance (cd/m²) distributions at a y-position of 45mm are given.

3. POLARIZED WAVEGUIDES BASED ON SELECTIVE TOTAL INTERNAL REFLECTION

3.1 Introduction

In the polarised light emitting waveguide approach the polarisation separation process was spatially separated from the outcoupling process. However, as the micro-groove structure is present in the oriented layer, the possibility arises to combine the polarisation separation and the outcoupling into a single step, by coating the microstructure (Figure 3). It is aimed to couple out s-polarised light by T.I.R. at the micro-structure interface. It is therefore evident that the extraordinary refractive index $n_{e,x}$ of the oriented layer must be significantly larger than the corresponding refractive index of the coating $n_{c,x}$ in order to achieve a sufficiently small critical angle at the interface. Additionally, for the p-polarised component such a critical angle for T.I.R. should not be present at the interface, or be so small that it is of little practical interest. Preferentially, the p-polarised light should also not be disturbed significantly by refraction or reflection.

Figure 3: Outcoupling structure consisting of a micro-grooved anisotropic layer adhered to an isotropic substrate and filled with an isotropic coating matched in refractive index to the ordinary refractive index of the oriented layer. Emission of linearly polarised light is mainly due to T.I.R. at the micro-structure.

3.2 Experimental

Poly(ethyleneterephthalate) (PET) extruded film was kindly supplied by Uniphase (Arnhem, The Netherlands). Poly(methylmethacrylate) (PMMA) sheets were purchased from Goodfellow. The monomers bisphenol A ethoxylated (1EO/phenol) diacrylate, tripropyleneglycol diacrylate (TPGDA), phenoxyethylacrylate (POEA) and the UV-initiator 1-hydroxycyclohexylphenylketone were purchased from Aldrich. PET sheets with an initial length l_0 of 80 mm, initial width b_0 of 40 mm and initial thickness d_0 of 480 μm were cut from the PET film and uniaxially stretched on a tensile tester to a draw ratio of 4.2 at a speed of 200 mm/min and a temperature of 125 $^{\circ}\text{C}$. The draw ratios were determined by measuring the displacements of ink marks on the sheets. The stretched PET films were cut into pieces of 27 mm length and 20.5 mm width, which were laminated onto PMMA substrates of 2 mm thickness, 29 mm length and 29 mm width. Several films were adhered to the substrates using an acrylate monomer mixture (adhesive 1: 91.2 wt% bisphenol A ethoxylated diacrylate + 8.3 wt% TPGDA + 0.5 wt% UV-initiator) and several films with POEA (adhesive 2: 99wt% POEA + 1 wt% UV-initiator) that were subsequently cured with UV-light. The adhered PET was flattened with a diamond chisel with a radius of 2 mm perpendicular to the orientation direction. The films were subsequently micro-machined by cutting micro-prismatic line structures with a diamond chisel in the orientation direction of the films. Two diamond tools were used in order to machine different prismatic line structures. A triangularly shaped tool with a straight face of 0° and a tilted face of 26° (both with respect to the normal) was used to micro-machine the PET films which were adhered with the bisphenol A ethoxylated diacrylate mixture. A

symmetrically shaped tool with 2 faces of 25° (top angle 50°) was used to micro-machine the PEN films adhered with POEA. The line spacing in both cases was approximately $200\text{ }\mu\text{m}$ and the groove depth $50\text{ }\mu\text{m}$. Finally, the micro-machined PEN films were coated with an acrylate monomer (99 wt% bisphenol A ethoxylated diacrylate + 1 wt% UV-initiator) between the structured PEN film and a cover sheet and subsequently this layer was cured by a UV-exposure. After curing the cover sheet was removed.

3.3 Results

Microscope images of the symmetric micro-machined grooves within the oriented PEN layer are shown in Figure 4.

Figure 4: Microscope images of symmetric micro-grooves in oriented PEN prior to coating adhered to a PMMA substrate (a) side view (b) top view.

The grooves were found to be accurately machined in the oriented PEN, i.e. no debris were found to be present (Figure 4b) and the side faces were accurately tilted and straight with a sharp angle at the bottom of the groove. The groove spacing was found to be $200\text{ }\mu\text{m}$, the groove width $52.5\text{ }\mu\text{m}$ and the groove depth $56.5\text{ }\mu\text{m}$. This corresponds well with a tilt angle of the faces of 25° with respect to the normal. A scratched structure is however present at the surface of the film perpendicular to the orientation direction (Figure 4b), which is due to the flattening of the film prior to the machining of the grooves. This structure is likely to result in some unwanted surface scattering. The corresponding three-dimensional polarised outcoupled luminance distributions are shown in Figure 5.

