Simulation of Beam Shaping by Micro-textures for Curved Displays

Urs Aeberhard, Roman Hiestand*, and Beat Ruhstaller*,***

***Fluxim AG, 8400 Winterthur, Switzerland**

****ZHAW - Zurich University of Applied Sciences, 8400 Winterthur, Switzerland**

Abstract

We simulate the guiding and out-coupling of light in strongly curved backlight units with edge illumination using a 3D ray-tracing tool with custom light emission and scattering features. The impact of the display curvature is assessed regarding the uniformity and angular characteristics of light outcoupling in a complex backlight with position-dependent bottom roughness, a diffuser element and a textured brightness enhancement film.

Author Keywords

Simulation; Ray-tracing; Curved displays; Flexible displays; Backlight units; Light scattering

1. Introduction

Curved (Organic) Liquid Crystal Displays [(O)LCD] are becoming increasingly popular in the consumer electronics and automotive sectors (see, e.g., www.flexenable.com for a range of example applications). An essential component of (O)LCD are the backlight units (BLU), which provide uniform white illumination to the (O)LCD pixel array. In order to achieve the required level of spatial and angular uniformity as well as of luminance, modelling of the BLU is an instrumental element in the BLU design process, but in general represents a major challenge [1]. In the case of flexible, thin and lightweight applications, an edge-lit configuration (indirect illumination) is often favored, where the light needs to be scattered as a function of distance from the source, and light extraction is at an angle normal to injection. Ray-tracing simulations were shown to be useful for the design of various beam shaping features for optimized light-guide plate design [2-12]. However, the beam shaping features were optimized for flat display applications. As this might no longer be ideal for non-flat light guide plates, we investigate the simulation of backlights in bent geometries for use with curved (O)LCD.

2. Simulation approach

The simulation is performed using the newly developed optics module of the large area optoelectronic simulator LAOSS [13], which has previously been used to study electrical and optical cross-talk in AMOLED pixel arrays [14,15]. The core of this tool is a 3D ray-tracing engine. The structure is defined via layers and interfaces, to which optical properties are attributed. In addition to the thickness, the layer properties contain the optical constants (refractive index and extinction coefficient) as a function of wavelength. Ray propagation at interfaces is described either via Fresnel equations for simple refraction, or by angle dependent transmission and reflection coefficients, or, in the case of diffuse scattering, by a bi-directional scattering distribution function (BSDF) read from external files. In this way, behavior inferred from coherent sub-wavelength optics can be combined with ray optics for a multi-scale optical simulation. The topography of an interface, on the other hand, is specified either via an XYZ topography or via an explicit surface including the triangulation required to run the ray-trace algorithm. As a special feature of LAOSS, user-defined or generated topographies can be transformed onto cylindrically curved surfaces with arbitrary radius of curvature.

The interfaces can be provided with a geometry, defining two-dimensional domains to which specific interface properties such as the aforementioned transmission, reflection, or scattering functions, but also emission with a spectrum that can be specified with full angular (polar and azimuth) and spectral dependence. In this way, arbitrary light sources can be defined.

Rays are detected at two planes at the top and the bottom of the simulation domain. Lateral walls are described via corresponding boundary conditions, which can be absorbing, periodic or mirroring. The ray statistics at the detectors is evaluated in terms of the angular integrated intensity with spatial resolution, and also regarding the angular dependence of the detected light in the far field (i.e., after spatial integration over the detector plane). The detector can be adjusted to the device geometry, i.e., to curved configurations in the present case. In addition to the characteristics of the light at the detector plane, ray statistics in terms of absorption and extinction are evaluated for each layer of the structure.

The intuitive layer-based definition of the structure, the freedom in the choice of geometry and the possibility to import optical data directly from the OLED device simulator SETFOS makes LAOSS a suitable tool to design and investigate flexible OLED/OLCD displays for application in curved configurations.

3. Curved Backlight Unit

In order to showcase the capabilities of this dedicated display simulation tool, we investigate the impact of curvature on the guiding and out-coupling of light in a state-of-the-art flexible BLU. In order to keep the computational burden at a manageable level, the simulation domain is restricted to a subset of the BLU (Fig. 1), however with the full complexity in terms of functional components. The implemented BLU with its key elements is shown in Figure 2. In the following, the details are given for the implementation of the different components.

