

Light Extraction From Solution-Based Processable Electrophosphorescent Organic Light-Emitting Diodes

Benjamin C. Krummacher, Mathew Mathai, Franky So, Stelios Choulis, and Vi-En Choong

Abstract—Molecular dye dispersed solution processable blue emitting organic light-emitting devices have been fabricated and the resulting devices exhibit efficiency as high as 25 cd/A. With down-conversion phosphors, white emitting devices have been demonstrated with peak efficiency of 38 cd/A and luminous efficiency of 25 lm/W. The high efficiencies have been a product of proper tuning of carrier transport, optimization of the location of the carrier recombination zone and, hence, microcavity effect, efficient down-conversion from blue to white light, and scattering/isotropic remission due to phosphor particles. An optical model has been developed to investigate all these effects. In contrast to the common misunderstanding that light out-coupling efficiency is about 22% and independent of device architecture, our device data and optical modeling results clearly demonstrated that the light out-coupling efficiency is strongly dependent on the exact location of the recombination zone. Estimating the device internal quantum efficiencies based on external quantum efficiencies without considering the device architecture could lead to erroneous conclusions.

Index Terms—Electrophosphorescence, light extraction, micro cavity, organic light-emitting diodes (OLEDs), solution-based processable.

I. INTRODUCTION

IN RECENT years, the activities to develop solid state lighting based on organic electroluminescent devices are on the rise. The efficiency of organic light-emitting diodes (OLEDs) has improved to an extent where they are being considered for lighting applications [1]. A major contribution to this

efficiency improvement is the application of heavy metal complexes as light-emitting dyes, where strong spin-orbit coupling leads to singlet-triplet state mixing resulting in high-efficiency electrophosphorescence from OLEDs (PHOLEDs).

While the use of phosphorescent emitters implies that the internal quantum efficiency can be as high as 100% the overall device efficiency is typically much lower. Poor light out-coupling from the organic films limits the external efficiencies of both vapor deposited small molecule devices (SMOLED) as well as solution processed polymer based devices (PLEDS). The multi-layer approach in SMOLED devices ensures that the device can be engineered to be optimized for light out-coupling by means of a well-defined light-emitting zone within the device thin-film stack. However, even in this case, light out-coupling has been calculated by Gu *et al.* to be not more than $\sim 22\%$ of the actual light generated in the emissive layer [2].

In this publication we focus on solution processed OLEDs, where the light-emitting polymer layer (LEP) is formulated from a non- π -conjugated polymer. Light emission is achieved by means of dispersing phosphorescent dyes in suitable proportions within the LEP. In order to maximize the quantum efficiency of the device, electron-hole transporting moieties are incorporated into the LEP formulation, thus resulting in an optimum balance of holes and electrons in the device. This process of molecular doping provides a tool to control the location of the emission zone within the device.

In order to better quantify the results of the molecular doping experiments, an optical model was used to study the effect of the carrier recombination zone location on light out-coupling. The model is initially applied to hybrid devices where an additional vapor deposited layer is deposited on top of the LEP. The use of hybrid devices ensures a more controlled variation of the thin-film geometry in the device. The devices are further modified by means of a light out-coupling film, and the performance with and without the film is compared. The results indicate that the conventional method of reporting the efficiency of light extraction by taking the ratios of light emitted with and without the light out-coupling film is erroneous as this ratio depends on the device geometry. An alternative method is hence suggested.

Having successfully applied the optical model to hybrid devices, the study is then further extended to simple bilayer solution processed blue phosphorescent devices where molecular doping result in a high efficiency of 22 cd/A. In spite of the added complexity of the absence of a well-defined emission zone (unlike in the case of the hybrid devices) the model can be used to simulate the electroluminescence (EL) spectrum of the

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B. C. Krummacher was with the OSRAM Opto Semiconductors Inc, San Jose, CA 95134 USA. He is now with Osram Opto Semiconductors GmbH, D-93055 Regensburg, Germany (e-mail: Benjamin.Krummacher@osram-os.co).

M. Mathai was with the OSRAM Opto Semiconductors Inc., San Jose, CA 95134 USA. He is now with PLEXTRONICS, Pittsburgh, PA 15238 USA.

F. So was with the OSRAM Opto Semiconductors Inc., San Jose, CA 95134 USA. He is now with the Department of Materials Science and Engineering, University of Florida, Gainesville, FL 32611-6400 USA.

S. Choulis was with the OSRAM Opto Semiconductors Inc., San Jose, CA 95134 USA. He is now with the Konarka Technologies GmbH, D-90443 Nürnberg, Germany.

V.-E. Choong was with the OSRAM Opto Semiconductors Inc., San Jose, CA 95134 USA. He is now with the Invitrogen Corporation, Carlsbad, CA 92008 USA.

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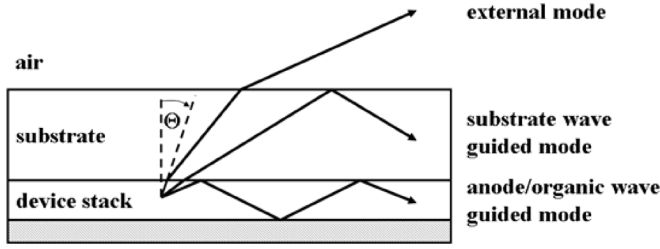


Fig. 1. External mode, the substrate waveguided mode and the anode/organic waveguided mode in an organic EL device. Dependent on the emission angle Θ the generated photons are outcoupled or waveguided.

device which is a function of the location of the emission zone within the stack. From the analysis it is evident that molecular doping not only improves the charge balance within the device, but also the overall light out-coupling efficiency. The device is further modified by means of a phosphor layer resulting in light down conversion to obtain white light as well as enhanced light out-coupling. This results in an overall efficiency of 25-lm/W white light emission.

II. LIGHT EXTRACTION

The processes taking place in an OLED which result in a given external quantum efficiency is described by the following equation [3]:

$$\eta_{\text{ext}} = \gamma \eta_{\text{ex}} \phi_p \eta_{\text{ph}} \quad (1)$$

where η_{ph} is the light-out-coupling efficiency, η_{ex} is the fraction of total excitons formed which result in radiative transitions ($\eta_{\text{ex}} = 1/4$ for fluorescent materials, and 1 for purely phosphorescent materials), γ is the ratio of electrons to holes injected from opposite contacts (the electron-hole charge-balance factor), and ϕ_p is the intrinsic quantum efficiency for radiative decay (including both fluorescence and phosphorescence).

