Simulating Optical and Electrical Pixel Cross-Talk in WOLED/CF Displays

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ABSTRACT

We employ the simulation software Laoss to quantitatively analyze optical and electrical cross-talk in white organic light-emitting diode (WOLED) / color filter (CF) displays. Optical light leakage is found to be highly influenced by the topography of the pixel definition layer (PDL) while it only shows little correlation with some OLED parameters, such as the emitter orientation. Electro-optical simulations exemplify the importance of electrical and optical cross-talk to be dominant in different voltage ranges.

1 Introduction

A considerable amount of smartphone and television displays are nowadays made of OLEDs due to its high level of sharpness, contrast ratio, and stunning color gamut. There are basically two different ways how the primary colors are generated. Either they are directly generated through the use of blue, green and red OLEDs, or a common white OLED is employed whose light is filtered by selective color filters. Because of the higher defect tolerance, the WOLED/CF approach is often used for large area applications, such as television screens.

Common to both technologies is that increasing the pixel density and brightness requires the pixels to be close to each other. Besides being a complex fabrication process, this can be a technological challenge also for the rise of the pixel cross-talk, i.e., the electrical or optical coupling between adjacent pixels in the matrix. While the former is caused by lateral current flow through common layers,[1,2] the latter is arising because of light leakage through non-addressed pixels. Pixel cross-talk reduces the contrast ratio and hampers the color gamut of the final display. Therefore, understanding and reducing these effects are of great importance for future display designs.

In WOLED/CF displays both electrical and optical cross-talk effects can occur and their interplay might become important as well. In order understand their origin and optimize material and layouts of displays, the use of simulation software is highly desirable.

We first focus solely on optical cross-talk and analyze the effect of different display parameters, such as OLED – filter distance or pixel definition shape, on the cross-talk parameters. In a second step, we also consider electrical cross-talk between the individual WOLED pixels and investigate the effect on emitted color after the CF display. Combining both electrical and optical cross-talk for a single device layout demonstrates that at a luminance of 1000 cd/m^2 both effects contribute roughly equally while for lower (higher) voltages the electrical (optical) contribution dominates.

Our results demonstrate that numerical simulations can capture the nature of pixel cross-talk in OLED arrays. Such simulations are thus a suitable tool to optimize the characteristics of the pixel matrix without costly and time-consuming processes of device fabrication and testing.

2 Methods

The optical simulation of a WOLED/CF display is performed in the commercial software Laoss.[3] The model is based on a 3D ray-tracing algorithm. In Laoss, the display is represented by two interfaces (OLED and CF plane) separated by a certain distance d. Inputs are the lateral dimensions and topography of OLED and CF planes as well as the thickness and refractive index of the material in between (called encapsulation layer). The layout for the WOLED/CF was previously analyzed by Lee et al. using simulations based on a finite-difference time-domain method.[4] For simplicity, we neglect the topography of the filter plane and only consider a real and constant refractive index for the encapsulation layer. Further input are the angle-dependent optical properties of the WOLED and the CFs. Those were simulated using the software Setfos.[3] The necessary input data was taken from a publication by Chang et al.[5] as well as the Setfos refractive index database.

The electrical simulation is based on a 2+1D finite element method (FEM) implemented in Laoss. Laoss solves the current continuity equation through the FEM in 2D domains, i.e. the top and bottom electrodes of the WOLED. The two domains are coupled via a “coupling law” given by the current density-voltage (J-V) characteristics of the pixel. For the structure employed in this study, the J-V coupling law are extracted from the experimental data previously reported.[5]

For all the simulations we address the OLED below the green color filter. We directly analyze the emitted intensity above the CF interface displayed in the Laoss software. In order to quantify the cross-talk we define the cross-talk indices defined as the integrated intensity of the adjacent pixel, e.g. white, divided by the integrated radiant intensity R above the addressed pixel, i.e. green.