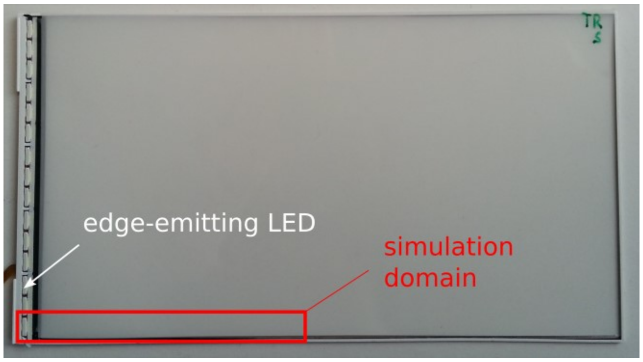

Figure 1. Picture of a flexible BLU with reduced simulation domain (red rectangle).

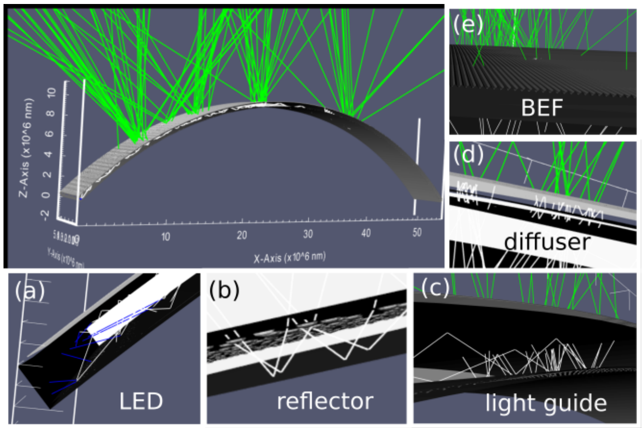

Figure 2. Curved backlight with sample rays and details of the different functional components.

(a) Light source. We use an edge emitting cool white light-emitting diode (LED) with spectrum shown in Figure 3(a). The spectrum is assumed to be Lambertian in the polar angle and rotationally symmetric in the azimuth. Edge emission is achieved by implementation of a surface topography with a vertical wall at the position of the LED, and by defining the corresponding interface geometry such that the LED domain lies within the vertical part [Fig. 3(b)].

(b) Specular reflector. The reflection is described using the optical constants for silver, and Fresnel equations for specular reflection are used.

(c) Light guide. Features position dependent bottom roughness for uniform light outcoupling. A refractive index of n=1.5 is assumed. The light scattering features are implemented in the form of a dome-shaped bottom surface texture, with a dome spacing with positional disorder decreasing with distance from the LED (Fig. 4).

(d) Diffuser sheet. A diffuser sheet is included using the specifications of IMOS-LDO-310-B (PET type material). The function of this element is to widen a beam at any angle of incidence into a cone with opening angle of 20 degrees and is implemented via a corresponding BSDF for the top surface, while Fresnel-type reflection and transmission is assumed for the bottom surface. The BSDF is generated based on a 3D-Lissajous type parametrized surface (Fig. 5a). The BSDF is normalized to provide unit overall transmission probability (Fig. 5b).

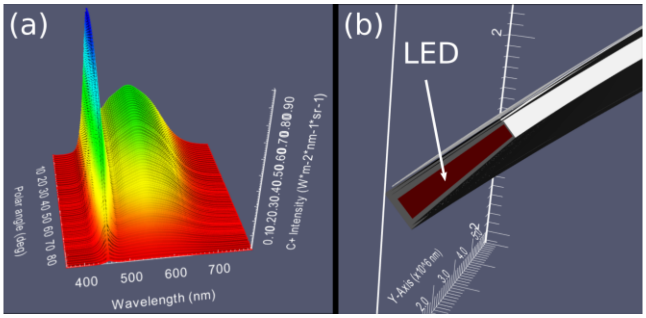

Figure 3. (a) Spectrum and (b) spatial domain of light source at the left edge of the backlight.

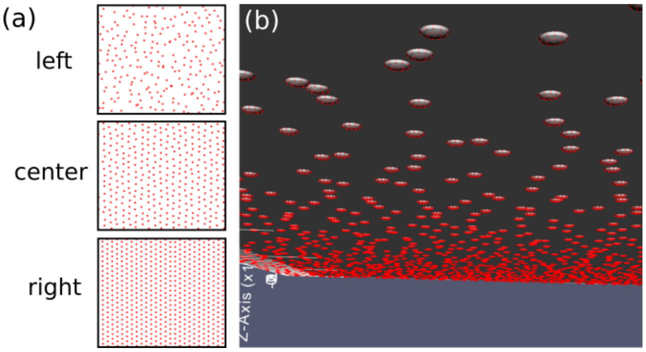

Figure 4. Dome-shaped light-scattering/out-coupling features at the bottom surface of the light guide plate. (a) Both density and ordering increase with growing distance from the light source (i.e., from left to right). (b) View of the surface texture close to the LED.

