Light extraction for a doubly resonant cavity organic LED: the RC^{2}LED

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Abstract

The RC^{2}LED is a substrate emitting OLED which has three additional interference layers between the ITO electrode and the glass substrate. This creates two resonant optical cavities. The RC^{2}LED has 2 resonant optical cavities. The first cavity is also present in regular devices and is formed by metal/organic layers/ITO. The second cavity is formed by 3 additional layers: a high refractive index layer (Nb_2O_5), a low refractive index layer (SiO_2) and a high refractive index layer (Nb_2O_5). The additional layers introduce a strong wavelength dependent improvement of the extraction efficiency compared to the OLED without the additional layers.

Our simulations show an improvement of the extraction efficiency of over 70% over a wavelength range of 75 nm compared to an OLED without the 3 layers. Light extraction is worse compared to the reference OLED for wavelengths outside this wavelength range. This improvement has been experimentally verified for a green OLED with an emission between 500nm and 650 nm.

A numerical study shows a relative improvement of 10% for the luminous power efficiency of a 3 color white OLED with the additional layers. The emitted white corresponds with the light emitted by illuminant A. The WOLED has been composed of a fluorescent blue emitter, green and red phosphorescent emitters.

Keywords: OLED, extraction efficiency, RC^{2}LED, white, numerical, wavelength dependence

1. INTRODUCTION

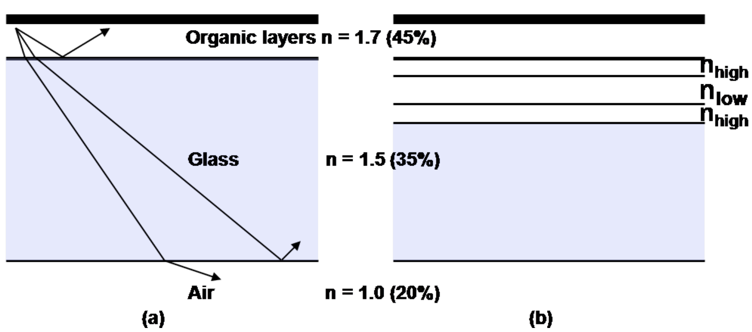


Figure 1. (a) Light extraction is limited by total internal reflection. The percentages are an estimation of the amount of light in each layer. (b) An RC^{2}LED is an OLED fabricated on top of a cavity. The cavity is made from a high refractive index material sandwiched between 2 low refractive index layers.

The organic light emitting diode (OLED) is a promising technology for future lighting and display applications. An OLED consists of a substrate on which a stack of organic layers has been deposited. The area of an OLED should be a few hunderds square cm for lighting applications. The thickness of the stack of organic layers is only a few 100 nms thick. Light is generated in the organic layers by injecting a current through two electrodes of which one should be transparant. The light subsequently is emitted to air through the substrate. A key requirement is a sufficiently high wall plug efficiency. A high wall plug efficiency can be achieved by a large internal quantum efficiency at low voltage and efficient light extraction of the photons.[12] The internal quantum efficiency indicates the amount of excitons which decay radiatively. Only 20% of the generated photons are extracted, figure 1(a). This also means that 80% of the generated light is lost in planar OLEDs by total internal reflection. For lighting applications the wavelength dependent behaviour of emission and light extraction also plays an important role.

The luminous power effiency has improved by at least an order of magnitude during the last decade.[3] The luminous power efficiency indicates the ratio of the luminous flux to the electrical power. This improvement has been made possible due to an increase of the internal quantum efficiency and a decrease of the required voltage. The internal quantum efficiency has been increased by replacing the fluorescent emitters by phosphorescent emitters, which theoretically have a 4 times higher internal quantum efficiency than the fluorescent emitters. One method to achieve a low driving voltage, is doping some of the organic layers.[4] These improvements have been realised for OLEDs with only one emitter and white OLEDs (WOLED). A WOLED can be created by combining multiple emitters. The first white OLED, which was demonstrated in 1993, had a luminous power efficiency below 1 lm W^{-1}. Stable WOLEDs with a luminous power efficiency at least equal to an incandescent light bulb (15-20 lm/W), have already been demonstrated.[5] To the best of our knowledge, the best WOLED to date still have a luminous power efficiency below that of a fluorescent tube, which is 90 lm W^{-1}. It should be noted that present day inorganic LEDs achieve 138 lm W^{-1} with an external efficiency (η_{ext}) of over 60%.[6]

Light extraction needs to be improved to reach such high luminous power efficiencies. Light extraction is limited by total internal reflection (TIR). TIR occurs when light makes the transition between a high index material to a low index material at an oblique angle. Figure 1(a) clearly indicates 2 interfaces at which TIR occurs. The interface between organic layers and glass substrate has a refractive index shift from approximately n=1.7 to approximately n=1.5. The interface between glass substrate and air exhibits a refractive index shift from approximately n=1.5 to n=1.0. A corrugation of these interfaces can be used to eliminate TIR.