The parameter η_{ph} , resulted from the mismatch of the refractive index between air and the OLED, leads to most of the generated light being lost through total internal reflection (TIR) into wave guiding modes and self absorption. As indicated in Fig. 1, the light emitted by the device can be classified into three modes: the external mode, the substrate waveguided mode, and the anode/organic waveguided mode. Depending on the value of the emission angle with respect to the normal to the substrate, the generated photons are out-coupled or waveguided into the substrate and the active layers, respectively.

Many approaches have been utilized to improve the out-coupling efficiency. These can be divided into six generic schemes: 1) the patterning of polymer microlens array on the substrate surface [4], or placing a large size index matching hemispherical lens on top of the substrate [5]; 2) introducing scattering effects at the substrate surface by means of techniques such as applying a transparent coating on the substrate with embedded small particles [6], or texturing the substrate surface (for example, by sand blasting [7] or sand paper [8]); 3) incorporating the light-emitting diode in a reflecting mesa structure [2]; 4) Inserting an extremely low refractive index ($n \approx 1.03$) silica aerogel porous layer between the ITO

transparent anode and the glass substrate [9]; 5) Application of lateral periodic nano structures on the substrate leading to increase of light out-coupling through Bragg scattering [10], [11], and (6) making use of micro cavity effects [12], [13]. In all cases, the OLED architecture results in the formation of a micro cavity, due to the double mirror structure formed by the two electrodes and the organic layers sandwiched in between. Electrons and holes injected from the respective contacts recombine in the emission zone (EMZ) to form excitons which undergo radiative emission to generate light. The rate and direction of emission of excitons that are physically close to the metallic cathode, are strongly affected by optical interference effects [14], which in turn affects the efficiency of the device. The internal device efficiency is related to the rate of emission. The external device efficiency is determined by the fraction of light, which is generated in the device stack and extracted to air. Total internal reflection into wave guiding modes and self absorption are two mechanisms reducing external device efficiency. The distribution of the light into the external mode, the substrate waveguided mode and the anode–organic waveguided mode (see Fig. 1) is affected by the emission angle of the light and the location of the emission zone. By optimizing the location of the emission zone the external efficiency of OLED devices can be improved.

III. THEORETICAL DESCRIPTION OF THE OLED MICRO CAVITY

The radiative emission from the recombining excitons in an OLED device can be modelled by oscillating dipoles in front of a mirror [14]. In this model the recombining exciton is a two-level system whose transition rate is given by Fermi's golden rule [5]. The electric field emitted by electric dipoles can be expressed in terms of superposition of s-(TE) and p-(TM) polarized waves, while the dipole source can be decomposed into three orthogonal components (d_s , d_p , d_v), where d_s and d_p are in-plane dipole components, and d_v is the out-of plane component. It can be shown that the powers per solid angle θ and surface emitted by such dipoles in an unbounded medium of refractive index n_{emit} are of the form:

$$P_0^s = \frac{3}{8\pi} \quad (2a)$$

$$P_0^p = \frac{3}{8\pi} \cos^2 \theta \quad (2b)$$

$$P_0^v = \frac{3}{8\pi} \sin^2 \theta. \quad (2c)$$

For a sheet of dipoles at distance z from the cathode-reflector, the power per unit solid angle and surface $P_{\text{front}}^{s,p,v}$ radiated outside the micro cavity by the s-, p- and v-dipoles can be calculated from the following equations:

$$P_{\text{front}}^s = \left| 1 + r_1^s e^{2i\varphi^I} \right|^2 \frac{1 - |r_2^s|^2}{|1 - r_1^s r_2^s e^{2i\varphi^I}|^2} P_0^s \quad (3a)$$

$$P_{\text{front}}^p = \left| 1 + r_1^p e^{2i\varphi^I} \right|^2 \frac{1 - |r_2^p|^2}{|1 - r_1^p r_2^p e^{2i\varphi^I}|^2} P_0^p \quad (3b)$$

$$P_{\text{front}}^v = \left| 1 + r_1^v e^{2i\varphi^I} \right|^2 \frac{1 - |r_2^v|^2}{|1 - r_1^v r_2^v e^{2i\varphi^I}|^2} P_0^v. \quad (3c)$$

where r_1 is the reflectivity coefficient of the anode mirror and r_2 the reflectivity of the cathode mirror of the microcavity, φ and φ^I are given by

$$\varphi = \frac{2\pi z}{\lambda} n_{\text{emit}} \cos \theta_{\text{emit}} \quad (4)$$

$$\varphi^I = \frac{2\pi d}{\lambda} n_{\text{emit}} \cos \theta_{\text{emit}} \quad (5)$$

where λ is the wave length of the emitted light and d is the optical path length.

Only the radiation emitted in the source medium (refractive index n_{emit}) with angles θ_{emit} smaller than the critical angle: $\theta_{\text{emit}}^0 = \arcsin(n_a/n_{\text{emit}})$, where n_a is the refractive index of the outside medium, can be extracted out of the micro cavity. The interval $[0, \theta_{\text{emit}}^0]$ corresponds to the escape window of the radiation. If $\theta_{\text{emit}} > \theta_{\text{emit}}^0$, the light will undergo total internal reflection. The amount of extracted light is a fraction of the light generated in a distance z from the cathode:

$$P_{\text{extr}}^{s,p,v} = P_{\text{front}}^{s,p,v} \quad \text{for } 0 \leq \theta_{\text{emit}} \leq \theta_{\text{emit}}^0. \quad (6)$$

Considering an emission zone profile $E(z)$ ($0 < z < Z$), the total power radiated out of the device is given by

$$P_{\text{total}}^{s,p,v} = \int_0^Z E(z) dz \int_0^{\theta_{\text{emit}}^0} \sin \theta d\theta \int_0^\infty d\lambda P_{\text{front}}^{s,p,v}(\theta, \lambda). \quad (7)$$

Further refinements are based on the optical constants as a function of wavelength for all layers of the device stack.

Equations (2) to (7) above clearly indicate that the variation in the location and shape of the exciton profile ($E(z)$) formed within the LEP can result in significant differences in the extent to which light can be out-coupled from the device due to the presence of a microcavity in the OLED stack. It is also evident that such micro cavity effects can lead to changes in the EL spectrum, as light corresponding to different wavelengths are outcoupled to a different extent for a given location of the emission zone. This important fact is utilized in order to model the differences in the EL spectra obtained for the molecularly doped blue PHOLED devices described later.

