Employing a 2D surface grating to improve light out coupling of a substrate emitting organic LED.

Peter Vandersteegen*[a], Angel Ullan Nieto[b], Carl Van Buggenhout[a], Steven Verstuyft[a], Peter Bienstman[a], Peter Debackere[a], Kristiaan Neyts[b] and Roel Baets[a]

[a] Department of Information Technology, UGent-IMEC, St-Pietersnieuwstraat 41,9000 Gent, Belgium

[b] Department of Electronics and Information Systems, UGent, St-Pietersnieuwstraat 41, 9000 Gent, Belgium

Peter.Vandersteegen@intec.UGent.be

Abstract

We present simulation and experimental results to achieve increased light extraction of a substrate emitting OLED. We present a comparison between a grating surface on the OLED and an array of microlenses at the interface between substrate and air. This experimentally gives -in both cases- a relative improvement of approx. 30 %. We also demonstrate the concept of a RC^2LED, applied to an OLED. The RC^2LED is composed by adding a high, low and high index layers between ITO and glass, i.e. the interface between organic layers and glass. These extra layers create a cavity which numerically gives a relative improvement of over 60% at the resonance wavelength of the cavity over a wavelength range of 50-100 nm. The influence of an array of micro lenses in addition to the RC^2 layers is also investigated in this paper.

Keywords: OLED, grating, extraction efficiency, RC^2LED, microlenses

1. INTRODUCTION

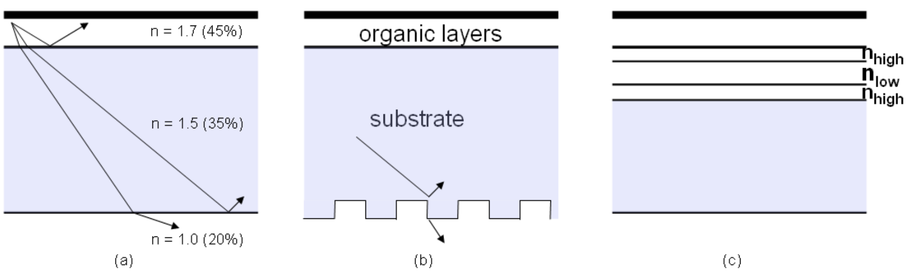


Figure 1. (a) Light extraction is limited by total internal reflection. The percentages are an estimation of the amount of light in each layer. (b) The grating at the interface between substrate and air. (c) An RC^2LED is an OLED fabricated on top of a cavity. The cavity is made from a low refractive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

A key requirement for future lighting sources is the energy efficiency. At present it is estimated that 19 % of all primary energy is used for lighting. Enormous amounts of energy and money can thus be saved by more efficient lighting. Recent progress has made White Organic LEDs (WOLED) a candidate for tomorrow's lighting. The efficacy of white OLEDs has indeed made a huge leap in the last 10 years. The first white OLED, which was demonstrated in 1993, had an efficacy below 1 lm W^{-1}. This summer a press release by Konica Minolta showed a phosphorescent white OLED with an efficacy of 64 lm W^{-1}. This surpasses the efficacy of an incandescent light bulb, which only achieves 15-20 lm W^{-1}. It however is still below the efficacy achieved by fluorescent emitters, which is 90 lm W^{-1}.[1,2] It should also be noted that present day inorganic LEDs achieve 138 lm W^{-1} with an external efficiency (η_{ext}) of over 60%.[3] In order to increase the efficacy of OLEDs it is absolutely necessary to improve their light extraction. For an OLED with planar interfaces, the optical outcoupling is limited to approximately 20%. This means that 80% of the generated light is trapped by total internal reflection, see figure 1(a). Increasing light extraction therefore is crucial to achieve efficient WOLEDs.