An array of micro lenses at the interface between glass-air results in a relative improvement of more than 50%.[7,8,9] The same holds true for a diffusive layer on the interface between substrate and air.[10] The interface between organic layers and glass can also be adjusted to increase light extracition. A grating between ITO and substrate results in a relative improvement of 80%.[11] Additional planar layers placed between ITO and glass also increase light extraction.[12,13] To the best of our knowledge, all these techniques will likely have a wavelength dependent extraction efficiency. Tuning the extraction efficiency to match with the peak of emission is necessary to achieve the best luminous power efficiency.

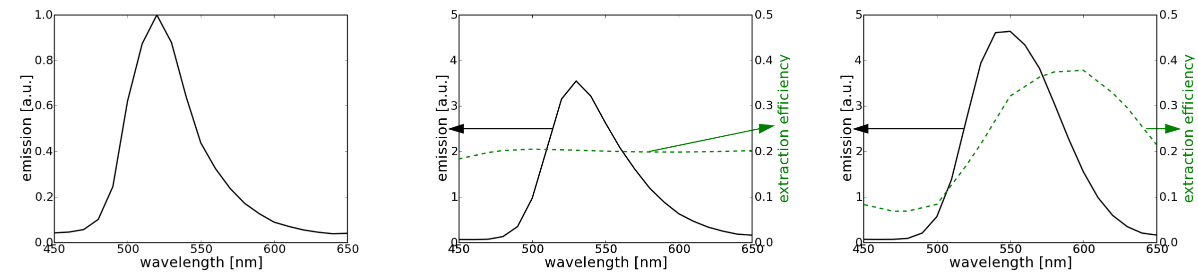
We propose the RC^{2}LED[14] shown by figure 1(b) to increase light extraction. The RC^{2}LED is composed by 2 optical cavities. The first cavity is created by the cathode, organic layers and ITO. The second cavity is a resonant cavity enclosed by two mirrors. The cavity of figure 1(b) corresponds with the layer of a low refractive index, the two mirrors correspond with the layers of a high refractive index. This design has been proposed for inorganic LEDs. Problems with current injection however prevented a succesful demonstration for inorganic LEDs. These problems however not an issue for OLEDs. The RC^{2}LED with one emitter is discussed in the following section. The light extraction of this RC^{2}LED at a given resonance wavelength is almost 2 times higher than the ligh extraction of a reference OLED. The relative improvement of the extraction efficiency stretches over 50-100 nm. Light extraction is decreased compared to the reference OLED outside this wavelength region. White light corresponds with the wavelength range from 450 nm to 750 nm. The last section of this paper therefore discusses the RC^{2}LED for such a large wavelength range.

2. RC^{2}LED WITH ONE EMISSIVE LAYER

The RC^{2}LED[14] has an extra set of planar layers which are located between ITO and glass. These layers create 2 resonant optical cavities. The main impact of these planar layers is an adjustment of the angular emission in glass. More light is emitted inside the extraction cone for a given resonance wavelength. This effect however is

	Reference OLED	RC^2LED
Al	150 nm	150 nm
Hole Transport Layer (HTL)	80 nm	80 nm
Electroluminescent Layer (EL)	40nm	40 nm
Electron Transport Layer (ETL)	20 nm	20 nm
ITO	50 nm	50 nm
NbOx $[\frac{\lambda_{res}}{4n_{NbOx}}]$	none	45 nm
SiOx $[\frac{\lambda_{res}}{2n_{SiOx}}]$	none	146 nm
NbOx $[\frac{\lambda_{res}}{4n_{NbOx}}]$	none	45 nm
glass	mm	mm
air		

Table 1. data RC^2LED



(a) The emission spectrum of the EL layer of table 2. (b) Simulated light extraction and emission of the reference OLED (c) Simulated light extraction and emission of the RC^2LED