IV. RESULTS AND DISCUSSION

A. Application of Model to Quantify Light Extraction Efficiency in Hybrid Devices

Unlike entirely solution processed devices, the use of hybrid devices allows the deliberate and accurate alteration of the geometry of the device stack, which is better for correlating with the predictions determined from the model. Fig. 2 shows the structure of the green emitting OLEDs (peak wavelength $\lambda = 510$ nm) used in this study. Each substrate has 4 individual OLEDs with a 0.4-cm^2 active area. The glass substrate has a thickness of 0.7 mm and a refractive index $n = 1.52$. The OLED devices were fabricated as follows. A thin (60 nm) film of

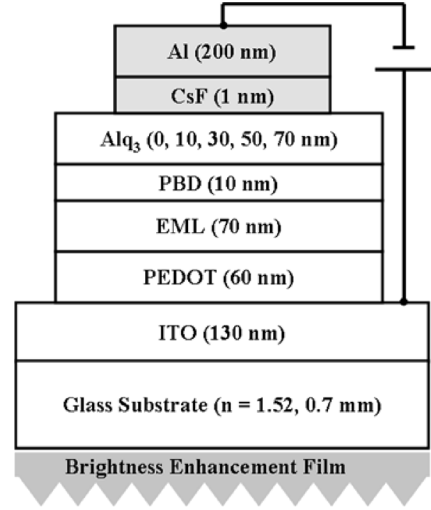


Fig. 2. Structure of the OLEDs used in this study.

poly(3,4)-ethylenedioxythiophene doped with poly(styrene sulfonate) (PEDOT:PSS) was spin coated atop the ITO-anode and then baked for 30 min at 200°C . The green emitting layer (EML) was then spin coated on the top of the PEDOT:PSS with conditions to yield a 70-nm thick light-emitting layer.

The light-emitting layer was then annealed at 80°C for 30 min. The solution for the EML consisted of 24% wt 2-(4-biphenyl)-5-(4-tert-butylphenyl)-1,3,4-oxadiazole (PBD), 9% wt 4,4'-bis(m-tolylphenylamino)biphenyl (TPD), 6% wt fac-tris(2-phenylpyridine)iridium $\text{Ir}(\text{ppy})_3$ and 61% wt polyvinylcarbazole (PVK) in chlorobenzene [15]. On the top of the EML a 10 nm thick 2-(4-biphenyl)-5-(4-tert-butylphenyl)-1,3,4-oxadiazole (PBD) hole-blocking layer was thermally evaporated in a vacuum coater. This was followed by thermal evaporation of a tris(8-hydroxyquinoline) aluminium (Alq_3) layer on top of the PBD layer. Devices with five different Alq_3 -layer thicknesses (0, 10, 30, 50, 70 nm) were prepared. Then a caesium fluoride (CsF) layer with a thickness of 1 nm was deposited as an electron injection layer. Finally a 200-nm thick Al layer was deposited as the cathode. All the thermally evaporated layers were deposited in a vacuum evaporator sequentially in a single pump down cycle. Following evaporation of the cathode, the devices were encapsulated with a glass lid and getter. All other device fabrication steps from the EML spin coating to device encapsulation were carried out in an inert nitrogen atmosphere.

After measuring the light output of the unmodified devices (the method is described in more detail below), a Brightness Enhancement Film (BEF) prepared from 3M (Vikuiti BEF II 90/50) was applied on the surface of the devices. The BEF film consists of an acrylic resin with prismatic features on its surface coated on a polyester substrate. The prism angle is 90° and the prism pitch is $50\ \mu\text{m}$. The BEF film has a nominal thickness of $155\ \mu\text{m}$ and was optically coupled to the glass substrate with optical laminating tape (3M No. 8141, $n = 1.49$).

Using substrate surface modification for the improvement of external device efficiency, the waveguided light originally

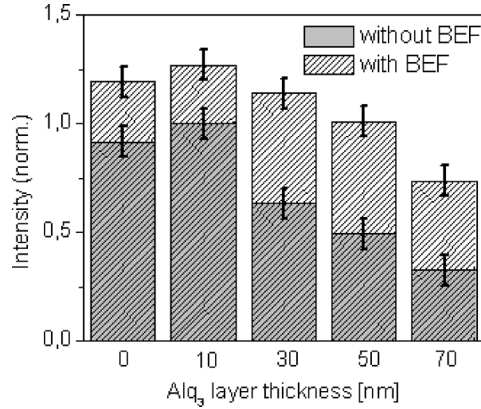


Fig. 3. Light output of the devices before and after applying the brightness enhancement film. Intensities are normalized on the output of the light output of the device with a Alq_3 -layer thickness of 10 nm. The error bars represent the standard deviations of the measured values.

retained within the substrate of the unmodified device (standard flat glass substrate) is extracted. The improvement in light out-coupling by various methods of modifying the substrate surface is often quantified by an apparent enhancement factor, $k = \eta_2/\eta_1$, where η_1 is the efficiency of the unmodified OLED and η_2 is the efficiency of the device after modifying the substrate. In this section we show a strong dependence of the enhancement factor k on the device architecture itself. Furthermore we demonstrate an alternative method to determine the enhancement of light extraction using light out-coupling approaches of scheme (1) or (2) discussed earlier in Section II. The proposed method thus eliminates dependence on device architecture which would otherwise lead to inaccurate conclusions regarding the efficiency of the device itself. This will be demonstrated by means of green light-emitting OLEDs with prismatic film.

The OLED emission intensity was measured using a large area (18 mm × 18 mm) Si photodiode according to a method described by Nakamura [16]. The distance between the Si photodiode and the OLED substrate's surface was kept at < 0.5 mm. Considering the size of the OLEDs active area in comparison to the area of the Si photodiode, this setup offers a nearly entire solid angle collection of the light emitted by the devices. Measurements were carried out alternatively with an air gap and an optical gel (index of refraction = 1.56) obtained from Norland. When the air gap was filled with optical gel, TIR at the glass/air interface vanished, enabling the emitted light of the external and substrate waveguided modes to be measured by the Si photodiode simultaneously. Thus three intensities I_{air} , I_{gel} and I_{film} were measured, where I_{air} and I_{gel} were the emission intensities detected by the Si photodiode at the air and gel gaps before modifying the device, and where I_{film} was the emission intensity detected at the air gap after applying the BEF film. All intensities were measured at a current density of 1 mA/cm².

Fig. 3 shows the external light output of the devices before and after applying a BEF film as a function of the Alq_3 thickness. It was independently confirmed that the emission from the device originated from $\text{Ir}(\text{ppy})_3$ with negligible (if any) emission from Alq_3 . It is observed that with increasing Alq_3 thickness the light output in both cases (i.e., without and with the

TABLE I
FACTOR OF ABSOLUTE LIGHT OUT-COUPLING ENHANCEMENT k , AND RATIO BETWEEN THE OUTPUT OF THE SURFACE MODIFIED DEVICE AND THE LIGHT INTENSITY, WHICH IS COUPLED INTO THE SUBSTRATE ($I_{\text{film}}/I_{\text{gel}}$).

