Recent Advances in OLED Lighting

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ABSTRACT

In this work we present our most recent advances in OLED lighting panel performance: By employing a new (improved) device structure in combination with an internal light extraction concept and a highly reflective top contact, we are able to drastically increase the light extraction efficacy of our OLEDs. The new device structure comprises improved (red, green and blue) dyes, featuring more optimal emission spectra w.r.t. color rendition. The remaining loss mechanisms (such as light extraction, overvoltage, EQE droop and near infrared emission) will be analyzed.

1. INTRODUCTION

In 2014 PHILIPS introduced the warm white OLED lighting panel “Brite FL300” featuring a very high brightness of 3 lm/cm^2 [1] [2] [3] [4] [5] [6]. Even though FL300 is (to the best of our knowledge) the brightest commercially available OLED lighting panel, it clearly does not achieve the full potential of OLED lighting with respect to luminous efficacy and color rendition.

In order to achieve high luminous efficacy it is crucial to suppress the formation of waveguide modes within the organic layer stack and to avoid light absorption due to poor reflectivity of the top contact [7][8][9]. By employing an internal light extraction layer in combination with a highly reflective top contact, we are able to drastically increase light extraction efficacy.

When it comes to color rendering, the CRI value is typically considered the primary figure of merit. More recently however, attention is also being paid to the R9 value (which is a measure for the color rendering of skin-colored objects) [10]. Our new device structure comprises an improved red-green emitting unit, featuring more optimal emission spectra w. r. t. color rendition. As a result an extraordinarily high CRI of 93 and an R9 of 80 is achieved.

2. EXPERIMENTAL

Indium tin oxide coated glass substrates comprising a (high-n) scattering layer were patterned in-house so that an (active) area of 11.5 cm^2 per device was obtained. All organic layers (as well as the top contact) were vacuum deposited at a base pressure of about 10^{-7} mbar. Electroluminescence spectra were measured using an integrating sphere and a *Keithley 2700E Multimeter*. Prior to each measurement devices were driven for 180 sec for the purpose of thermal stabilization.

Fig. 1 shows the four different device structures which shall be discussed in this work: In order to demonstrate the advantages of higher order stacking (especially at high brightness), we compare 6-fold, 3-fold and single stacked device structures. Devices A, B and C comprise the above mentioned newly developed red-green unit, an internal scattering layer and a silver top contact. The reference device comprises our standard organic stack, an Aluminum cathode and no internal scattering layer.

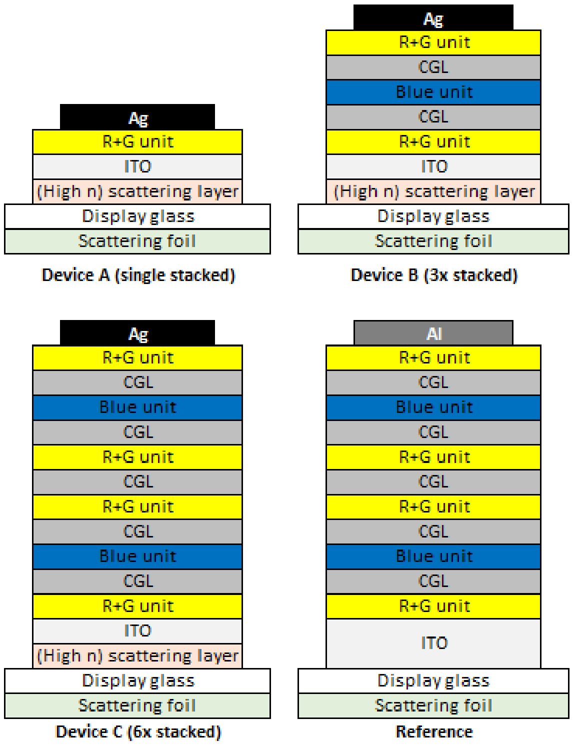


Figure 1: Device structures

3. RESULTS

Figure 2 shows electroluminescence spectra of both device C and the reference device. The reference spectrum comprises a blue peak and only one broad yellow peak (similar to most inorganic phosphor converted white LEDs [12]). The spectrum of device C however, comprises three distinct emission peaks in the blue, green and red respectively.