Light-Emitting Diodes: Research, Manufacturing, and Applications XI, edited by Klaus P. Streubel, Heonsu Jeon, Proc. of SPIE Vol. 6486, 64860H, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.701344

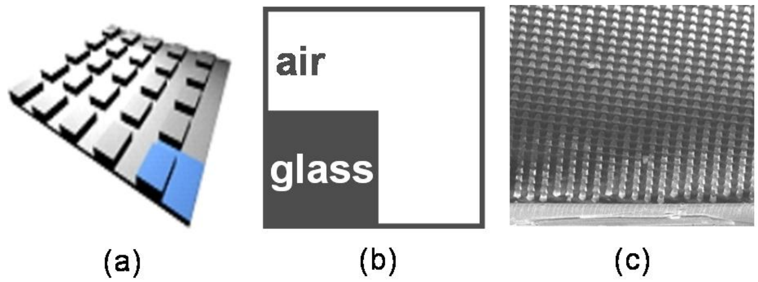


Figure 2. A 2D grating of pillars. (a) perspective view, (b) one elementary cell and (c) actual fabricated grating.

In this paper we will focus on increasing light extraction from a bottom emitting OLED. Light is trapped 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. 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. These refractive indices allow us to estimate the amount of light in each layer, see also figure 1(a). This estimation implicitly assumes a uniform emission of light in the organic layers. Optical extraction can be improved by adjusting the interfaces between organic layers-substrate and substrate-air.

Placing microlenses at the glass-air interface results in a relative improvement of 50 %.[4] This however results in a surface corrugation with a depth of tens of μm, which might make packaging visually less attractive/more difficult. Adjusting the interfaces between the organic layers and the glass substrate can also increase light extraction. This can be done by either using a grating[5,6] or by using additional layers.[7,8,9] It should be noted that placing the corrugation close to the organic layers can possibly negatively influence the light generation.

We propose the use of a grating at the substrate-air interface to minimize the corrugation of the surface, figure 1(b). The design of an optimal grating requires a rigorous numerical integration of the equations of Maxwell. Section 2 discusses the simulation method we have developed. The experiments described in section 3 indeed verify that gratings perform as well compared as micro lenses.

In order to extract light trapped in the organic layers, we propose the use of the RC^{2}LED,[10] figure 1(c). This concept already has been proposed for inorganic LEDs. The design of an RC^{2}LED requires additional layers which causes problems with current injection in inorganic LEDs. We however will demonstrate a succesful implementation based on organic LEDs. The layer stack is described in detail in section 4. A combination of the RC^{2}LED and micro-lenses finally concludes this paper.

2. SIMULATION METHOD

The grating under discussion is shown in figure 2. The characterizing parameters are the depth, period and fill factor. The last 2 parameters can vary independently in the horizontal and vertical direction of figure 2(b). We have used the following layer stack to optimize the grating: glass (n = 1.528) substrate, ITO (n=1.622, 100 nm)/ SiON (n=1.806-0.012j, 120 nm)/ α-NPD (n=1.807, 30 nm)/ AlQ3 (n = 1.655, 30 nm) and an Al-cathode (n=1.031-6.81j, 150nm). This method has also been used for the simulation of the RC^{2}LED with and without grating, as described in section 4.

Our simulation method calculates the light extraction for a given wavelength in 2 steps. During the first step the radiant intensity of the organic layer stack is calculated by means of a plane wave expansion of a randomly oriented dipole located between α-NPD and AlQ3. This gives us an angular distribution of the radiant flux emitted in glass. The second step convolves the radiant intensity with the angular dependent gra-ting transmission. The grating transmission is defined as the transmission of the power flux for any plane wave incident on the grating, incident at a given angle. This transmission takes into account the multiple reflections, as seen in figure 1(a) and all power carrying diffraction orders. Contrary to the organic stack, light in the substrate is assumed to behave spatially incoherent. The reflectance and transmittance of the diffracted orders at the grating are calculated with Rigorous Coupled Wave Analysis.[11]

An optimization has been performed for each parameter, while keeping the other parameters constant. This local optimization already gives a good indication for the global optimum, because each grating parameter influences the efficiency largely independently. Best performance is achieved for symmetrical structures, i.e. period and fill factor are equal in both direction of figure 2(b). There is hardly any wavelength dependency for the optimal fill factor and depth. (optimal: depth = $0.5\mu m$, fill factor = 70%, period = $1.4 - 2.0\mu m$) The absolute extraction efficiency is also considerably influenced by light absorption of the organic layer stack. If we simulate a organic layer stack which absorbs all incident light, we only see a negligible increase of extraction efficiency compared to a planar structure. This indicates the importance of multiple reflections as sketched in figure 1(a).