$$C_{wg} = \frac{\int R(\theta, \phi, \lambda)d\lambda d\theta d\phi \text{ above } \textbf{white} \text{ pixel}}{\int R(\theta, \phi, \lambda)d\lambda d\theta d\phi \text{ above green pixel}} \quad (1)$$

$$C_{bg} = \frac{\int R(\theta, \phi, \lambda)d\lambda d\theta d\phi \text{ above } \textbf{blue} \text{ pixel}}{\int R(\theta, \phi, \lambda)d\lambda d\theta d\phi \text{ above green pixel}} \quad (2)$$

$$C_{rg} = \frac{\int R(\theta, \phi, \lambda)d\lambda d\theta d\phi \text{ above } \textbf{red} \text{ pixel}}{\int R(\theta, \phi, \lambda)d\lambda d\theta d\phi \text{ above green pixel}} \quad (3)$$

Moreover, we can analyze the emission integrated over all x and y dimensions. This is used to determine the emitted color (far-field) of the display in forward direction.

3 Results

In the first section, we will present the effect of different layout parameters on the optical cross-talk of a WOLED/CF display. In the second part, the electrical and optical simulations are coupled for one specific display layout. The electrical and optical cross-talk are analyzed and compared for different driving levels of the addressed pixel.

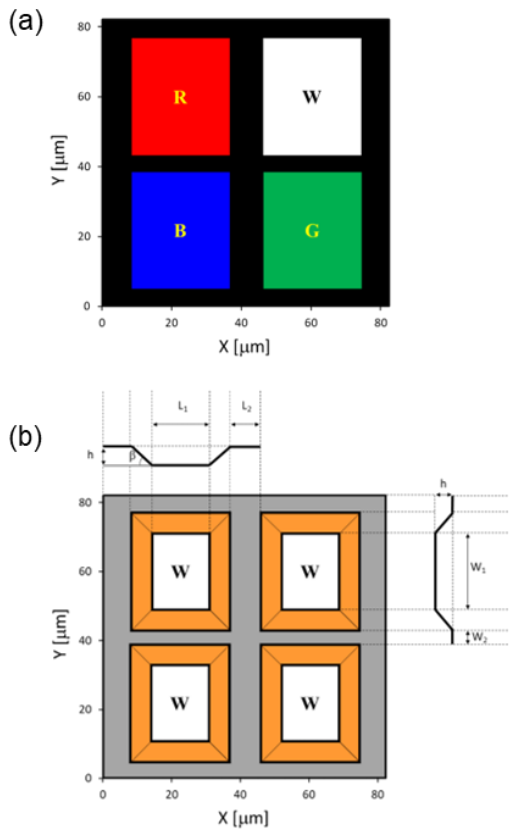

Fig. 1 Layout of the CF (a) and WOLED (b) plane used in the optical simulation.

3.1 Optical Pixel Cross-Talk

The layout of the CF and WOLED layer is shown in Figure 1. One repeating pixel unit consists of red, green, blue and white pixels which all have the same dimensions. The size of this repeating unit corresponds approximately to a display resolution of 300 PPI. In order to reproduce the extended 2D structure in a real display within our simulation, we use periodic boundary conditions, i.e. we assume that every ray that exits the stack on the side is entering on the opposite side. The unit and pixel dimensions are kept constant for all the simulations.

The parameters that are varied in the following optical simulations are (the base case settings are listed in brackets)

- The distance d between the WOLED and CF plane (d = 3.6 µm)
- The angle β of the PDL structure (β = 45°)
- The refractive index n of the encapsulation material (n = 1.5)

The intensity map above the four pixels for the base case simulation is shown in Figure 2(a). The edges of the four pixels are indicated as a guidance. The highest intensity can be observed for the green pixel which is the one that is being addressed. Some light leakage is also observed for the white pixel above, predominantly at the edge of the pixel. This feature is specific for optical cross-talk in contrast to electrical cross-talk which results in homogeneous lighting up of adjacent pixels.[1,2] The cross-talk to the red and the blue pixels is much lower due to (a) the larger distance to the green pixel and (b) the color filters which block a certain wavelength range, reducing the integrated intensity.