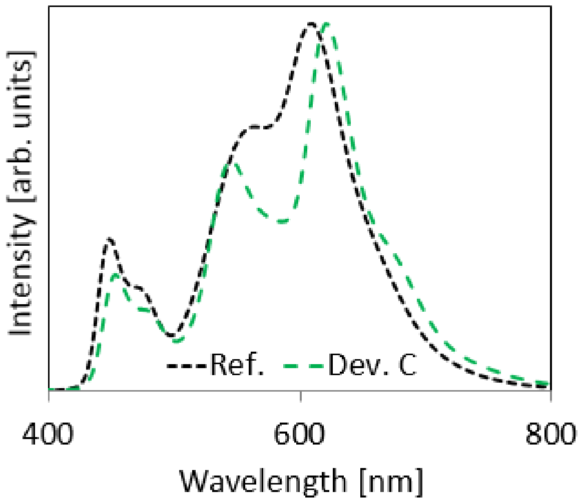


Figure 2: Electroluminescence spectra @ 5 mA/cm^2

The positive impact of the spectral changes on the color rendering can be seen in Table 1: The CRI is boosted to an excellent value of 93. Furthermore, R9 reaches an outstanding value of 80.

The color coordinates of (the 3x stacked) device B are located slightly above the black body curve. For this reason we do not specify CCT, CRI and R9 of device B since this data might be misleading.

Device	CIEx @3knits	CIEy @3knits	CCT @3knits	CRI @3knits	R9 @3knits
A	0.512	0.479	n.a.	n.a.	n.a.
B	0.462	0.433	n.a.	n.a.	n.a.
C	0.456	0.412	2756	93	80
Ref.	0.446	0.405	2861	78	< 0

Table 1: Color coordinates and color rendering. (Note: CCT, CRI and R9 of device B are not specified as its color coordinates are located slightly above the BBC)

The major downside of the changed EL spectrum lies in its potential luminous efficacy: The so called Luminous Efficiency of Radiation (LER) is reduced by about 11% compared to the reference device (see Table 2) due to enhanced "near infrared emission" (see Figure 2). I.e. in order to boost CRI and R9 a good portion of luminous efficacy had to be sacrificed.

Device	Color	Type	Stacked units	Luminous Efficiency of Radiation (LER)
A	Yellow	Phosphorescent	1	340 lm/W
C	White	Hybrid	6	298 lm/W
Ref.	White	Hybrid	6	336 lm/W

Table 2: Luminous efficiency of radiation

The luminous power efficacy of all four devices as a function of brightness is displayed in Figure 3. Naturally, (the phosphorescent yellow) device A exhibits a very high peak efficacy of about 140 lm/W. However, at higher luminance it suffers a pronounced efficacy droop: Already at a luminance of about 4000 cd/m^2 the efficacy of the (6x stacked) device C starts to exceed the efficacy of the (3x stacked) device B and the single stacked device A. Thus, the efficacy curves of those three devices nicely visualize the advantage of higher order stacking at high luminance (but also the underperformance of stacked OLEDs at low luminance).

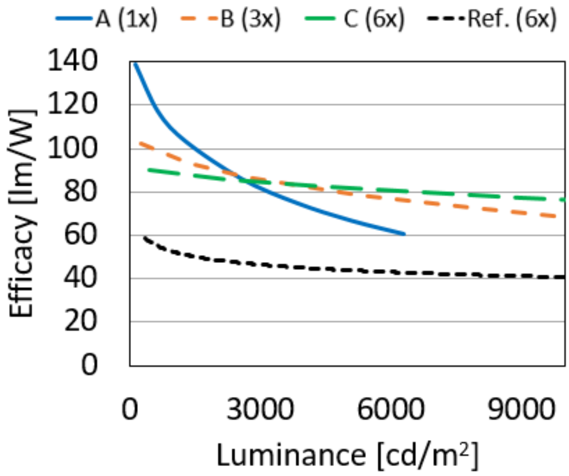


Figure 3: Luminous efficacy

In order to understand this underperformance of the stacked devices it is useful to take a look at the external quantum efficiency (EQE):

Since the devices A, B and C comprise a different number of stacked units, their EQE values cannot be compared directly. Therefore, EQE values have been divided by the number of stacked units of each device. The obtained "EQE per unit" is displayed in Figure 4.