Alq_3 -layer thickness [nm]	$k = I_{\text{film}}/I_{\text{air}}$	$I_{\text{film}}/I_{\text{gel}}$
0	1.30	0.63
10	1.27	0.60
30	1.80	0.63
50	2.04	0.60
70	2.25	0.58

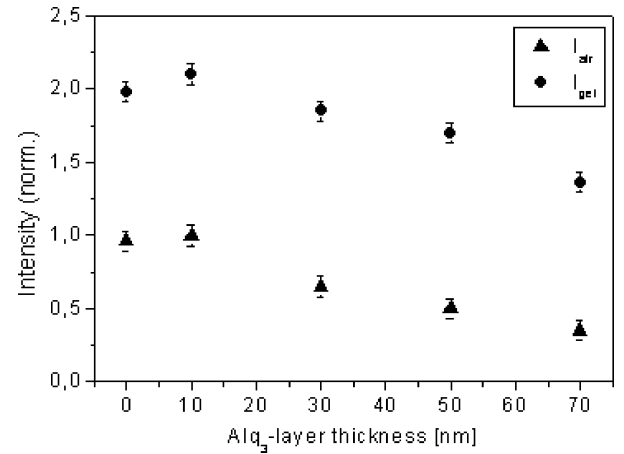


Fig. 4. Emission intensities detected by the Si photodiode at the air and gel gaps before substrate surface modification of the devices. Intensities are normalized on the output of the light output of the device with a Alq_3 -layer thickness of 10 nm. The error bars represent the standard deviations of the measured values.

BEF film) decreases. The intensity I_{air} , which is equal to the light output of the device before applying the BEF film, decreases with increasing values of Alq_3 layer thickness to 1/3 of the output of the device without Alq_3 . Quasi-sinusoidal variation of current efficiency versus Alq_3 thickness is attributed to the interference effect between direct emission and emission reflected from the metallic mirrors of the electrodes. This behavior has already been reported [16], [17]. However, the effect of light out-coupling *enhancement* due to the BEF film is increased and shows a strong dependence on the device structure itself. This enhancement is calculated and the results are shown in Table I, where the values of k (given by $k = I_{\text{film}}/I_{\text{air}}$) are listed.

Using a substrate surface modification, a fraction of the waveguided light retained within the substrate of the unmodified device (standard flat glass substrate) is extracted. In order to investigate the dependence of k on the device structure, the intensity I_{gel} , which is related to the sum of the external light output and the substrate waveguided light, was measured for all (unmodified) devices as a function of the Alq_3 layer thickness. Fig. 4 shows the measured intensities I_{air} and I_{gel} . With increasing Alq_3 layer thickness the intensity I_{gel} decreases to 2/3 of the value for the device without Alq_3 .

Table II shows the ratio between the amount of substrate waveguided light to the external light output for each device structure used in this study. This ratio is given by $I_{\text{subst}}/I_{\text{air}} =$

TABLE II
CALCULATED AMOUNT OF WAVEGUIDED LIGHT I_{subst} AND RATIO $I_{\text{subst}} : I_{\text{air}}$.

Alq ₃ -layer thickness [nm]	I_{air}	I_{gel}	$I_{\text{subst}} = I_{\text{gel}} - I_{\text{air}}$	ratio $I_{\text{subst}} : I_{\text{air}}$
0	0.96	1.98	1.02	1.06
10	1.00	2.10	1.10	1.10
30	0.65	1.85	1.20	1.85
50	0.50	1.70	1.20	2.4
70	0.35	1.36	1.01	2.88

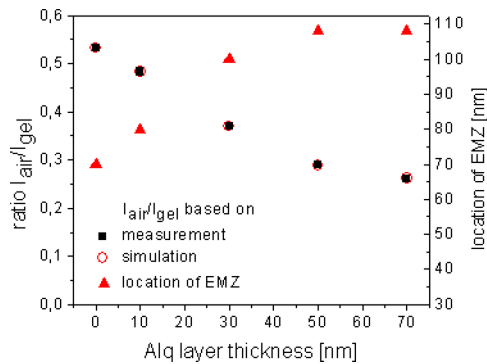


Fig. 5. Fit of the ratio $I_{\text{gel}}/I_{\text{air}}$ based on the shown dependence of the location of the EMZ.

$(I_{\text{gel}} - I_{\text{air}})/I_{\text{air}}$. With increasing Alq₃ layer thickness, the fraction of substrate waveguided light intensity increases compared to the fraction of the out-coupled light intensity. This was further studied by means of the optical simulation tool UNIMCO 4.0,¹ which is based on the model described above.

In the simulation, the ratio $I_{\text{air}}/I_{\text{gel}}$ based on the measurements was fitted by the ratio between the simulated amount of light, which is generated in the device stack and the simulated amount of light coupled into the substrate (Fig. 5). This ratio obtained by the simulation is given by the calculation of the power radiated outside of the cavity for air ($n_a = 1$) as outside medium respective glass ($n_a = 1.52$) as outside medium. In order to compute the ratio based on simulation, the location of the emission zone (EMZ) in the device is needed. Here, we have defined the location of the EMZ as the distance between the cathode and the centre of a Gaussian distribution of excitons within the light-emitting polymer with a full width at half maximum of 20 nm [18].

The distance between the EMZ and the cathode was varied to obtain the best fit. The resultant dependence of the location of the EMZ is shown in Fig. 5. Also shown is the location of the EMZ obtained by the fit. Except for the prediction of the model for 70-nm thickness of Alq₃, it is seen that the location of the EMZ scales with the actual device architecture.

The simulation as implemented above used the ratio $I_{\text{air}}/I_{\text{gel}}$, which does not depend on the actual light out-coupled at the glass-air interface for each device. With the location of the EMZ

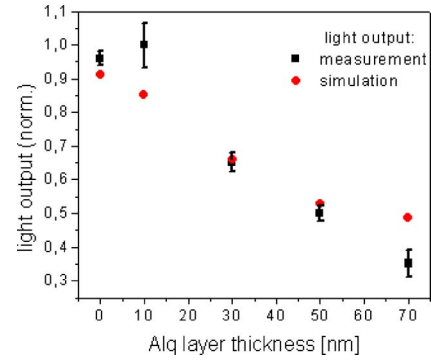


Fig. 6. Measurements of the external light output and computed light output as a function of Alq₃-layer thickness. The effect of different Alq₃-layer thickness on the intrinsic device efficiency is not considered for the simulated values.