3. COMPARISON BETWEEN GRATING AND MICROLENS FOR A 3*3 MM^2 OLED

For the experiments the gratings and the micro lenses were fabricated on a different substrate than the one on which the OLED stack of 9 mm^2 was deposited. The measurement procedure consisted of successive measurements of the OLED stack with or without the gratings/micro lenses. The grating/micro lenses were attached to the OLED substrate by pressing the OLED substrate and the gratings/micro lenses substrate together. An optical contact fluid was used to minimize reflections. The measurements were done with an integrating sphere.

The grating has been fabricated with ion etching of a SiOx deposited layer on top of a basic glass substrate. The grating pattern of a few tens of mm^2 was defined in positive resist with interference lithography. Our interference lithography setup is not able to fabricate gratings with a width larger than 1 cm. The filling factor of our gratings is also limited to 50%, which is below the optimal value of 70%. The microlenses have been fabricated on a PMMA substrate by Philips Research Aachen. The PMMA substrate has an index mismatch with the glass substrate of the OLED.

Figure 3(a) shows the relative improvement in function of the depth of the grating both theoretically and experimentally for $\lambda = 520nm$. Our maximum measured relative improvement is 30% with almost optimal grating parameters. The deviation between measurement and simulated results could be explained by a larger than expected absorption in the organic layer stack.

Figure 3 gives a comparison between a grating and an array of microlenses attached to the surface of an OLED. The simulations indicate an almost wavelength independent relative improvement of 50% for the grating. The measured relative improvement of figure 3 however is highly wavelength dependant. The maximum value also is 10% lower than the simulated value.

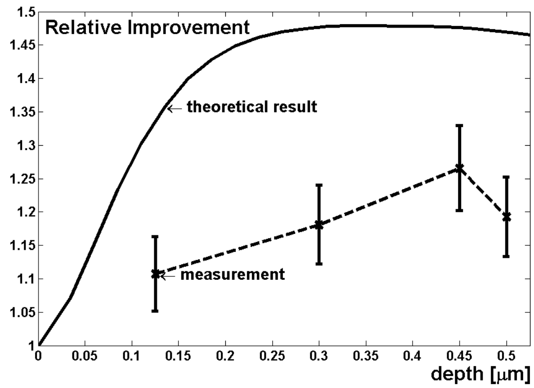
We consider the most likely reason for the wavelength dependant behaviour the low ratio noise/signal for wavelengths outside [500nm, 540nm], figure 3. Only in a small in the neighbourhood of the peak (50nm), the ratio noise/signal is sufficiently high to completely rule out noise behaviour.

We have a relatively similar behaviour between gratings and microlenses. We conclude that gratings are very tolerant concerning fabrication tolerance. The experiments indicate that optimally designed gratings and microlenses perform equally well. A surface corrugation of minimally 500 nm is sufficient to have optimal performance.

