Influence of waveguide thickness on the angular color impression of nanostructured organic emission layers

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***Abstract*— Photoluminescence measurements exhibit an angle-dependent color impression for Alq3 emission layers on a periodically nanostructured substrate. We demonstrate that the color impression is reduced for thick waveguides due to the plurality of outcoupling features.**

OLED; photonic crystal; guided mode extraction; angular dispersion

I. Introduction

Organic light-emitting diodes (OLEDs) are highly promising as energy and cost efficient light sources. Thin-film guided modes trap about 40% of the generated light in a conventional OLED emission layer [1]. Nanostructuring of the emission layer is one technique to extract the thin film guided modes [2]-[5]. Bragg scattering at the nanostructure causes distinct outcoupling peaks in the emission profile. These lead to angular color impressions [3],[6]. Here, we present a study on the influence of the waveguide thickness on the angular color impression.

II. Fabrication and Characterization Method

The gratings were fabricated by nanoimprint lithography (UV-NIL). A 200 nm layer of imprint resist was spin-coated onto a glass substrate and structured with a master stamp (grating period Λ=460 nm). The grating depth is 35 nm. By thermal evaporation, a layer of tris(8-hydroxyquinolinato)aluminium (Alq3) was deposited onto the resist and subsequently passivated by a layer of silicon monoxide (SiO). Samples with three different layer thicknesses were fabricated as shown in Fig. 1.

Exciting the samples with a laser diode at 394 nm, an angle-dependent color impression is visually observed in the emission. Fig. 2 shows as an example a series of photographs of sample B taken at different tilts of the sample with respect to the camera. While the emission appears green at 0° and 30°, it shows an orange-red hue at 15°. Such an inhomogeneous illumination is unwanted in many illumination applications. To investigate the origin of this effect in more detail, we measured the photoluminescence (PL) spectra of the samples at different angles θ in a plane perpendicular to the grating grooves. TE and TM polarization were measured separately.

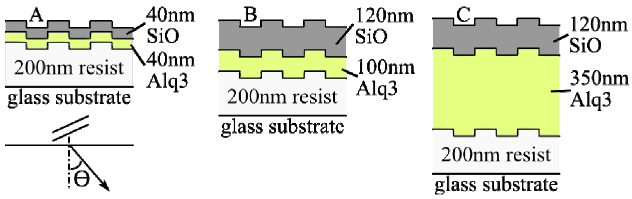

Figure 1. Schematics of fabricated devices A, B, and C with varying layer thicknesses. For all samples the grating period is Λ=460 nm.

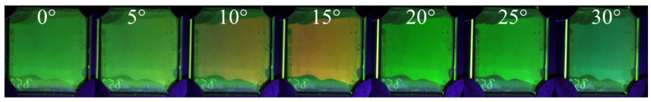

Figure 2. Photographs of the color impression of sample B with the angle θ.

III. Results and Discussion

A. Emission spectra

Fig. 3 a1), b1), and c1) depict the angle-resolved mixed polarization PL spectra of samples A, B, and C, respectively. The spectra exhibit a modified Alq3 emission with angularly dispersive outcoupling peaks. With the Bragg formula [4], we calculated the effective indices of the modes at $\lambda_0 = 550$ nm from the spectra (see Table 1). Each supported mode leads to two outcoupling features in the angular-resolved emission spectrum, one feature per mode propagation direction. Thicker waveguides support more modes and thus lead to more outcoupling features. The TE0 mode of sample A and the TM1 mode of sample C are partially cut-off in the recorded wavelength range, as their effective indices below the substrate refractive index of 1.52 indicate. These cut-off modes show only low intensity outcoupling at longer wavelengths.

TABLE I. Effective indices of the different guided modes in samples A, B, and C at a wavelength of 550 nm calculated from the emission spectra.

Sample	**Effective index ($\lambda_0 = 550$nm)**			
	TE0	***TM0***	***TE1***	***TM1***
A	1.48[a]	-	-	-
B	1.59	1.56	-	-
C	1.72	1.68	1.55	1.51[a]

The modes denoted with an a are not fully guided.