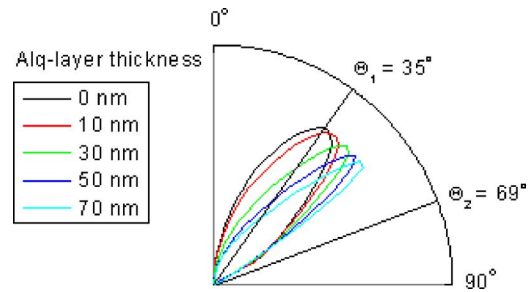


Fig. 7. Normalized EL pattern of the devices used in this study (integrated over all wavelengths). Θ_1 and Θ_2 are the critical angles for substrate wave guiding respective anode/organic waveguiding.

obtained by the fit, we can now see the effect of device architecture on the extent to which light is out-coupled depending on the cavity as defined by the OLED stack and substrate. Accordingly Fig. 6 shows the measurements of the external light output and the computed light output as a function of Alq₃ layer thickness at a fixed current density. It is observed that the light output calculated here (red symbols) decreases steadily with increasing Alq₃ layer thickness. However, it is important to note that the experimentally measured light output (black symbols) shows a more exaggerated dependence on Alq₃ thickness. This is due to variation in the internal device quantum efficiency as a function of Alq₃ thickness. In spite of this, the fit of $I_{\text{air}}/I_{\text{gel}}$ is more accurate. This is because the ratio $I_{\text{air}}/I_{\text{gel}}$ automatically eliminates the dependence on internal device efficiency.

Fig. 7 shows the electroluminescence (EL) pattern (the power per unit solid angle radiated outside the microcavity) integrated over all wavelengths for devices with different Alq₃ thicknesses. This was obtained by simulation using the values for the location of the EMZ determined by the fit. The angle of 0° corresponds to the direction normal to the substrate, where the angle of 90° corresponds to the direction parallel to the substrate. With increasing values of Alq₃ layer thickness the distribution of intensity is shifted to higher angles with respect to the normal of the substrate (0°), leading to large optical loss due to substrate modes.

We can now consider the efficiency of light out-coupling by usual substrate surface modification techniques as a function of

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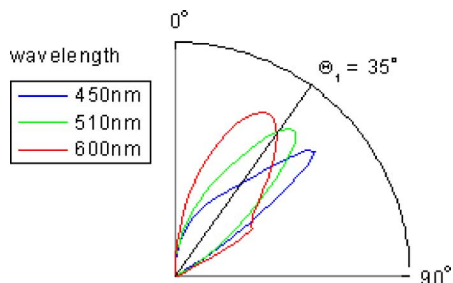


Fig. 8. EL pattern of the device without Alq₃-layer for the wavelengths 450, 510, and 600 nm. Each distribution is normalized on its intensity maximum.

device architecture. In the case of unmodified devices, with increasing Alq₃ layer thickness, the fraction of substrate waveguided light compared to the fraction of the external light output increases (Table I) as a result of the shift of the EL pattern to higher angles (see Fig. 7). Only the photons, which are emitted by the EML at angles smaller than the escape cone of the substrate are extracted out of the device. After applying the BEF film, photons of higher emission angles can be extracted due to the prismatic structure of the film. The higher the fraction of substrate waveguided light the stronger is the light out-coupling enhancement of the BEF film. Thus, the light out-coupling enhancement obtained by calculating the ratio between the light output of the surface modified and the output of the unmodified device by itself does not lead to accurate conclusions on the effectiveness of the light out-coupling method. Instead, the performance of the BEF film can be determined by considering the ratio between the external output of the BEF film laminated device and the total amount of light, which is measured with the gel. This ratio is given by $I_{\text{film}}/I_{\text{gel}}$ and is approximately constant ($I_{\text{film}}/I_{\text{gel}} \approx 0.6$, Table I) for all device structures. With the BEF film, the light-out-coupling efficiency is about 60% and it is independent of device structure.

In all of the above calculations, the cavity effect was simulated over the entire range of wavelengths comprising the device spectrum. We furthermore discuss the dependence of the light out-coupling enhancement factor k (apparent light out-coupling enhancement) on the wavelength of the emitted light. In this case we consider the device without the Alq₃ layer. Fig. 8 shows the EL pattern for light of wavelengths 450, 510, and 600 nm, respectively, calculated using the microcavity simulation mentioned above. The peak wavelength of the used green emitter is 510 nm. The calculations for the wavelengths 450 and 600 nm were computed, in order to obtain typical distributions for blue and red emission, respectively.

The EL pattern for 450 nm is shifted to higher angles in comparison to that obtained for 510 nm. Thus, we hypothesize, that the fraction of waveguided light is higher for the blue emitting device than for the green emitting device. Hence, the light out-coupling enhancement due to substrate surface modification is higher for the blue emitting device than for the green emitting device. Contemplating the imaginary red emitting device, the EL pattern of the red emitting device is shifted to lower angles. In this case, we hypothesize, that the fraction of waveguided light is lower than for the green emitting device. This leads to a

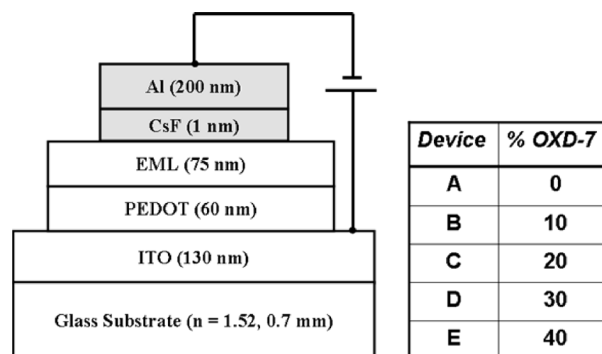


Fig. 9. Architecture of the devices used in this study. The table contains the device nomenclature based on the composition of the LEP.

lower light out-coupling enhancement for the red device due to the same substrate surface modification technique.

In particular, the dependence of light out-coupling enhancement on the wavelength has to be considered when modifying the substrate surface of a device emitting in a broad range of wavelengths (for example a white light-emitting device). In the case of a device with the structure and location of the EMZ discussed above, the light out-coupling enhancement is expected to be stronger in the shorter wavelength range of the spectrum. Thus, substrate surface modification can result in differences between the spectra of the devices before and after surface modification for light extraction.