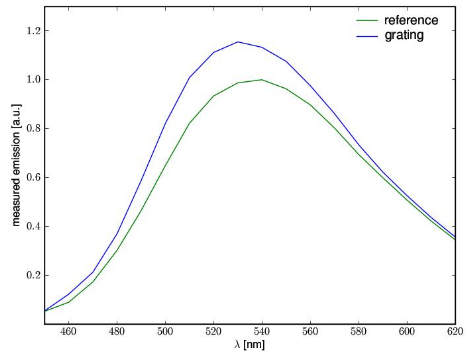
4. RC^{2}LED

4.1. Planar interfaces

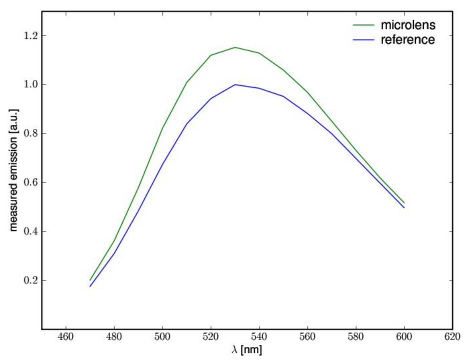
In order to extract light from the organic layers it is absolutely necessary to make adjustments to the interface between the organic layers and the glass substrate. As mentioned in the introduction the two most popular methods are the use of a micro-cavity effect and the use of a grating. In this section, we will introduce the RC^{2}LED for OLEDs. This concept has already been introduced in 2001 for inorganic LEDs,.[10] Electrical contact problems have however prevented succesful demonstration of an inorganic LED. Our simulations indicate an improvement of the extraction of 80% compared to the same OLED without additional RC^{2}LED layers. This



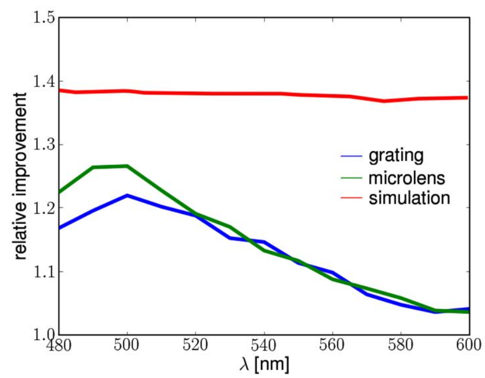
(a) Relative improvement in function of the depth for $\lambda = 500$ nm, depth = 500 nm, fill factor 50% and period = $2.0 \mu m$.



(b) Absolute measurements: grating



(c) Absolute measurements grating

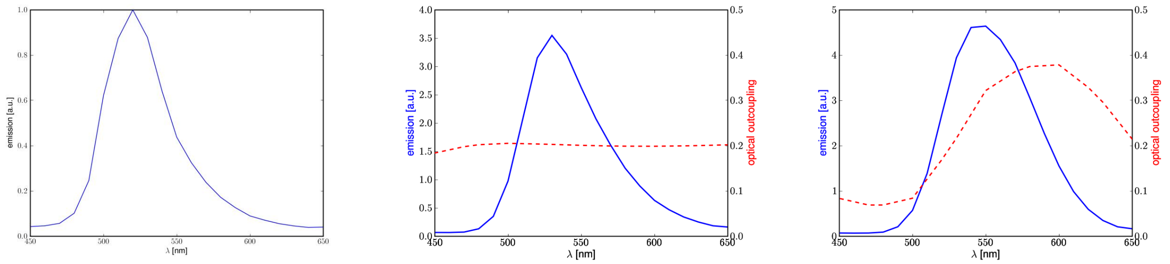


(d) Comparison between grating and microlens

Figure 3. Comparison relative improvement grating and micro lenses.

	Reference OLED	RC²LED
Al	150 nm	150 nm
HTL	80 nm	80 nm
EL	40nm	40 nm
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