(e) Brightness enhancement film (BEF). This component is again implemented as a 3D surface topography in the shape of triangular prisms (in the direction of curvature), as implemented, e.g., in standard 3M BEF films. The refractive index is set at n=1.5 also for this component.

Additionally, the BLU is framed in white reflecting plastic, which is implemented as reflective walls surrounding the simulation domain. The simulation is then performed with absorbing boundary conditions, such that there is no spurious reflection from the domain boundaries. For the suppression of the direct emission of steep rays close to the LED, a 5 mm wide black cover is used, which is implemented in the form of an angular reflection-transmission file with unit absorptance (T=R=0).

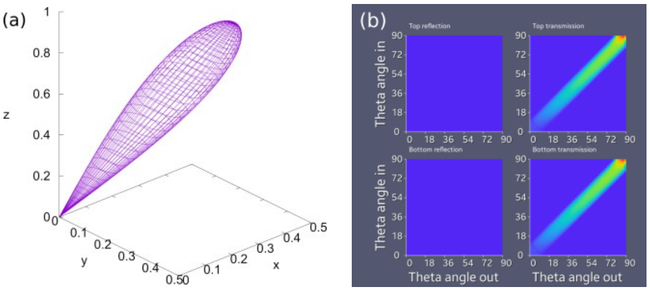

Figure 5. (a) Angular dependence of the transmission function used in the definition of the diffuser BSDF. (b) Corresponding azimuthal BSDF for azimuth angles (in and out) fixed at 0°.

4. Results and Discussion

We simulate the BLU described in the previous section in a flat configuration and for bending with different radii of curvature. We thereby assess the impact of the different functional components and how this differs when passing from flat to curved geometry in dependence of the curvature radius.

Uniformity: Figure 6 displays the enhancement of the light outcoupling uniformity at the top surface by application of the bottom texture. In the flat case (a), a high level of uniformity is achieved. Using the same bottom texture in the curved situation (b), on the other hand, does not lead to the same level of uniformity. The reduction in width is due to the smaller projected area of the curved surface.

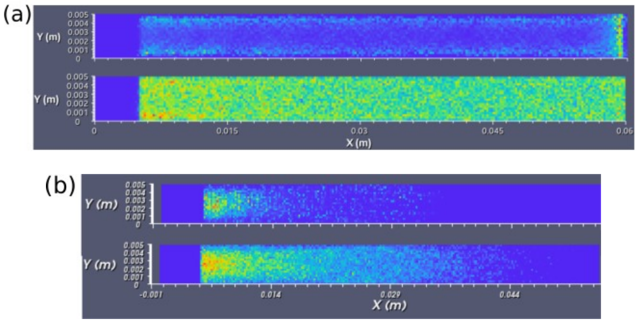

Figure 6. Position resolved intensity at the top surface, for smooth light guide (top) and with bottom texture, in the flat situation (a) and for the curved light guide (b).

Angular characteristics: Figure 7 displays the evolution of the angular characteristics of the light emitted at the top detector for increasing complexity of the layer stack: In the left image, only the bottom texture is present, while in the central figure, the diffuser sheet was added, and the right figure shows the result for an additional prism film. The top row (a) refers again to the planar case while the bottom row (b) refers to the curved case. Contrary to the situation for the uniformity, the diffuser and BEF act similarly on the angular characteristics, with a final pattern that is comparable, with even slight advantage of the curved structure. Hence, angular characteristics seem to be more robust than spatial characteristics if strongly diffusing and redirecting elements are present.