Starting from this base case we now varied the distance between WOLED and CF plane as well as the steepness of the PDL structure. On the one hand, increasing the thickness of the encapsulation layer results in a clear increase in the cross-talk index C_{wg} (Figure 2(b)). This is not really a surprising result. On the other hand, the angle of the PDL structure has a rather unexpected effect on the white cross-talk index C_{wg}. Interestingly, a slope of 0°, i.e. no PDL structure, results in almost no cross-talk for small values of d. For steeper PDLs up to about 60°, the cross-talk effect increases to several percent, while it decreases again for steeper walls. Typical PDL structures feature an angle of 30° - 45°.[6,7] This demonstrates that there could be some optimization potential in this direction to reduce cross-talk.

All the other cross-talk indices are given in Figure 2(c). In general we can see that the C_{rg} and C_{bg} is always more than one order of magnitude lower than the C_{wg}, as explained above. However, the trends are the same for the various parameter variations.

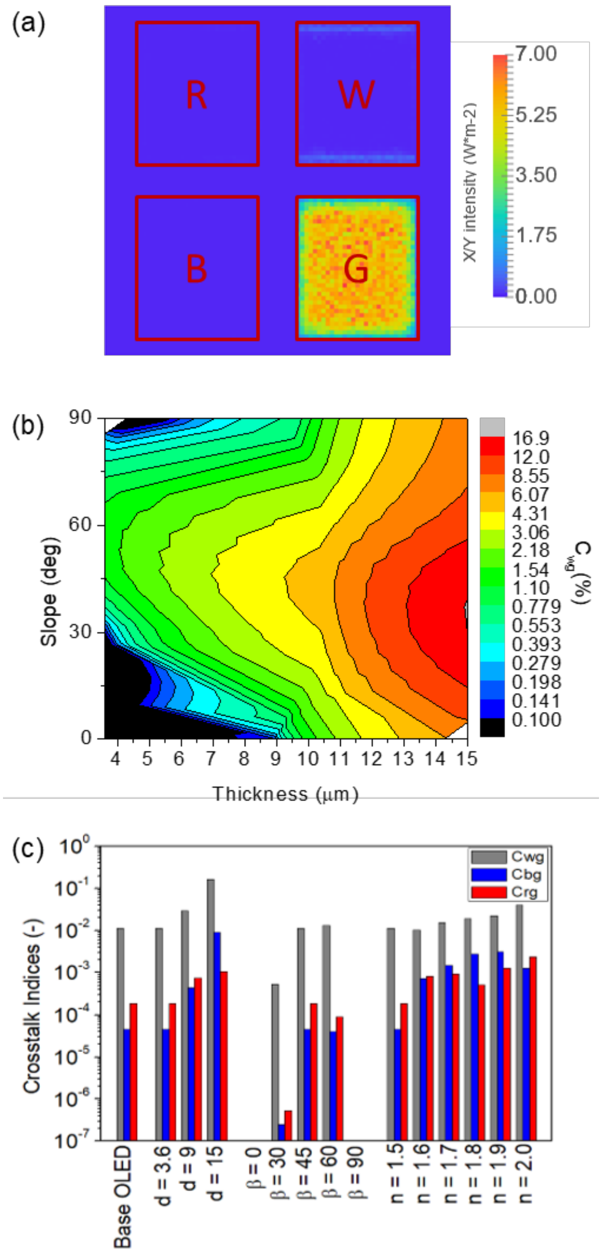

Fig. 2 (a) Simulated intensity map of one simulation unit with indicated positions of red, blue, white and green pixels. (b) white cross-talk index as a function of encapsulation layer thickness and PDL slope. (c) Optical cross-talk indices for all performed variations.

In addition, we present the effect of the refractive index of the encapsulation material on the optical cross-talk. Interestingly, there is a small trend that the cross-talk increases with increasing n. The reason for this behavior currently not yet understood.

3.2 Electro-Optical Pixel Cross-Talk

In order to compare the electrical and optical contribution of the cross-talk in a WOLED/CF display, the base case simulation from the previous section is used and extended with the electrical simulation of Laoss.[3] The required sheet resistance values and the IV curve of the white OLED are taken from previous publications.[1,5] Electrical and optical cross-talk indices are evaluated as a function of applied voltage to the green pixel (see Figure 3 (a)).