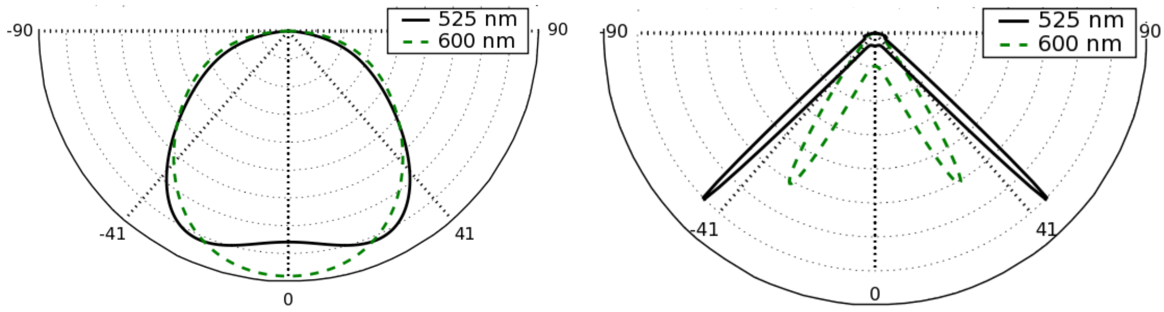
Figure 2. Simulated pectrum of the reference OLED and the RC^2LED.

highly wavelength dependent. The first cavity is the one that is also present in regular devices and is formed by metal/organic layers/ITO. The second cavity corresponds with the 3 additional layers: a high refractive index layer (Nb_2O_5), a low refractive index layer (SiO_2) and a high refractive index layer (Nb_2O_5). The theoretical thickness of these layers is respectively $\frac{\lambda_{res}}{4n_{high}}$, $\frac{\lambda_{res}}{2n_{low}}$ and $\frac{\lambda_{res}}{4n_{high}}$, λ_{res} is the wavelength at which maximal light extraction occurs. The refractive indices for NbO_x and SiO_x are respectivitely 2.4 and 1.45 at 500nm. The refractive indices of the organic layers are around 1.75-1.8.

Preliminary results of this concept have been presented at SPIE Photonics West 2007.[15] Measurement results of newly fabricated OLEDs have been incorporated in this section. A reference OLED, i.e. without additional layers, is compared to an OLED with the same organic layer stack but with additional layers, i.e. the RC^2LED. These OLEDs are described by the layer thicknesses of table 2. The fixed organic layer stack, which is used for the reference OLED and the RC^2LED, has been optimized to achieve maximal extraction efficiency for the reference OLED. The RC^2LED has been locally optimized to achieve maximal extraction efficiency. A global optimum can be found by optimizing both organic layer stack and the additional RC^2LED.

The simulation technique uses a plane wave decomposition of a dipole located in the emitter layer, i.e. in the middle of the ElectroLuminescent Layer (EL). This calculation has to be done for each wavelength indepenently. Each of the plane waves is propagated through the structure. The dipole can be either a dipole parallel to the interfaces and a dipole perpendicular to the interfaces. A random dipole is equal to the combination of 2 parallel dipoles and 1 perpendicular dipole. This technique is described in detail in[16] .

The light intensity emitted by an OLED ($E(\lambda)$) is the multiplication of the electroluminescent spectrum $\phi_{EL}(\lambda)$ and the light extraction $\eta_e(\lambda)$:



(a) reference OLED (b) RC^2LED

Figure 3. Angular intensity P(θ) in **glass** for a reference OLED and an RC^2LED at 525 nm and 600nm. Total Internal reflection occurs at 41^o.

wavelength	reference OLED	RC^2LED
525 nm	51%	50 %
600 nm	53%	53 %

Table 2. Fraction of light emitted in the glass substrate

$$E(\lambda) = \phi_{EL}(\lambda)\eta_e(\lambda) \tag{1}$$

This equation is valid as long the spontaneous emission is not influenced by the micro-cavity effect.