The highly s-polarised angular emission towards the backward direction is found to be well centred at near normal angles. The emission is one-dimensionally collimated in the backward direction, i.e. collimated perpendicular to the grooves and a broad distribution in the parallel. P-polarised light is only slightly emitted at high inclination angles. At the normal direction, high polarised contrasts are found, which locally exceed 150.

Figure 5: Polarised angular luminance distribution (cd/m²) of the forward outcoupling at a central position ($y=10$ mm) at the coated micro-machined ($2 \times 25^\circ$) PEN/PMMA waveguide. Comparison between no end reflector and a HRM end reflector. The edge-illumination direction is indicated by the arrows. (a) s-polarised (b) p-polarised (c) s/p contrast

4 HOLOGRAPHIC WAVEGUIDES USING BRAGG PHASE GRATINGS

4.1 Introduction

In several LCD applications, holographic volume gratings are used as they provide a versatile means to control the direction of incident light. In these applications, transmission or reflection gratings are used that operate for angles incident from air. For instance, holographic reflectors were developed for reflective display applications, which diffract incident ambient light into a controllable viewing cone which is redirected from the glare angle and provides higher brightness and contrast.^{5,6} Similar results can be obtained using holographic front diffusers. Holographic reflective and transmissive colour filters were produced for reflective LCD and projection LCD applications respectively. Also, holographic projection screens were developed. In stead of static holographic components, switchable Bragg gratings based on holographic polymer dispersed liquid crystal (H-PDLC) materials, were studied and developed for reflective colour displays or projection displays.^{7,8,9} These holographic components can hence have versatile characteristics: they can focus, diverge, diffuse or spectrally filter incident light. Here, holographic gratings are studied which diffract waveguided light in order to be used as outcoupling structures in back- and frontlight systems for LCD illumination. Figure 6a shows an untilted transmission grating formed by interference of a reference and an object beam which are both incident from the same side at the holographic layer. At the playback of the holographic grating, the incident reference beam is partly diffracted into the original object beam direction, which reconstructs the original object beam (Figure 6b). The hologram acts therefore as a beam splitter.

Figure 6: Holographic transmission phase grating (a) recording (b) reconstruction.

The polarisation dependence of the diffraction efficiency is present within the coupled-wave theory of Kogelnik in the coupling constants κ_s and κ_p . As the κ_p is reduced compared to κ_s , the diffraction efficiency for p-polarised light is less affected by changes in thickness or refractive index modulation than s-polarised light. As a result, at specific grating characteristics significant polarised contrasts can be expected. This is illustrated in Figure 7 at a refractive index modulation of 0.01.

Figure 7: Diffraction Efficiency as a function of grating thickness for s- and p-polarised light and polarised contrast for various wavelengths as calculated using Kogelnik's coupled wave theory at exact Bragg matching ($\Lambda = 450$ nm, $n=1.55$, $\Delta n=0.01$).

4.2 Experimental

Poly(styrene) ($M_w = 45.000$ g/mole), the monomers diethyleneglycoldimethacrylate (DEGDMA) and cyclohexyl methacrylate (CHMA) and UV-initiator 1-hydroxycyclohexylphenylketone were purchased from Aldrich.

An Argon-Ion Continuous Wave (CW) laser (Spectra-Physics Beamlock 2085-25S) was operated at a UV-laser line with a wavelength of 351.1 nm. An etalon was used in the laser cavity to obtain single frequency operation. A TEM₀₀ mode laser beam was emitted, which results in a Gaussian intensity profile across the beam. A

Polarising cube Beam Splitter (PBS, 25.4 mm, fused silica) was used to split the beam. The transmitted beam and reflected beam were recombined using two UV-mirrors ($D=50$ mm). A half-wave plate ($\lambda/2$) ($D=20$ mm) was applied in front of the lens system in order to control the vertical linear polarisation of the laser beam. By rotating this $\lambda/2$ -plate the percentage of transmission and reflection at the PBS could be controlled in order to achieve equal intensity per unit area of both beams at the sample. A second $\lambda/2$ -plate was used to rotate the horizontally polarised transmitted beam by the PBS to vertically polarised light.

Two photo-polymer mixtures were used to record the interference pattern: mixture 1: 49.4 wt% PS, 49.6 wt% DEGDMA, 0.98 wt% UV-initiator and mixture 2: 49.5 wt% PS, 49.5 wt% CHMA, 1 wt% UV-initiator. Thin films were prepared by coating the mixtures between two glass slides (slide 1 (substrate): 76 * 26 mm area, 1 mm thick, slide 2 (top layer): 50 * 24 mm area, 150 μm thickness). The beams are made to overlap at the position of the sample, which corresponds to a half angle $\langle e$ between the beams. To perform waveguide mode holographic writing a glass cube (50*50*50 mm) was used to which the sample was adhered with a refractive index contact fluid (benzylmethacrylate (BzMA), $n_{D20} = 1.512$) of approximately equal refractive index as the glass cube and glass slides. The combined power of both beams was approximately 0.5 mW/mm². The samples were holographically illuminated for 60 seconds and subsequently uniformly cured with UV-light for 30 minutes.