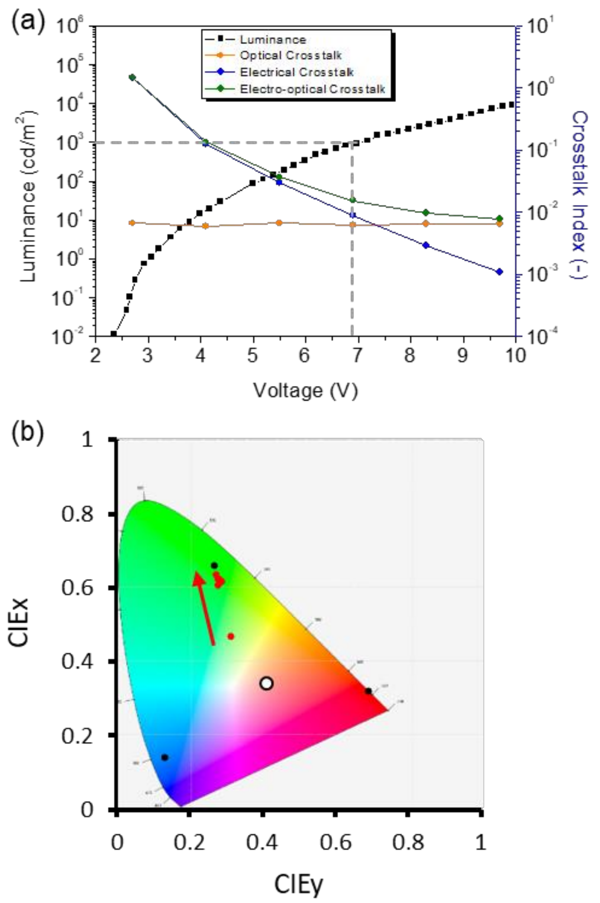

Fig. 3 (a) Electrical, optical and electro-optical cross-talk index as a function of OLED driving voltage. The luminance of the white pixel is shown as a reference. (b) Color coordinates of the primary colors (black and white circles) and far-field color point (red circles) with increasing voltage.

At voltages right above turn-on the C_{wg} value arises to about 10% and decreases steadily for increasing voltage. This value is in close agreement with previous reports.[1,2] When we disentangle both contributions we can see that the optical cross-talk shows no voltage dependence and stays at a constant value of about 0.7%. This is expected from a light leakage effect as both the addressed and the adjacent pixel's intensity would be scaled with the same factor. The strong voltage dependence can thus be solely attributed to the electrical cross-talk. Moreover, there is crossing point at about 7.5 V at which the optical contribution overtakes the electrical contribution. At high brightness values, which are used in real applications, the optical cross-talk is dominating the overall effect and counter measures should therefore predominantly address the reduction of the optical cross-talk contribution.

In Figure 3 (b) the far-field color (red points) of the display is shown as a function of voltage. The color gamut is clearly reduced at low driving voltages of 2.7 V. As the cross-talk reduces quickly, the color point moves close to the theoretically achievable green color point defined by the chosen WOLED and green color filter.

4 Conclusions

We simulated optical and electro-optical cross-talk in WOLED/CF displays with the commercial software Laoss. For a test structure with a typical layout, we demonstrated that our method can estimate the light leakage and give information about the expected modification of the display color gamut. Topography variations of the WOLED layer give insights into optimized PDL structures. Similarly, the refractive index of the material between WOLED and CF can be optimized to reduce optical cross-talk effects. Combining electrical and optical simulations allow to investigate the overall cross-talk effect and evaluate the different contributions separately. We have shown the detrimental effect of electro-optical cross-talk on the color gamut of the display as a function of applied voltage.

Together, the presented results demonstrate that it is possible to describe and quantify cross-talk in OLED displays with numerical simulations and, eventually, minimizing these parasitic effects without the need of fabricating multiple test devices. Further studies could analyze the contribution of CF topography, increasing pixel density or varied OLED arrangements in order to minimize cross-talk and explore the full color gamut of the display.

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