Abstract

A backlight for liquid crystal display illumination is presented, consisting of a commercially birefringent liquid crystalline polymeric layer innovatively laminated onto a micro-structured plastic light guide. S-polarized light is preferentially extracted from the light guide, and the efficiency was measured to be 1.78 time higher than in for a conventional unpolarized light emitting backlight.

1. Introduction

Major efforts have been directed to produce a polarized light emitting backlight for liquid crystal displays, because of the large gain in energy efficiency and the associated display brightness. Polarized light emitting backlights are potentially twice as efficient as conventional backlights, because no energy will be absorbed in the back polarizer. Provided that the polarization selectivity of the backlight is high enough, the back polarizer might even be left out of the display module altogether leading to a thinner module and a reduction of cost.

In earlier work polarized backlights have been designed by using anisotropic scattering foils (Jagt et al.,), or by using microstructures that are inclined at the Brewster angle (Tanase et al.). These approaches suffer from several drawbacks, like the non-uniform extraction of light or the necessity to inject collimated light with associated efficiency losses.

The basic principle for our work is published by Jagt et al. and is achieved by microstructuring a thermoplastic oriented polymeric film, which is subsequently coated with an isotropic layer. Very high polarization contrast are realized, exceeding 100.

We recently presented a microstructured backlight filled with an anisotropic layer. The anisotropic layer consisted of monomeric liquid crystalline material, which was polymerized using UV light. The maximum achieved polarization contrast was 15. The contrast value of 15 was in sharp contrast with numerical results, in which a contrast of more than 150 was obtained. We attribute the low experimentally achieved contrast to imperfect alignment of the LC director leading to domain formation and associated scattering losses.

In the current approach we again use a microstructured backlight with an anisotropic layer on top, to improve the polarization contrast and manufacturability of the backlight. The microstructured backlight has a relief structure instead of the grooves presented in the earlier work. The anisotropic layer is a slightly crosslinked birefringent film, which is applied on top of the microstructured backlight. The mechanical performance of this film is such that it deforms following the profile of the optical relief structures, while the average molecular orientation is maintained. This rather remarkable preservation of orientation during deformation probably originates from the liquid crystalline nature of the polymeric film in combination with the lightly crosslinked, chemical network structure. The birefringent film has an ordinary index of refraction, n_o, that closely matches the index of the light guide and an extra-ordinary index of refraction, n_e, which is as high as possible. In this way, one polarization state of light remains unaffected by the micro-optical structures at the interface, while the orthogonal polarization is extracted from the light guide.

The advantage of the approach described in the present work is that it implies a straightforward way for controlling the birefringence and improving the method of manufacturing. In this paper we determine the optical properties and explore a suitable method of manufacturing.

2. Design and Manufacturing of the backlight device

The backlight consists of an optically transparent isotropic light guide. Isotropic microstructures are formed on top of the isotropic light guide. Subsequently, a birefringent film is applied on top of the microstructures see also Fig. 1 that shows the layout of the whole set-up.

The light guide is a 1 mm thick slab of an isotropic optically transparent material like polymethyl methacrylate (PMMA), polycarbonate or a cyclic-olefin (like Arton or Zeonor). The light guide is microstructured by applying relief structures on top of the planar light guide. These structures can be manufactured in a simple manner, for instance by injection moulding or by photo-replicating a mould using photo-polymerizable acrylates, well known as the 2P-technique. The relief structures are designed to have a top angle of 52° and a depth of 6 µm. The spacing between the ridges is 25 µm. The shape and spacing of the relief structure

Figure 1 Schematic representation of the polarized light backlight. S-polarized light is extracted along the normal, whereas P-polarized light remains in the light guide.
The birefringent film is an uniaxially aligned liquid crystalline polymer (LCP) film from Dejima Optical Films. We have chosen for an LCP coated film as in this way the LC director is frozen in and therefore well controlled. The LCP layer can be mechanically deformed such that the optical relief structures are pressed into the LCP and the film adheres to the substrate like a pressure sensitive adhesive. During and after deformation, with the long axes of the microstructures parallel to the average orientation of the LCP, the uniaxial orientation is maintained. The LCP is chosen such that the birefringence \( n_e - n_o \) is high. The LCP layer has a thickness of about 8 µm and is applied onto a carrier substrate TAC (tri-acetyl-cellulose).

The ordinary refractive index of the birefringent film \( n_o \) is 1.51 and the extra-ordinary refractive index \( n_e \) is 1.66. The refractive index of the 2P-acrylate microstructure is 1.52. This implies that the ordinary refractive index is almost equal to the refractive index of the isotropic light guide, while the extraordinary refractive index is significantly higher. As a result, light that is polarized along the x-direction (s-polarized light, see Fig. 1) will be extracted by (total internal) reflection, while light that is orthogonally polarized (p-polarized light) will continue its propagation inside the light guide, since it is virtually not affected by the microstructures. The p-polarized light can be effectively recycled by application of a diffuse end-reflector.

It is essential that the aligned liquid crystal polymer is capable of being indented by means of the relief structures present on the isotropic substrate by applying suitable pressure at a suitable temperature. During indentation the alignment of the LC director during mechanical deformation originates from the liquid crystalline nature of the polymeric film in combination with its loosely cross-linked chemical network structure and the low glass transition temperature. Also the relief structure has to provide sufficiently good adhesion in order to obtain the backlight via a simple lamination step under pressure as is shown in Fig. 3. The lamination is carried out at a pressure of 0.2 kg/mm² at an elevated temperature of 85 ºC. A microscope picture of a cross section of a laminated LCP foil is shown in Fig. 4.