B. Influence of Charge Balance and Micro Cavity Effects on Resultant Efficiency of OLEDs

In the following we further extend the model to simpler device architectures involving only two organic layers. Molecular doping is utilized to alter the location of the EMZ, which in the case of such bilayer devices is not easy to quantify. We consider OLED devices whose light-emitting polymer layer (LEP) is comprised of polyvinylcarbazole (PVK) as the hole transporting matrix, 1,3,4-oxadiazole, 2,2'-(1,3-phenylene)bis(5-(4-(1,1-dimethylethyl)phenyl) or OXD-7 as an electron transporter and the blue phosphorescent dye Iridium (III)bis[(4,6-di-fluorophenyl)-pyridinato-N, C²]picolinate (Flrpic). Fig. 9 shows the structure and the nomenclature of the devices used in this study. Keeping the amount of Flrpic in the LEP constant at 10% by weight, the relative concentrations of PVK and OXD-7 were changed in order to tune the balance of the hole and electron transport within the LEP. PEDOT and the LEP are deposited on indium–tin–oxide (ITO) coated glass substrates sequentially, followed by thermal evaporation of the cathode layers comprising CsF and Al. The LEP (thickness of 75 nm) was spin coated from a chlorobenzene solution and was baked at 80 °C for 30 min. Device characterization was carried out after encapsulating the OLEDs. All device fabrication steps were carried out in an inert atmosphere except for the PEDOT spin coating.

In Fig. 10, the luminous efficiency of these devices is plotted as a function of current density. Given that the device in the absence of OXD-7 is hole dominated, the rise in device efficiency with increasing OXD-7 concentration in the LEP is the result of better injection and transport of electrons within the LEP [19].

This trend is seen to exist between devices A-D. Part of the fall

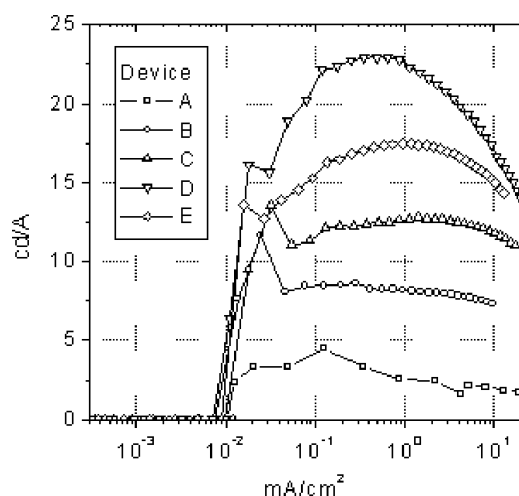


Fig. 10. Current efficiency (cd/A) versus current density for devices with varying OXD-7 concentration in the light-emitting polymer layer.

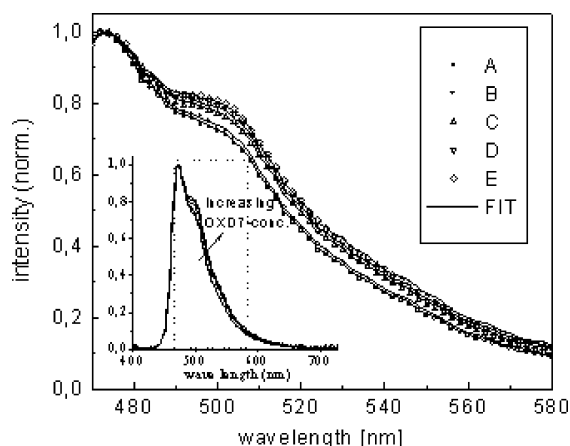


Fig. 11. Variation in EL-spectra at a fixed current density of 1 mA/cm² for devices with varying OXD-7 concentration. The inset shows the total EL spectrum for the devices over the entire wavelength range in the visible region.

in efficiency of device E could be due to imbalance of charge injection and transport due to the high concentration of OXD-7.

In addition to carrier balance, microcavity effects need to be considered. Using the EL-spectra of devices A-E (Fig. 11), the presence of micro cavity effects can be demonstrated. The spectra were measured at a fixed current density of 1 mA/cm². The inset shows the entire spectrum, while the main portion of the figure is a magnified portion of the same spectrum in the 500 nm region for all devices. As observed, the shoulder at 500 nm is seen to increase with increasing OXD-7 concentration in the LEP. Thus, at a fixed current density, the spectrum of the FIrpic devices changes as a function of the OXD-7 content in the LEP. Changes in the photoluminescence spectra due to the different OXD-7 concentrations were not observed for the devices used in this study. We will show that these changes observed in the EL spectra can be attributed to the variation in the location of the exciton recombination zone within the LEP as its composition is changed.

Using the micro cavity simulation tool UNIMCO 4.0 the EL-spectra in Fig. 11 were simulated. The parameters used for the simulation was the location of the EMZ and the internal

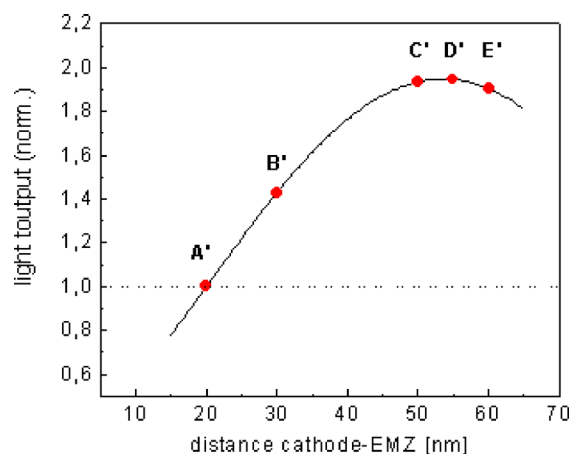


Fig. 12. Calculated external light output (@ 1 mA/cm²) as a function of the location of the EMZ. The exciton formation rate was assumed to be constant. The circles in the graph mark the light output for the imaginary devices A', B', C', D', E', which all have the corresponding locations of the EMZ as the real devices A, B, C, D, E. The graph describes the efficiency improvement in comparison to device A due to the micro-cavity effect dependent on the location of the EMZ.

emission spectrum of the material (EL0). We assume that the photoluminescence spectrum of FIrpic corresponds to EL0. The complex index of refraction as a function of wavelength was determined by the means of standard ellipsometry for all organic layers in electrode materials used in this study in order to ensure accurate simulation. For the calculation, the location of the EMZ is needed. The location of the EMZ is defined as the distance between the cathode and the center of a Gaussian distribution of excitons within the LEP. In a work published by Wu *et al.* a scope of the exciton distribution of approximately 25 nm was determined experimentally for FIrpic in CBP [18]. As both PVK and CBP contain carbazole as functional group a similar behaviour for exciton diffusion is expected. Thus, a full width at half maximum of 20 nm was chosen for the distribution of excitons within the LEP in the simulation. Given the EL spectrum of each device, the distance between the EMZ and the cathode was varied till the calculated spectrum matched measured spectrum. According to the simulation results the distance between cathode and EMZ increased from 20 nm for device A to 60 nm for device E. This can be explained as follows. As the amount of OXD-7 in the LEP increases, more electrons are able to penetrate into the LEP. This results in EMZ shifting away from the cathode.