4.3 Results

A slanted grating was recorded with the beams under an angle of approximately 18.4° and 32.8° in a PS/CHMA mixture. Using a CCFL light input into the substrate, the holographic grating was reconstructed with VIS light. The resulting polarisation dependent emission by diffraction is shown in Figure 8 in a cross-section perpendicular to the grating planes. The emission by the holographic waveguide is highly linearly polarised, especially near the aimed design angle of -10°. The polarised contrast exceeds 75 at -8° and diminishes at larger and smaller angles. The peaked angular distribution observed in Figure 8 is actually the result of four major factors.

Figure 8: Polarised outcoupling of waveguided light by a holographic grating on a glass substrate using conventional CCFL edge-lighting. R=red, Y=yellow, G=green, B=blue. Approximate grating parameters: $\Lambda_i = 250.9$ nm, $\square p = 38.6^\circ$, $d = 100$ μm . (a) forward s- and p-polarised diffraction. (b) corresponding s-p polarised contrast.

Firstly, the emission is a representation of the angular luminance distribution within the waveguide system, as the emission at different angles corresponds to different internal waveguided angles due to the high angular

selectivity of the grating. Not all internal angles are equally probable, due to the precise incoupling conditions, angular redistribution effects and angular dependent refraction/reflection at the substrate/grating layer interface. Secondly, as the grating is inherently wavelength selective, different wavelengths are emitted at different angles (roughly indicated in Figure 8). The measured emission is therefore also a representation of the peaked CCFL spectrum. Thirdly, the diffraction efficiency of the grating is wavelength dependent which will influence the emitted intensity of the different colors. Finally, in the measuring set-up an eye-sensitivity filter was integrated which mimics the spectral response of the human eye. In daylight conditions, the peak sensitivity of the eye occurs at the yellowish green wavelength of 555 nm.¹⁰. The combination of the photometric measurement and the CCFL spectral distribution is the cause that green light corresponds to the highest luminance and that blue and red are relatively suppressed in Figure 8. The highest polarised contrasts are found for this green part of the spectrum, which corresponds well with the grating design. As larger and smaller wavelengths result in deviations from the 45° Bragg angle, the corresponding polarised contrasts diminish. For red light a polarised contrast of approximately 7.5 is found, for yellow light 15 and for greenish-blue light 6.5. All wavelengths therefore clearly emit more linearly s-polarised than p-polarised light. The three-dimensional polarised angular luminance distributions of the emission by the holographic waveguide in the forward direction and the corresponding polarised contrast, are shown in Figure 9.

Figure 9: Polarised angular luminance (cd/m²) distribution emitted by a holographic waveguide (cured PS/CHMA, $\Lambda_i = 250.9$ nm, $\phi_p = 38.6^\circ$, $d = 100$ μ m) using conventional CCFL edge-lighting into the glass indicating the wavelength dependency of diffraction.

5 CONCLUSIONS

Anisotropically scattering polymer films were evaluated for use in a new polarised waveguide system. For optimal performance, it was found that the light from the lamp has to be coupled into the side-face which has its normal perpendicular to the orientation direction of the anisotropic top film. By changing the scattering power of the anisotropic film, the outcoupled angular distribution of the preferentially emitted s-polarised light could be influenced from an emission at high inclination angles to angles near the normal direction. In all cases, the p-polarised light was coupled out of the waveguide to a much smaller extent than s-polarised light and in a narrow distribution at large inclination angles (e.g. 70°). The polarised contrasts achieved were highest at near normal directions and amounted up to 23. A positional dependence of the outcoupled s-polarised light distribution was found. At positions far from the incoupling side, skewed waveguided rays dominate the light outcoupling, resulting in a splitting-up of the maximum intensity region. The resulting contrast ratios were found to be highest close to the lamp side. The substrate refractive index has a significant influence on the polarised contrast values. Highest contrasts (in between 21 and 14 at a 50*50 area) were found in the case of a substrate such as PC, which has a refractive index in between the ordinary and extraordinary refractive index of the PET top film.