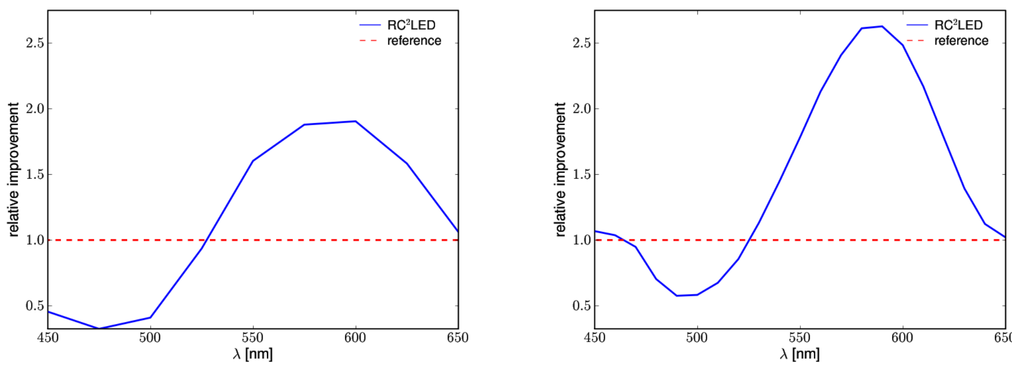


(a) The emission spectrum of the EL layer of table 4.1.

(b) Emission and (simulated) optical extraction of the reference OLED

(c) Emission spectrum and (simulated) optical extraction of the RC^{2}LED

Figure 4. Absolute measurement of the spectrum of the reference OLED and the RC^{2}LED.



(a) simulations

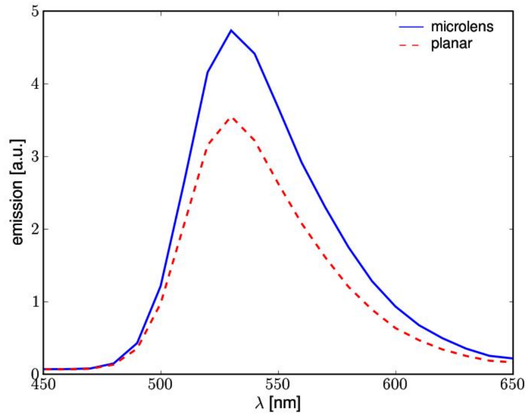
(b) experiment

Figure 5. Relative improvement of the RC^{2}LED and the reference OLED

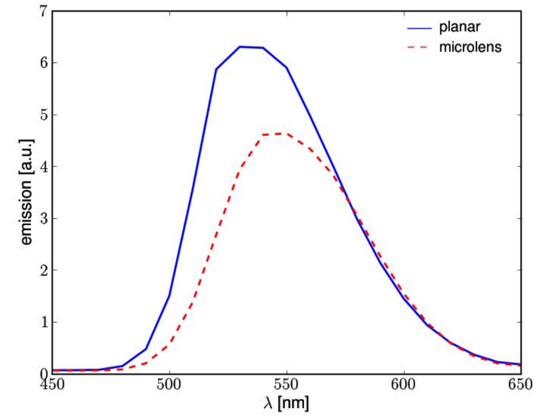
improvement is restricted to a wavelength region of approxitemately 100 nm. Our preliminary measurements confirm this behaviour.

The layer stack used for an RC^{2}LED is given in table 4.1. This organic layer stack has been deposited on two types of substrates. The first substrate is a normal glass substrate on which the reference OLED will be fabricated. The second substrate however has 3 additional layers on which the RC^{2}LED has been fabricated. 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. Two consecutive fabrication runs of the same layer stack result in an emission with a relative deviation of up to 5%. As can be seen from the table, the additional layers of the RC^{2}LED comprise of a low index material enclosed by two high index materials. The theoretical thickness of these layers is respectively $\frac{\lambda_{res}}{4n_{high}}$, $\frac{\lambda_{res}}{2n_{low}}$ and $\frac{\lambda_{res}}{4n_{high}}$. The refractive indices for NbO_x and SiO_x are respectivitely 2.4 and 1.45 at 500nm. The wavelength for which of the cavity has been optimized, has been chosen at 565 nm. This wavelength turned out to be slightly different from the electroluminescent peak.