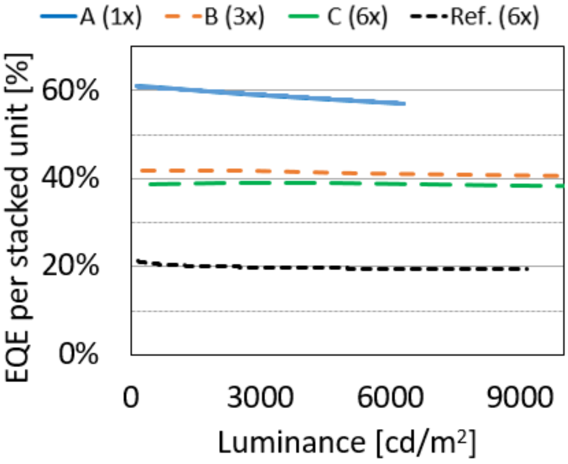


Figure 4: External quantum efficacy per stacked unit

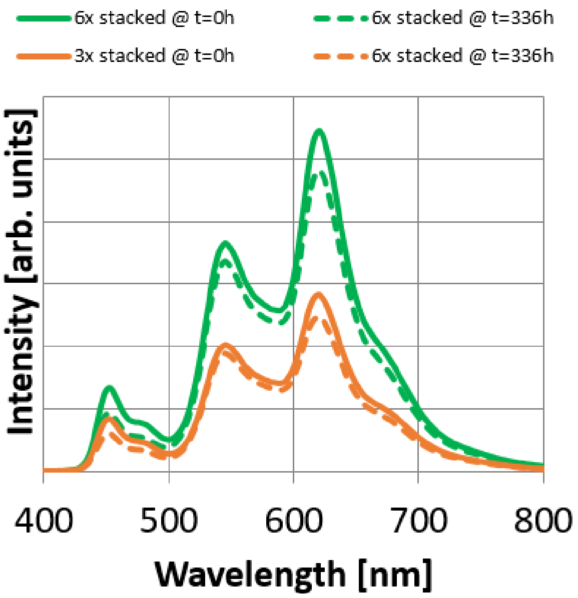
At low brightness (the phosphorescent yellow) device A reaches an EQE of more than 61%. Assuming an internal quantum efficacy (IQE) of about 95% this corresponds to a light extraction efficacy (=EQE/IQE) of about 64% (see Table 2).

In contrast to device A, (the white) devices B and C comprise a fluorescent blue unit (which typically exhibits an IQE of only 30%). Thus, we assume an IQE of only 74% for devices B and C (see Table 3). However, this means that devices B and C exhibit a significantly lower light extraction efficacy (namely 57% and 53% respectively) than the single stacked device A. The more stacked units a device comprises, the lower will be its light extraction efficacy. We attribute this effect mainly to light absorption within the charge generation layers (as all other layers of the organic stack exhibit very little absorption within the visible spectrum).

Device	Efficacy @ 0.1mA/cm2	Efficacy @3knits	EQE per unit @ 0.1mA/cm2	IQE (assumed)	Light extraction
A	139 lm/W	84 lm/W	61%	95%	64%
B	102 lm/W	86 lm/W	42%	74%	57%
C	90 lm/W	84 lm/W	39%	74%	53%
Ref.	49 lm/W	46 lm/W	20%	74%	27%

Table 3: Luminous efficacy

As an accelerated lifetime measurement devices B and C were driven at a current density of 13 mA/cm^2 on a hotplate adjusted at 50°C for 336 hours and then measured again. Figure 5 shows the aged EL-spectra of both devices in comparison to the original measurement at t=0.



The luminous flux of both devices decayed to 91% of its initial value (see Table 4). At a brightness of 1 lm/cm^2 we extrapolate a lifetime of more than130 kh for device B and 380 kh for device C respectively.

Device	Luminous flux after 336h @13mA/cm2	Extrapolated lifetime (LT70) @ 1lm/cm2 or 3000cd/m2
B	91%	> 130 kh
C	91%	> 380 kh

Table 4: Extrapolated lifetime

4. CONCLUSION AND OUTLOOK

By combining the concept of 6-fold stacking with a newly developed organic layer stack, an internal scattering layer and a highly reflective top contact we were able to realize both excellent color rendering and high brightness. However, light extraction efficacy does still hardly exceed 50% (for our 6-fold stacked devices and thus remains a challenge which bears enormous potential.

Furthermore, we conclude that the optimization of the spectrum w.r.t. CRI and R9 comes at the expense of a reduced luminous efficacy (-11%) due to enhanced near infrared emission. I.e. in order to achieve both high LER and R9 values it is crucial to develop even narrower emitting red phosphorescent materials.

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