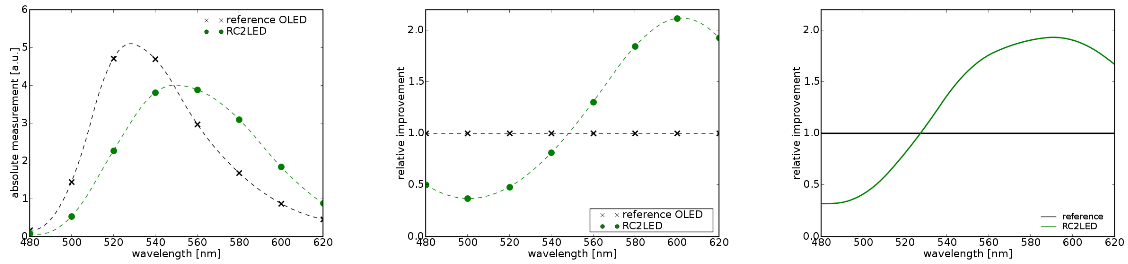
The electroluminescent spectrum $\phi_{EL}(\lambda)$ of the emissive layer is given by figure 2(a). The light extraction $\eta_e(\lambda)$ of both the reference OLED and the RC^2LED, defined by table 2, are given by figure 2(b) and 2(c). Light extraction of the reference OLED is 20% and (almost) wavelength independent. Light extraction of the RC^2LED is highly wavelenghth dependent with a maximum of almost 40% at 600 nm. This results in a red-shift of the emission peak of the RC^2LED in comparison to the emission-peak of the reference OLED.

The angular light emission in glass for 525 nm and 600 nm are given by figure 3(a) and 3(b), respectively the reference OLED and the RC^2LED. The angle of total internal reflection (TIR) for the interface glass-air occurs at 41^o. The total fraction of light which is emitted in glass, i.e. both in glass and air, is given by table2. The RC^2LED does not decrease the total amount of light absorbed by the organic layers. The beneficial effect of the RC^2LED is due to an improvement of the emission pattern in glass. Fresnel equations indicate that almost all light inside the extraction cone is transmitted through the glass-air interface, regardless of angle or polarization. All light with an angle larger than the angle of TIR is reflected. The total amount of power inside the extraction cone can be found with the given angular intensity P(θ):

$$\begin{aligned} E &= \int P(\theta)d\Omega \\ &= \int_0^{2\pi}\int_0^{\theta_{TIR}} P(\theta)\sin(\theta)d\theta d\phi \end{aligned} \tag{2}$$

The space angle $d\Omega$ corresponds with $\sin(\theta)d\theta d\phi$. The emission of a random dipole is indepent on the angle ϕ. The angle θ is relative to the normal on the interface glass-air.

Experimental verification has been done with the layer stack given by table 2. These results confirm the results described in[15] . The organic layer stack has been deposited on two types of substrates. The first substrate is a



(a) Absolute measurement of both OLEDs. (Dots indicate measurement points.)

(b) Relative improvement compared to the reference OLED: experimental results. (Dots indicate measurement points.)

(c) Relative improvement compared to the reference OLED: simulated results

Figure 4. Relative improvement of the RC^{2}LED and the reference OLED

normal glass substrate on which the reference OLED is deposited. The second substrate however has 3 additional layers on which the same layers as the reference OLED are deposited. Deposition of the Organic Layer stack has been performed by Philips Research Aachen. The substrates have a size of 5 cm * 5cm, the organic layers have a size of 4 cm * 4 cm. The emission of the organic layer stack is primerly focussed in the visible green. The emission spectrum of the electroluminescent layer is given by 2(a). Two consecutive fabrication runs of the same layer stack result in an emission with a relative deviation of up to 5%. The wavelength for which the cavity has been optimized wavelength turned out to be slightly different from the electroluminescent peak. Figure4(a) shows the measured spectrum of the reference OLED and RC^{2}LED. Measurement were done by attaching the OLED to an integrating sphere. Both OLEDS were driven by a current of 5.5 mA. The measured voltage over the reference OLED and the RC^{2}LED was respectively 6.2 V and 5.4 V. A small operating voltage can be achieved by using PIN technology available at NOVALED. These voltages are a relative deviation of 10-20% from the results reported in[15] .

The relative improvement of the RC^{2}LED compared to the reference OLED can be found by dividing the spectral intensities of figure 4(a). The experimental relative improvement of figure 4(b) correspond with the theoretically found values of figure 4(c). This last curve is obtained by dividing the light extraction of the RC^{2}LED, figure 2(c), by the light extraction of the reference OLED, figure 2(b). The location of the dipoles had to be tuned in our simulations to achieve good correspondance between simulations and experiments, 4(c) and 4(b). The dipoles used for figure 4(c) are placed at 10 nm from the interface between HTL and EL. Simulations indicate that a deviation of 10 nm for the dipole location results in a shift of the peak of the relative improvement in the order of 10nm.