In the following, we quantify the effect of the change in the location of the EMZ on device performance due to improved charge balance and micro cavity effects. First, the external light output as a function of the location of the EMZ was determined for the device geometry used in this study. In the calculation, a constant electron-hole balance leading to a uniform recombination rate was assumed. Finally, by analyzing the external light output, the micro cavity effect is determined. The circles in Fig. 12 mark the light output for the imaginary devices A', B', C', D', E', which all have the same locations of the EMZ as the corresponding real devices A, B, C, D, E. To obtain the actual effect of charge balance, the micro cavity effect is superimposed onto the actual measured experimental data. The portion of the

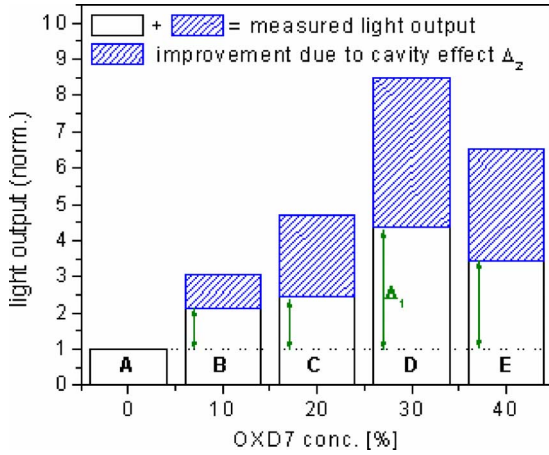


Fig. 13. Measured external light output of the devices used in this study. The cross hatched area represents the efficiency improvement compared to device A due to the micro cavity effect. The improvement in efficiency due to better charge balance is marked by the double ended arrows.

light output not due to micro cavity effects is attributed to the charge balance. We will illustrate this with device A and D.

When considering micro cavity effects alone, we see that the light output of Device D' is almost twice as high as the output of device A' (Fig. 12). However in the case of the real devices A and D, the light output of device D is 8.5 times more than that of device A for the same current density (Fig. 10). Based on the comparison of devices A' and D', the improvement in device efficiency due to the micro cavity effect is given by the measured output of device D divided by two. The rest of the improvement is due to the effect of improved charge balance.

A more rigorous description of the above calculation can be stated as follows- the improvement due to better charge balance in comparison to device A is given by

$$\Delta_1(X) = \frac{O_m(X)}{O(X')} - O_m(A). \quad (8)$$

where $O_m(X)$ ($X \in [B, C, D, E]$) is the measured light output at constant current density and $O(X')$ ($X' \in [B', C', D', E']$) is the light output of the imaginary devices normalized on the output of A'. The improvement compared to device A due to the micro cavity effect is given by

$$\Delta_2(X) = O_m(X) - [\Delta_1(X) + O_m(A)] = O_m(X) - \frac{O_m(X)}{O(X')}. \quad (9)$$

The bar graph in Fig. 13 shows the external light output of the devices used in this study normalized on the output of device A (current density of 1 mA/cm²). The cross-hatched area represents the efficiency improvement compared to device A due to the micro cavity effect. The improvement in device efficiency due to better charge balance is marked by the double ended arrows.

The effect on the efficiency due to micro cavity and charge balance increase from device A to device D. In comparison to device A the internal efficiency of device D is increased by a factor of 4.4 due to the effect of improved charge balance. The micro cavity effect caused by the change in the location of the EMZ further improves the efficiency by a factor of 1.93 (an

overall improvement of 8.5) from device A to D. The drop of device efficiency from device D to device E is mainly caused by a decrease in internal device efficiency. This is attributed to the achievement of optimum charge balance for device D. Additional increase in OXD-7 tilts the charge balance and makes device E strongly electron dominant. Quenching effects due to the proximity to the PEDOT layer also could account for decrease in efficiency.

The above analysis clearly indicates the use of molecular doping can alter the hole-electron balance in the device, thus affecting both the device efficiency, the location of the recombination zone within the LEP. While the effect of the location of EMZ on out-coupling efficiency has often been neglected, based on our analysis it could have a strong effect affecting the overall device efficiency. Therefore, both charge balance and cavity effects need to be considered for optimum device performance. To further optimize the blue-emitting FIrpic device performance, phosphor down-conversion layers are used for white light conversion as well as for light out-coupling. The results are presented in the next section.

C. Generation of White Light and Improvement of External Efficiency by the Means of Phosphor Particles

Applying a diffusive layer on the light-emitting surface is a well-known approach to increase external efficiency of OLED devices [6], [16], [20]. A diffusive layer consists of transparent matrix embedding small particles. By incorporating such a film at the interface between glass and air the propagation angle of photons can be changed randomly, resulting in an improvement in external efficiency due to improved out-coupling of photons. With diffused layers, backscattering and absorption in the OLED-stack are the factor affecting the coupling efficiencies. Experimental and theoretical analysis of this light extraction technique and the determination of the optimum configuration for diffusive layers have been published by Shiang and Gärditz. Furthermore, scattering layers are used to diffuse the light emitted by the OLED. This leads to color homogeneity over all viewing angles and invisibility of small defects or invisibility of inhomogeneity in the active area of OLED-panels.

Going beyond diffusive layers, the application of a layer containing phosphor particles on the substrate surface of a blue-emitting OLED-device is a method to generate white light by means of down conversion and improve external coupling-efficiency. Here, the light extraction enhancement is based on the same mechanism described above for the diffusive layer. Furthermore the luminescence converting phosphor particles absorb a part of the photons emitted by the blue light source and emit them at longer wave lengths. The non-absorbed fraction of the photons emitted by the light source and the photons emitted by the phosphor constitute the white output spectrum of the device. White light-emitting devices by the means of luminescence conversion based on an inorganic blue light-emitting LED and down-conversion by phosphor were first published by Schlotter *et al.* [21] and are widely used in existing LED products. Duggal *et al.* were the first to implement the idea to the field of OLEDs generating white light by combining a blue OLED with down-conversion phosphor layers [22]. Based on this approach an illumination quality lighting panel with a

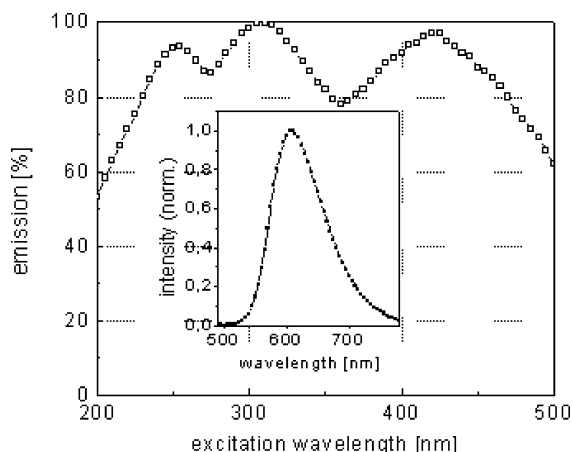


Fig. 14. Excitation and emission spectrum of the nitridosilicate phosphor used in the down-conversion layer.

power efficiency of 15 lm/W at 1000 cd/m² was demonstrated [23]. The efficiency of this device is limited by the efficiency of the blue OLED.