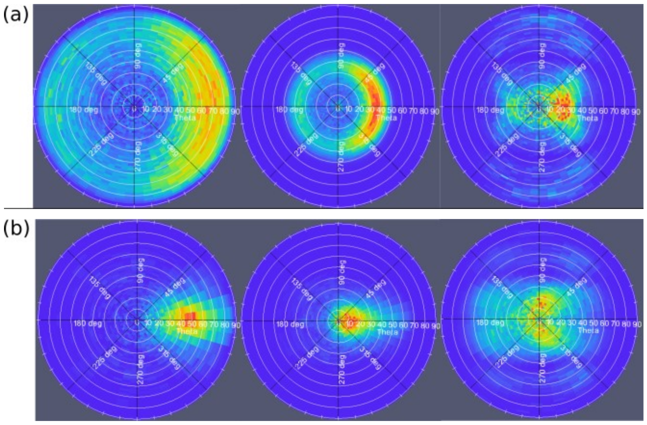

Figure 7. Polar map of emitted light at top detector, for configuration with bottom texture only (left), plus diffuser (center), plus prism sheet (right), for the flat configuration (a) and the curved light guide (b).

5. Conclusions

Conventional (O)LCD backlight units designed for flat displays may fall short of providing ideal illumination conditions in terms of uniformity and angular distribution of the light if applied in strongly curved geometries. Even nominally identical functional microstructures can lead to different angular and spatial light outcoupling properties. Using ray-tracing simulation with curvature adapted micro-textures and light scattering features allows to assess these shortcomings and provides the means for geometry dependent light guide optimization.

6. Acknowledgements

This project has received funding from the European Union's Horizon2020 research and innovation program under Grant Agreement n° 780278 (PHENOMENON). The authors would like to acknowledge fruitful discussions with the partners in the PHENOMENON consortium.

7. References

[1] Boyd G. (2016) LCD Backlights. In: Chen J., Cranton W., Fihn M. (eds) Handbook of Visual Display Technology. Springer, Cham.

[2] Okumura T, Tagaya A, Koike Y, Horiguchi M, and Suzuki H. Highly-efficient backlight for liquid crystal display having no optical films. Appl. Phys. Lett. **83**, 2515 (2003).

[3] Feng D, Jin G, Yan Y, and Fan S. High quality light guide plates that can control the illumination angle based on microprism structures. Appl. Phys. Lett. **85**, 6016–6018 (2004).

[4] Feng D, Yan Y, Yang X, Jin G, and Fan S. Novel integrated light-guide plates for liquid crystal display backlight. J. Opt. A **7**, 111-117 (2005).

[5] Lee J-H, Lee H-S, Lee B-K, Choi W-S, Choi H-Y, and Yoon J-B. Simple liquid crystal display backlight unit comprising only a single-sheet micropatterned polydimethylsiloxane (PDMS) light-guide plate. Opt. Lett. **32**, 2665 (2007).

[6] Fujisawa K, Onishi I, and Fujiwara Y. Edge-Light Backlight Unit Using Optically Patterned Film. Jap. J. Appl. Phys. **46**, 194 (2007).

[7] Li C-J, Fang, Y-C, Chu W-T, and Cheng M-C. Optimization of light guide plate with microstructures for extra light modern backlight module. Jap. J. Appl. Phys. **47**, 6683–6687 (2008).

[8] Grabovičkić D, Benítez P, Miñano JC, and Chaves J. LED backlight designs with the flow-line method. Opt. Express **20**, A62 (2012).

[9] Xu P, Huang Y, Zhang X, Huang J, Li B, Ye E, Duan S, and Su Z. Integrated micro-optical light guide plate. Opt. Express **21**, 20159 (2013).

[10] Xu P, Huang Y, Su Z, Zhang X, Luo T, and Peng, W. Research of micro-prism distribution on the bottom surface of the small-size integrated light guide plate. Opt. Express **23**, 4887 (2015)

[11] Yoon G-W, Bae S-W, Lee Y-B, Yoon J-B. Edge-lit LCD backlight unit for 2D local dimming. Opt. Express **26**, 20802 (2018).

[12] Huang Y, Zhang X, Yang W, Lei L, Peng W, and Xu P. Improvement of the microprism distribution expression of an integrated light guide plate. Appl. Opt. **58**, 6406 (2019).

[13] Laoss by Fluxim AG, version 4.0, www.fluxim.com/laoss.

[14] Penninck L, Diethelm M, Altazin S, Hiestand R, Kirsch C, and Ruhstaller B. Modelling crosstalk through common semiconductor layers in AMOLED displays. J. Soc. Inf. Disp. **26**, 546-554 (2018).

[15] Braga D, Jenatsch S, Penninck L, Hiestand R, Diethelm M, Altazin S, Kirsch C, and Ruhstaller B. Modeling electrical and optical cross-talk between adjacent pixels in organic light-emitting diode displays. SID Symp. Dig. Tec. **50**, 953-956 (2019).