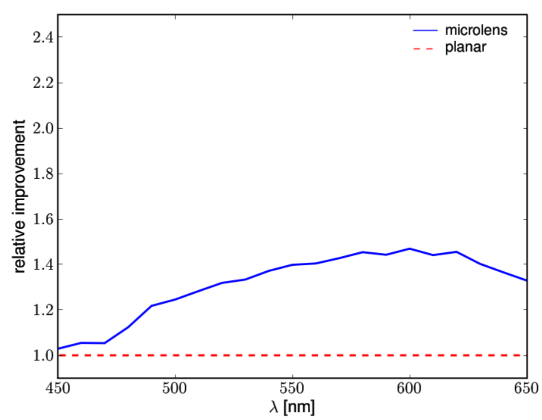
The emission spectrum of the Electroluminescent Layer is given by figure 4(a). This spectrum may shift due to the different optical extraction efficiency from an RC^{2}LED compared to the reference LED. The figures 4(b) and 4(c) show the measured spectrum of the reference OLED and RC^{2}LED. These figures also depict the optical extraction efficiency. Both OLEDS were driven by a current of 5.5 mA. The measured voltage over the reference



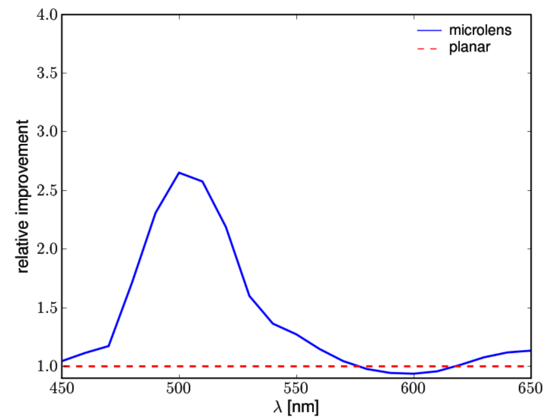
(a) reference OLED, absolute measurements, without and with mircolenses



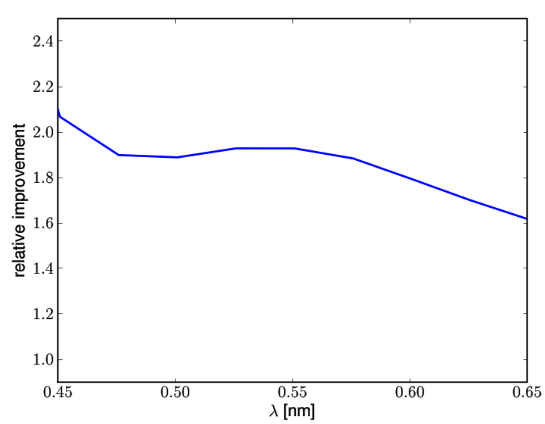
(b) RC^2LED, absolute measurements, without and with mircolenses



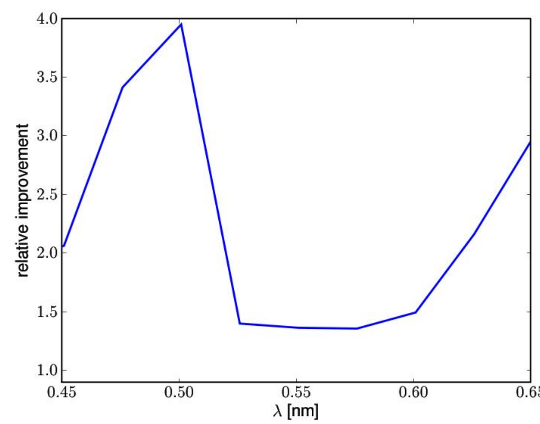
(c) reference OLED, measured relative improvement.



(d) RC^2LED, measured relative improvement



(e) reference OLED, simulated relative improvement by a grating



(f) RC^2LED, simulated relative improvement by a grating.

Figure 6. Influence of microlenses on a reference OLED and the RC^2LED

OLED and the RC^2LED was respectively 5.8 V and 6.0 V.