B. *Angular color-shift*

To quantify the angular color-shifts, the CIE (commission international de l'eclairage) 1931 color coordinates were calculated from the spectra and are shown in Fig. 3 a2), b2), and c2) as xy chromaticity diagrams. We measured the color coordinates of unstructured Alq3 to be (x=0.324, y=0.536), which is close to the 0°-emission of samples A and C. The 0°-emission of sample B is more reddish (x=0.357, y=0.505). With increasing observation angle, the emission color shifts as described by the depicted curves in the chromaticity diagrams. Sample A exhibits a blue shift that is maximum at 28.5° (x=0.289, y=0.448). This blue shift can be attributed to the TE0 outcoupling peak at 470 nm that is about 7 times the unmodified Alq3 intensity at this wavelength. Sample B shows the largest color shifts towards red (x=0.480,y=0.439) at 13.0° and green (x=0.266,y=0.633) at 25.0° degrees. At 25.0° the TE0 and TM0 outcoupling peaks are around 530 nm and approximately 10 times the unmodified Alq3 intensity at this wavelength. Sample C shows the smallest angular color shift. At 25° the outcoupling peaks of TE0 and TM0 are around 580 nm and approximately 2 times intensified, while TE1 and TM1 are around 520 nm and 2.5 times the unmodified Alq3 intensity. The angle-dependent color impression is significantly reduced for sample C due to the large spectral distance of 60 nm between the TE0/TM0- and the TE1/TM1-pair.

In order to compare the color shifts in terms of perceived color, we calculated the average color difference between angles from 0° to 30°, CD_{avg}, that is a figure of merit proposed for the angular color stability of OLEDs [7]. It is defined in the CIE 1976 u'v' color space that is more uniform with respect to the perceived color differences than CIE 1931 xyY. The CDavg values of the samples A, B, and C are 0.0119, 0.0625, and 0.0114, respectively, reflecting the large perceivable color shift of sample B.

IV. Conclusion

By comparing the emission of organic emitters in different nanostructured waveguides, we found that the angle-dependent color impression depends on the waveguide thickness. The number of outcoupling features as well as their position and intensity determine the angle-dependent color impression. If a plurality of modes is present as in sample C, the color impression can be reduced by channeling guided photons into different outcoupling features. Thus, when employing grating structures to increase OLED efficiency, the OLED should be designed such that photons are guided in a plurality of modes with different effective indices.

Acknowledgment

The authors gratefully acknowledge the support from the Bundesministerium für Bildung und Forschung within the project "NanoFutur" (03X5514).

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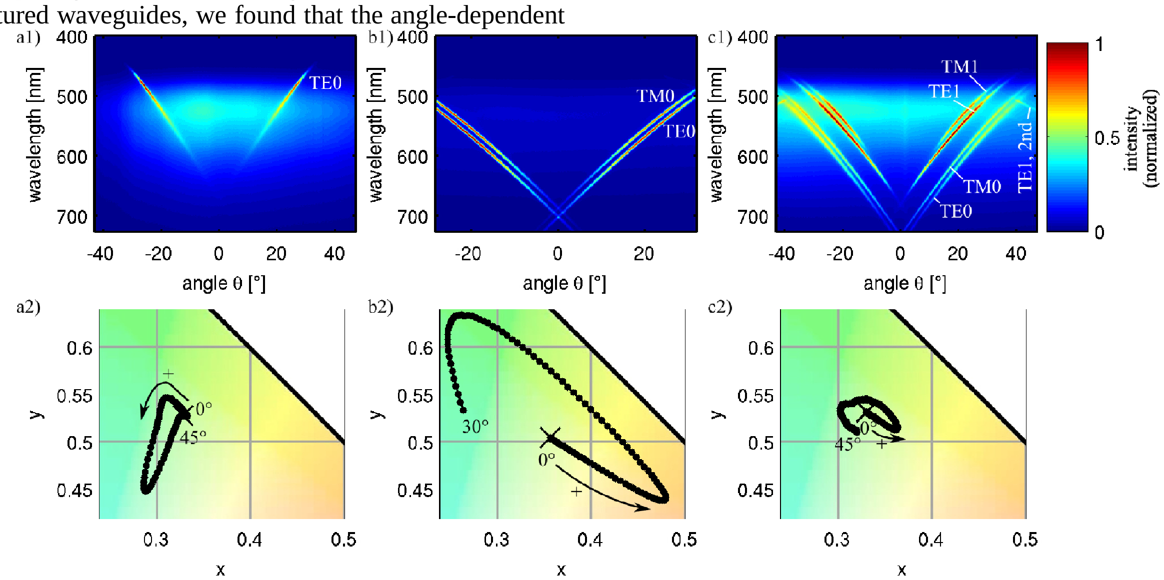

Figure 3. Upper row: Photoluminescence intensity as a function of wavelength and emission angle. Lower row: CIE xy color coordinates for angles from 0° (marked with a cross) up to 45° for samples A and C and up to 30° for sample B. Sample A: a1 and a2. Sample B: b1 and b2. Sample C: c1 and c2.