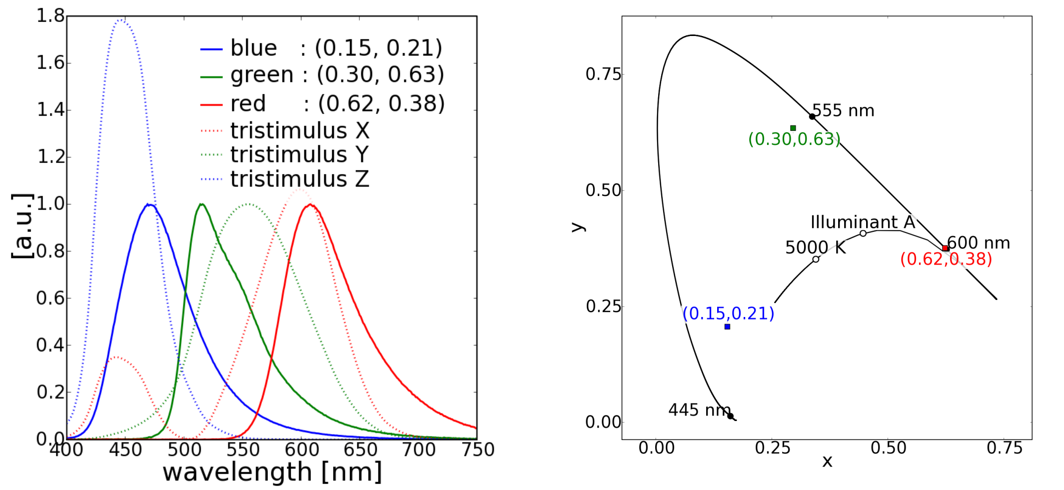
Our experiments confirm a relative improvement of over 80% for a given resonance wavelength.

3. A WHITE RC^{2}LED

The RC^{2}LED increases light extraction by a factor of 2 for one resonance wavelength. This effect is limited to a wavelength range of 50 nm, figure 4. Wavelengths outside this region show a decrease of light extraction. White light of high quality however stretches over a wavelength range from 450 nm to 750 nm. An optimization of the wavelength dependent light extraction therefore is necessary to achieve a high luminous power efficiency.

Several OLED architectures exist to generate light which spans the wavelength range from 450 nm to 750 nm,.[3] The RC^{2}LED obviously would yield the best efficiency by combining 3 seperate OLEDs, each with different color point. Our numerical optimization of the luminous power efficiency however has been done for one RC^{2}LED with one single organic layer stack with 3 distinct emissive layers.

The luminous power efficiency has been estimated with a numerical model which comprises 3 parameters for each emitter: internal quantum efficiency, light extraction and the emission spectrum. The last 2 parameters



(a) Electrolumiscent spectrum of the emitters.

(b) Color coordinate of the spectrums of 5(a)

Figure 5. Chromaticity of the 3 emitters of the WOLED, based on.[5]

material	refractive index	thickness: reference OLED	thickness: RC^2LED
Al	0.96+6.69j @ 550nm	100 nm	
Electron Transport Layer(ETL)	1.76 @ 550nm	t_{ETL}	
blue emitter/interlayer/green emitter/red emitter	1.80 @ 550 nm	28 nm	
Hole Transport Layer (HTL)	1.75 @ 550 nm	t_{HTL}	
ITO	1.82-0.0113j @ 550 nm	90 nm	
SiO_2	1.46	none	t_{low}
Nb_2O_5	2.38	none	t_{high}
SiO_2	1.46	none	t_{low}
glass	1.52	mm	
air	1.0		

Table 3. Layer thicknesses of the 3 color WOLED. The wavelength dependent refractive indices are given for $\lambda = 550$ nm.

are wavelength dependent. The color coordinate of the desired white light determines the relative fraction of intensity which needs to be emitted by each of the emitters.