We can calculate the relative improvement of the RC^2LED compared to the reference OLED with the spectrum of figures 4(b) and 4(c). This basically is achieved by dividing the spectrum of both OLEDs. We implicitly assume that the influence of the cavity on the lifetime is negligible. This means that the optical extraction efficiency is the only important parameter to determine the external quantum efficiency, which changes for the two designs. Figure 5 shows us that there is a very good quantitative agreement between simulation and experiments. For the simulations the dipoles are located 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. It is shown that in a wavelength region of 50 nm, the relative improvement is higher than 50%, with a maximum of roughly 100%.

The deviation for wavelengths smaller than 500 nm can be explained by the low emission at those wavelengths. The noise for those wavelengths is too high to have a representative measurement. The measured relative improvement is also higher than the simulated relative improvement. This can be explained by the angular dependancy of the emission. Because of the way our OLED is attached to the integrating sphere, we are not able to take account the radiation at oblique angles. The reference OLED indeed has quite more emission at oblique angles than the RC^2LED. This results in an underestimation of the light emitted by the reference OLED compared to the RC^2LED.

Microlenses at the interface air substrate an be used to complement the extra layers at the interface between organic layers-susbstrate. This has been done for both the reference OLED and the RC^2LED in figure 6. It is important to note that the improvement for 580nm-600 nm can be neglected compared to the improvement achieved in other wavelength regions. This shows that the improvement achieved by the RC^2LED for the resonance wavelength automatically diminishes the relative improvement which can be achieved with micro lenses.

Figures 6(e) and 6(f) show the simulated relative improvement when using a grating on top of the RC^2LED. We have made the implicit assumption that conclusions made for gratings can be extrapolated to microlenses. We indeed see a quantative resemblance between the experimental relative improvement for micro lenses and the simulated relative improvement for gratings. One possible explanation for deviations between both results is the index mismatch between glass substrate of the OLED and the PMMA substrate with micro lenses. A rough estimation with isotropic emission in the glass learns us that an index change from 1.45 to 1.5 already gives a reflection of 25% at the interface between glass and PMMA.

5. SUMMARY AND CONCLUSIONS

We have demonstrated the feasibility of using a grating at the glass-air layer to increase the light extraction with a surface corrugation depth of approx. 500 nm. A grating numerically achieves a relative improvement of 50%. We have seen a qualitative agreement between simulations and experiments, with a measured 30% improvement. In this paper, we have demonstrated the first use of the concept of an RC^2LED for an OLED. We have shown a quantative resemblance between the simulated spectrum and the measurements of an RC^2LED.

Acknowledgements

The authors thank the European Commission or funding of (part of) this work under contract IST-004607 (OLLA). Peter Bienstman acknowledges the Flemish Fund for Scientific Research (FWO-Vlaanderen). The authors also wish to thank the OLLA team of Philips Research Aachen, Horst Greiner, Volker Van Elsbergen and Helmut Bechtel, for all fabricated OLEDs and microlenses.

REFERENCES

1. Brian W. D'Andrade and Stephen R. Forrest, "White Organic Light-Emitting Devices for Solid-State Lighting", *Advanced Materials*, 16(**18**), 1585-1595, 2004.
2. Aparna Misra, Pankaj Kumar, M. NKamalasanan and Subhas Chandra, "White organicLEDs and their recent advancements", *Semiconductor science and Technology*, 21, R35-R46, 2006.