3. Optical performance

According to the ray tracing model, s-polarized light will be extracted on the foil side along the normal. The cone of the extracted light has a full width at half maximum of \( \pm 10^\circ \). In the present micro-groove design, light is also extracted towards the substrate side. This extracted light is also s-polarized and is extracted at angles of approximately 60-70º with the normal.

We have investigated the optical behavior of the polarized light emitting backlight experimentally, by illuminating it in a side-lit configuration, using a cold cathode fluorescent lamp (CCFL) surrounded by a reflector. Using an EZcontrast 160 conoscoscope from Eldim S.A., we have measured the luminance of the angular light distribution that is emitted from the light guide. To determine the selectivity of the backlight to the polarization direction of the light, we have placed a polarizer in between the backlight and the detector that could be rotated to have its transmission axis parallel or perpendicular to the extraordinary direction of the birefringent layer. The luminance has been measured on a central spot on the light guide without the use of a back- or end-reflector.

The luminance we have measured at the foil side for the two polarization directions is shown in Figs. 5a and b. The luminance is represented in a gray scale plot, as a function of the azimuth angle, \( \phi \), ranging from 0º to 360º, and the inclination angle, \( \theta \), that ranges from 0º to 80º. In addition, graphs are presented of the luminance as a function of the inclination angle ranging from \( \theta = 0º \) to \( \theta = 80º \) at a fixed azimuth angle of \( \phi = 90º \). From the figures, it is clear that at the foil side the backlight emits significantly more s-polarized light than p-polarized light. The s-polarized light is emitted from the light guide approximately along the normal, with a maximum intensity at around \( +5º \) with the surface normal. The p-polarized light is lower in intensity and it leaves the light guide at a much larger off-normal angle of 70º to 80º. We also observe a small peak in the s-polarized emission at these large angles. We attribute both this s- and p-emission to non-polarization selective scattering phenomena at the tips of the microstructures or in the LCP layer. Integrated over all angles, the intensity of s-polarized light is \( I_s = 234 \text{ lm/m}^2 \), while the
The integrated intensity of p-polarized light is 7.9 times as low ($I_p = 29.5 \text{ lm/m}^2$). In Fig. 5c, the contrast between s-polarized light and p-polarized light is plotted, again as a function of the azimuth angle and the inclination angle. Here, the contrast is defined as the ratio between the angular luminance of s-polarized light and p-polarized light. Fig. 5c shows that, along the normal, the contrast between s- and p-polarized light can reach values above 100. Ideally, the micro-structures are perfectly index-matched to the $n_c$-value of the LCP and consequently p-polarized light will not be extracted. If we assume in the modeling an index mismatch of 0.01 instead of 0, some p-polarized light is extracted. The calculated S/P ratio along the normal is 160, which is somewhat better than the experimentally obtained polarization contrast.

At the substrate side s-polarized light is extracted at angles of $60-70^\circ$, see Fig 6a, in accordance with optical modeling. The integrated intensity is $88.1 \text{ lm/m}^2$. P-polarized light is seen to appear at angles above $70^\circ$ off-normal with an integrated intensity of $16.9 \text{ lm/m}^2$, see Fig 6b. This is not expected from modeling, and we attribute this emission again to polarization unselective scattering losses. Fig 6c shows the ratio of S/P emission, and this can reach a factor of 15.

### 4. Discussion and Conclusions

The numerical and calculated optical behavior of the polarized light emitting backlight are in good agreement. The predicted angle of the peak in the luminance of s-polarized light at the foil side agrees well with the angle of the measured peak. This implies that during lamination we have a good control over the LC director of the birefringent LC material. The experimentally obtained polarization contrast has a value of more than 100. This also indicates that the LC director is stable during and after lamination.

For polarized backlight applications the extracted s-polarized light is used. In the direction of the surface normal 100 times more s-than p-polarized light is extracted towards the display in a collimated way. This collimated emission pattern reduces the need for prismatic brightness enhancement foils, leading to reduced thickness of the LCD module. We can increase the efficiency of the polarized backlight further by adding a diffuse end reflector and a specular back reflector.

The manufacturing process of LCD backlightings according to our design is extremely simple. The process is also flexible for modifications in the optical design for different LCD applications with respect to size, light source etc. The film with the uniaxially aligned LC layer remains in all cases the same. In addition, the shape and periodicity of the optical structures can be easily varied. For instance, for larger sized displays a gradient in optical relief elements will be needed in order to generate a homogeneous light distribution over the whole surface area of the display.

In conclusion, we have designed an effective and easily manufacturable polarized backlight, by applying a commercially available liquid crystalline polymer film as the anisotropic layer on top of a microstructured light guide. Our experimental results show that the angular luminance along the surface normal of the presented prototype backlight is up to 100 times higher for s-polarized light than for p-polarized light. This is supported by our numerical results, where the local contrasts are calculated to be as high as 160. Of the total emitted energy, the amount of s-polarized light is 88.8% which means we gain a factor of 1.78 over a conventional un-polarized light back light where this ratio is 50%.

We expect to get even closer to the theoretical gain factor of 2.0 by reducing the residual non-polarization selective scattering and by a further optimized design of the extraction structures.

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### 6. References


Figure 5 Measured angular luminance distribution at the foil side from the prototype polarized light emitting backlight, along with measured cross-section of the luminance at an angle of $\phi = 90^\circ$. a) S-polarized light foil side (Integrated intensity 234 lm/m²). b) P-polarized light (Integrated intensity 30 lm/m²). c) S/P ratio. Along the normal the extraction of s-polarized light is 100 times higher than for p-polarized light.

Figure 6 Measured angular luminance distribution at the substrate side from the prototype polarized light emitting backlight, along with measured cross-section of the luminance at an angle of $\phi = 90^\circ$. a) S-polarized light substrate side (Integrated intensity is 88 lm/m²). b) P-polarized light (integrated intensity 17 lm/m²). c) S/P ratio.