The organic stack of table 3 gives a WOLED with 3 distinct emissive layers, similar to the work presented in[5] . Light extraction is different for each of the different emitters. The electroluminescent intensity and color coordinates of the 3 emitters are given by 5. The internal quantum efficiency of the blue fluorescent emitters is 4 times smaller than the internal quantum efficiency of the green and red phosphorescent emitters.

3.1. Estimation of the Luminous Power Efficiency

The Luminous Power Efficiency of a WOLED ($\eta_P, [\frac{lm}{W}]$) is determined by the ratio of the total emitted luminous flux (F) to the total injected electrical power (P_{el}):

$$\eta_P = \frac{\sum_{i=b,g,r} F_i}{\sum_{i=b,g,r} P_{el,i}} \tag{3}$$

The index i indicates one of the three emitters: (b)lue, (g)reen and (r)ed. Three parameters are required to determine F_i and $P_{el,i}$: internal quantum efficiency, light extraction and the emission spectrum. The color coordinate of the desired white light determines the relative fraction of intensity which needs to be emitted by each of the emitters. We will implicitly assume that the stack is fixed, regardless of the intensity emitted in the organic layers by each of the emitters.

The total luminous flux is given by:

$$\begin{aligned} F &= \sum_{i=b,g,r} F_i \\ &= \sum_{i=b,g,r} 683 \int A_i E_{op,i}(\lambda) V(\lambda) d\lambda \end{aligned} \tag{4}$$

The eye photopic sensitivity curve V(λ) is defined in[17] . The ratio A_i between the different emitters needs to be tuned to reach the desired white color of the WOLED. This ratio can be calculated with the tristimilus color points of the emitters and the white color, resp. (X_i, Y_i, Z_i) and (X_w, Y_w, Z_w). The color point can be determined by either spectrum of color temperature.[17] The amplitudes A_i needs tosatisfy:

$$X_w = \sum_{i=b,g,r} A_i X_i, \; Y_w = \sum_{i=b,g,r} A_i Y_i, \; Z_w = \sum_{i=b,g,r} A_i Z_i \tag{5}$$

The emitted light intensity in air of one of the emitters $E_{op,i}$ is determined by the intensity of light generated in the organic layers $E_{el,i}$ and the light extraction $\eta_{c,i}(\lambda)$:

$$E_{op,i} = E_{el,i} \eta_{c,i} \tag{6}$$

The total injected electrical power (P_{el}) relies on the sum of the electrical power of the individual emitters:

$$P_{el,i} = \int A_i E_{el,i}(\lambda) \frac{1}{\eta_{int,i}} \frac{qV\lambda}{hc} d\lambda \tag{7}$$

The parameter $\frac{1}{\eta_{int}}$ indicates the amount of excitons to create one photon. The ratio $\frac{hc}{\lambda qV}$ gives the relation between the optical power of the photon and the energy of the exciton. One can use doped layers to minimize $P_{el,i}$ by minimizing the required voltage V. Any photon can have maximally an energy of qV, which gives an indication of the minimal voltage.[4]

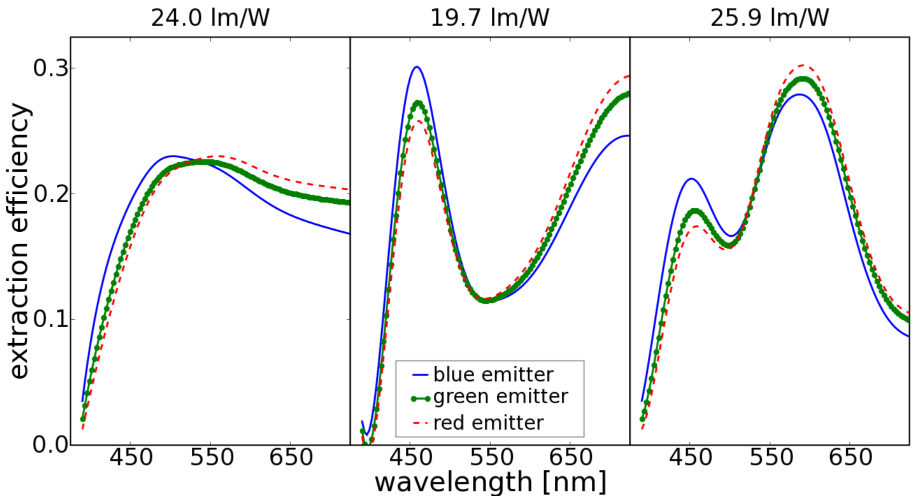


Figure 6. Extraction efficiency of 3 different sets of RC^2 interlayers with the same organic layer stack, table 4.