3. Yukio Narukawa, Junya Narita, Takahiko Sakamoto, Kouichiro Deguchi, Takao Yamada and Takashi Mukai, "Ultra-High Efficiency White Light Emitting Diodes", *Japanese Journal of Applied Physics*, 45(**41**), L1084-L1086, 2006.
4. S. Moller and S. R. Forrest, "Improved light out-coupling in organic light emitting diodes employing ordered microlens arrays", *Journal of Applied Physics*, 91(**5**), 3324-3327, March 2002.
5. Jonathan M. Ziebarth , Ameen K. Saafir ,Shanhui Fan and Michael D. McGehee ,"Extracting Light from Polymer Light-Emitting Diodes Using Stamped Bragg Gratings", *Advanced Functional Materials*, 14(**5**), 451-456, May 2004.
6. Masatoshi Kitamura, Satoshi Iwamoto and Yasuhiko Arakawa, "Enhanced Luminance Efficiency of Organic Light-Emitting Diodes Using Stamped Bragg Gratings", *Japanese Journal of Applied Physics*, 44(**4B**), 2844-2848, 2005.
7. Tetsuo Tsutsui, Masayuki Yahiro, Hiroshi Yokogawa, Kenji Kawano and Masaru Yokoyama, "Doubling Coupling-Out Efficiency in Organic Light-Emitting Devices Using a Thin Silica Aerogel Layer", *Advanced Materials*, 13(**15**), 1149-1152, August 2001.
8. A. Dodabalapur, L. J. Rothberg, and T. M. Miller, "Color variation with electroluminescent organic semiconductors in multimode resonant cavities", *Applied Physics Letters*, 65(**18**), 2308-2310, 1994.
9. Kristiaan Neyts, "Microcavity effects and the outcoupling of light in displays and lighting applications based on thin emitting films", *Applied Surface Science*, 244, 517523, 2005.
10. P. Bienstman and R. Baets, "The RC2LED: a novel resonant-cavity LED design using a symmetric resonant cavity in the outcoupling reflector",*IEEE Journal of Quantum Electronics*, 36(**6**), 669-673, 2000.
11. D. Delbeke, P. Bienstman, R. Bockstaele and R. Baets, "Rigorous electromagnetic analysis of dipole emission in periodically corrugated layers: the grating-assisted resonant-cavity light-emitting diode", *Journal of the Optical Society of America A*, 19(**5**), 871-880, 2002.
12. N.K. Patel, S. Cina and J.H. Burroughes, "High-Efficiency Organic Light-Emitting Diodes", *IEEE Journal on Selected Topics in Quantum Electronics*, 8(**2**), 346-361, March/April 2002.

PROCEEDINGS OF SPIE on CD-ROM

Photonics West 2007: Integrated Optoelectronic Devices

20-25 January 2007
San Jose, California, USA

SPIE Photonics WEST

Volumes 6468–6489

Single-User Edition

PROCEEDINGS OF SPIE on CD-ROM

Photonics West 2007: Integrated Optoelectronic Devices

20–25 January 2007 San Jose, California, USA **Volumes 6468–6489**

6468: Physics and Simulation of Optoelectronic Devices XV
6469: Optical Components and Materials IV
6470: Organic Photonic Materials and Devices IX
6471: Ultrafast Phenomena in Semiconductors and Nanostructure Materials XI and Semiconductor Photodetectors IV
6472: Terahertz and Gigahertz Electronics and Photonics VI
6473: Gallium Nitride Materials and Devices II
6474: Zinc Oxide Materials and Devices II
6475: Integrated Optics: Devices, Materials, and Technologies XI
6476: Optoelectronic Integrated Circuits IX
6477: Silicon Photonics II
6478: Photonics Packaging, Integration, and Interconnects VII
6479: Quantum Sensing and Nanophotonic Devices IV
6480: Photonic Crystal Materials and Devices VI
6481: Quantum Dots, Particles, and Nanoclusters IV
6482: Advanced Optical and Quantum Memories and Computing IV
6483: Complex Light and Optical Forces
6484: Vertical-Cavity Surface-Emitting Lasers XI
6485: Novel In-Plane Semiconductor Lasers VI
6486: Light-Emitting Diodes: Research, Manufacturing, and Applications XI
6487: Emerging Liquid Crystal Technologies II
6488: Practical Holography XXI: Materials and Applications
6489: Projection Displays XII

ISBN 9780819466259

9 780819 466259 90000

SPIE, PO Box 10, Bellingham, Washington, 98227-0010 USA
Tel: +1 360 676 3290 • Fax: +1 360 647 1445 • spie@spie.org • spie.org