A highly polarised and collimated emission to the backward direction at near normal angles was obtained from the waveguide system using an integrated polarisation separation and outcoupling process by selective T.I.R. at a filled micro-structure in an oriented polymeric layer adhered to a conventional polymeric substrate. With a proper micro-groove design, only linearly s-polarised light was totally internally reflected at the structure towards the backward side at near normal angles using conventional edge-lighting. The achieved polarised contrast did exceed 60 over a large angular range, which coincides with the high intensity region. Locally contrasts exceeding 100, and even 150, were realized. When asymmetric micro-grooves are used, end-face reflections are not coupled out by selective T.I.R. but mainly by refraction and reflection resulting in a much less concentrated and mainly forward directed emission of reduced polarised contrast. However, symmetric tilted groove structures provide an important improvement, which direct the reflected light at the end face mainly towards the backward side, without significant loss of polarised contrast or change in the outcoupling characteristics. The backward-forward s-polarised ratio is limited to 8, whereas the backward s-polarised - forward p-polarised ratio locally exceeds 100. The high polarised contrasts that were achieved enables the omission of a conventional absorbing polariser in a range of LCD back- or frontlight applications. The waveguides can therefore directly be used as a polarised backlight system. The backward-forward s-polarised ratio is however still too low for frontlight applications and requires further optimization. However, when the front polariser of the LCD system absorbs the s-polarised forward emission, the much lower p-polarised forward emission results in very high backward-forward ratios and a good transparency of the waveguide. A disadvantage of such a frontlight system is the contrast inversion that occurs when the frontlight is turned on.

Holographic waveguides were produced which couple out waveguided light by diffraction in a holographic grating layer. The holographic grating is a volume phase grating obtained by recording a UV-light interference pattern as a refractive index modulation in a photo-polymer mixture. Several grating structures were optimized with respect to their grating spacing and tilt angle to achieve an emission from the waveguide at near normal angles. Such grating structures were achieved by holographic UV-laser writing in transmission by sufficiently tilting the samples. These gratings diffract at relatively small waveguided angles (i.e. close to the critical angle). Alternatively, smaller grating spacings and larger corresponding tilt angles were produced using waveguide mode holographic UV-laser writing, which yields diffraction at much larger waveguided angles.

The holographic gratings showed several characteristic outcoupling properties, which offer potentials in waveguide applications. The emission through diffraction was highly collimated to a direction which can be accurately controlled and which was optimized along the normal. Furthermore, the diffraction is completely directed towards one-side of the waveguide when reflected light at the end face of the waveguide is suppressed yielding a forward-backward ratio of approximately 25. Additionally, the grating is inherently dispersive, which results in an emission of red, green and blue light at different angles upon reconstruction with visible light. Finally, an emission of highly linearly polarised light was demonstrated for green light near a Bragg angle of 45° , which locally exceeded an s/p contrast of 80. Deviating colors were still clearly linearly polarized but with reduced contrast.

The collimating, color separating and linearly polarised characteristics offer potentials to increase the energy/light efficiency of back- or frontlit LCDs by reducing light losses due to for instance absorbance at the color filters or polarisers. The one-sided (LCD side) emission characteristic is a prerequisite for a frontlight application in which the superb optical transparency of the grating layer is an important advantage compared to conventional microstructures.

Concluding, it is shown that various options exist to design illumination systems for transmissive, transreflective and reflective LCDs with a high contrast between s and p-polarised light and a high-energy efficiency. Different designs of the illumination systems were proposed, dependent on the LCD configuration and its specific applications, and it was shown that in most cases the requirements with respect to desired properties can be met.

Of course, further optimization and testing of the proposed systems is required within a display configuration and a more extensive assessment from an industrial point of view towards large scale manufacturing potentials is needed.

REFERENCES

- 1 H.J. Cornelissen, *private communication*.
- 2 D.J. Broer, J.A.M.M. van Haaren, P. van de Witte, C. Bastiaansen, *Abstracts ACS*, 1999, 218, 361.
- 3 Broer, D.J., Seppen, C.J.E., Boots, H.M.J. *US patent 5729311*, 1998.
- 4 Horibe, A., Baba, M., Nihei, E., Koike, Y. *SID 98 Digest*, 1998, 153.
- 5 Gambogi, W., Fickes, M., Steijn, K., Stevenson, S., Trout, J. *Proceedings of the 7th International Display Workshops (IDW'00)*, Kobe, Japan, 2000, 1049.
- 6 Chen, A.G., Jelley, K.W., Valliath, G.T., Molteni, W.J., Ralli, P.J., Wenyon, M.M. *SID95 Digest*, 1995, 176.
- 7 Tanaka, K., Kato, K., Date, M., Sakai S. *SID95 Digest*, 1995, 267.
- 8 Date, M., Naito, N., Tanaka, K., Kato, K., Sakai, S. *Asiadiplay'95 conference proceedings*, **1995**, 603.
- 9 Smith, R., Popovich, M. *Proceedings of the 7th International Display Workshops (IDW'00)*, Kobe, Japan, 2000, 1065.
- 10 Pedrotti, S.J., Pedrotti, L.S. *Introduction to Optics*, Prentice Hall, London, 2nd ed., **1993**, 14.