3.2. Optimization of a WOLED with RC^2LED layers

The luminous power efficiency for a given color point can be maximized by a combined action of electroluminescent emission, internal extraction efficiency and extraction efficiency of the emitters.

The color point of interest corresponds with Illuminant A. The maximal luminous efficacy of this color point, the ratio between luminous flux to radiant flux, is 512 lm/W.[18] This color can created with 2 monochrome sources, which emit at 450 nm and 579 nm. The resp. fractions of these 2 monochrome sources are 15% and 85%. Any realistic WOLED spectrum of sufficient high color quality will undoubtly have a much lower luminous efficacy.[19] Light, created by 2 monochrome sources, will never have color rendering index (CRI) above 80.

The emissive stack of table 3 has 3 emissive layers: blue fluorescent emitters, an interlayer, green phosphorescent emitters and red phosphorescent emitters. The spectrums of the blue, green and red emitters and their color coordinates are given by figure 5. The internal quantum efficiency of the blue emitters is 4 times smaller than the internal quantum efficiency of either green or red emitters. The voltage, used for equation 7 is 3.8 V. Such a small operating voltage can be achieved by using the PIN technology, available at NOVALED. The minimal voltage required for the photon of highest energy (blue) is 3 V.

The extraction efficiency of the reference OLED given by table 3 is dependent on the thicknesses of electron transport layer (t_{ETL}) and the thickness of the hole transport layer (t_{HTL}). The extraction efficiency of the RC^2LED has two additional parameters: the thickness of the low refractive index layer (t_{low}) and the thickness of the high index layer (t_{high}). The calculation of the extraction efficiency of one emitter for a given structure at a specific wavelength requires 10 seconds on a 2 ghz opteron processor. A complete scan of the 4 parameter space of the RC^2LED, i.e. (t_{ETL}, t_{HTL}, t_{low} , t_{high}), would therefore take unrealisticly long. The local optimization method first optimizes the organic layer stack of the reference OLED for maximal luminous power efficiency by brute force. This gives $(t_{ETL,max}, t_{HTL,max})$ The second step is an optimization of the additional parameters (t_{low}, t_{high}) for the RC^2LED with the previously found organic layer stack.

The brute force method calculates the luminous power efficiency for the parameter space (t_{ETL}, t_{HTL}). This parameter space -$t_{ETL} \in [0nm, 80nm[$ and $t_{HTL} \in [0nm, 80nm[$- is discretized by a square grid with an interspacing of 3 nm and 3 nm Twelve equidistant wavelengths between 390 nm and 750 nm are sufficient to approximate the wavelength dependent extraction efficiency. The luminous power efficiency is calculated with the extraction efficiency and equation 7. The optimum of the reference OLED is dependent on the final color

t_{ETL}	t_{HTL}	t_{low}	t_{high}	luminous power efficiency
44 nm	30 nm	0 nm	0 nm	24 lm/W
44 nm	30 nm	40 nm	50 nm	19.7 lm/W
44 nm	30 nm	170 nm	80 nm	25.9 lm/W

Table 4. Structure with an extraction efficiency given by figure 6

point and the internal quantum efficiency of the emitters. This stack with a fixed (t_{ETL}, t_{HTL}) is the starting point for the optimization of (t_{low} , t_{high}).

The results are shown in table 4 and figure 6. A relative increasement of luminous power efficiency of 10% is possible with the RC^{2}LED. Figure 6(b) shows the extraction efficiency of a cavity which has been optimized to extract light at 450 nm. The luminous power efficiency is far below the luminous power efficiency of the reference OLED. This conclusions is also valid for cavities which have been optimized for maximal extraction efficiency at other wavelengths. The maximal luminous power efficiency can not be obtained with a cavity which has been optimized to increase light extraction for one specific wavelength.

4. CONCLUSIONS

The RC^{2}LED shows an increasement of the light extraction by a factor of 2 for a given resonance wavelength when compared to a reference OLED , both numerically and experimentally. The improvement of the light extraction stretches over a wavelength range of 50-100 nm. This improvement however coincides with a decrease of the light extraction outside this wavelength range.

A simple numerical model shows a relative improvement of 10% of the luminous efficiency for a white OLED with 3 emissive layers.

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