The efficiency of a white light source developed by down-conversion method is determined by the underlying blue diode. In Section IV-B we have presented a highly efficient single-layer blue PHOLED based on iridium phosphorescent dye (FIrpic) and a non-conjugated polymer host molecularly doped with electron transporting molecules. The substrate of this device is further modified by means of a phosphor down conversion layer. The down-conversion layer was applied to the outside surface of the PHOLED glass substrate. The phosphor used is based on a nitridosilicate phosphor ([Sr, Ba, Ca]₂Si₅N₈ : Eu²⁺) [24], [25]. The phosphor material is an internal product of OSRAM with a quantum yield of about 90% of typical YAG:Ce. Fig. 14 shows the excitation spectrum and the emission spectrum of the phosphor used in our experiment². As can be seen from the excitation and emission spectra, the phosphor will absorb a fraction of the photons emitted by the blue PHOLED and reemit at wavelengths corresponding to the orange range of the visible spectrum. The resulting output spectrum of the device is the superposition of non-absorbed blue light and phosphor reemission. Using a masticator, the phosphor particles were thoroughly dispersed in a silicone matrix (refractive index 1.47), in order to prevent aggregation quenching. This mixture was then applied on the substrate using the doctor blade technique. The down-conversion layer was cured at 70 °C for 24 h. The thickness of the cured layer was 90 μm as measured by profilometry.

The photo in Fig. 15 shows the white source generated by down-converting our blue PHOLED with the OSRAM phosphor. The figure also shows the normalized output spectrum of the device, and the corresponding C.I.E. coordinates of this cool white light source were $x = 0.26$ and $y = 0.40$.

By varying the thickness of the down-conversion layer, the x -coordinate of the light source can be adjusted, while the y -coordinate is not significantly affected. Consequently, color coordinates closer to the Planckian locus can be obtained with thicker films.

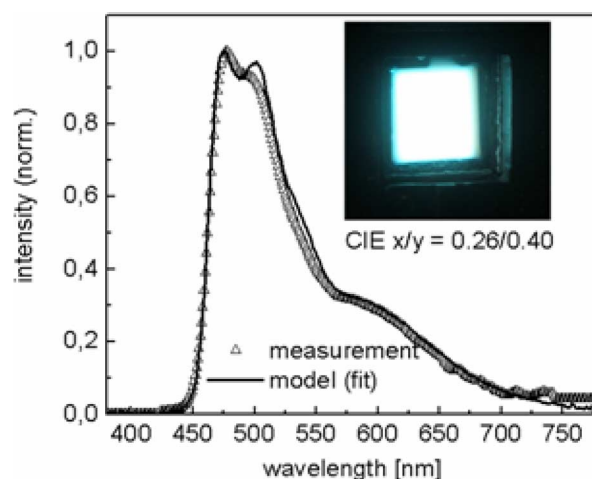


Fig. 15. Normalized output spectrum of the white light-emitting down-conversion device. The spectrum was fitted according a simple down-conversion model, in order to calculate the expected efficiency of the device without consideration of light extraction enhancement. The picture shows the white LED.

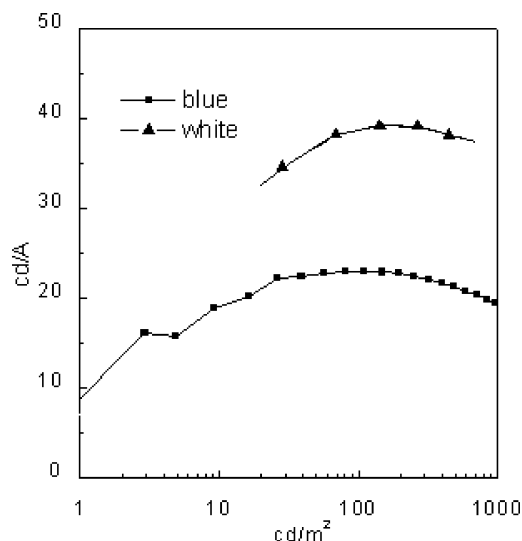


Fig. 16. Luminous efficiency as a function of brightness for the blue PHOLED and the white device.

Fig. 16 shows the device efficiency as a function of brightness (cd/m²) for the blue PHOLED used to provide white light by phosphor down-conversion. The blue PHOLED has a peak power efficiency of 14 lm/W at luminous efficiency reaching 22 cd/A at a brightness of 26 cd/m². The use down conversion results in an overall efficiency of 39 cd/A for the white light-emitting device and a peak efficiency of 25 lm/W; the highest efficiency reported to date for a solution processed device with a down conversion layer. This translates into a conversion efficiency of 180%.

Compared to the results previously reported by Duggal *et al.* [22], this value of conversion efficiency is much higher. To quantify the output spectrum due to phosphors, the output spectrum is calculated based on the FIrpic spectrum and the absorption and emission spectra of the phosphors. In this calculation, a model based on the absorption and emission spectra of the phosphor, the self-absorption correction of the down-conversion layer, the EL-spectrum of the blue PHOLED and the quantum

²Phosphor data was obtained by OSRAM GmbH.

yield of the phosphor was developed. The effective optical path length of the light in the phosphor layer was used as the only fitting parameter and was varied in order to obtain the best fit of the output spectrum (fit in Fig. 15). The calculations for the expected efficiency include parameters related to the sensitivity of the human eye and the Stokes shift between the energy of absorbed and reemitted photons. More details can be found in [22]. After determining the fitting parameter, a factor that relates the efficiency of the blue PHOLED and the efficiency of the resultant white device was obtained. The calculated blue-white conversion efficiency is only 94%, far lower than the 180% seen experimentally. This difference may be attributed to light extraction effects due to light scattering by the phosphor particles, which is not considered by the model.

Volumetric light scattering due to particles embedded in a coating on the substrate surface has been reported to enhance light extraction [6], [20]. The introduction of volumetric scattering mechanisms due to ZrO_2 particles embedded in a coating on the substrate surface has been reported to increase the output of OLEDs by as much as 40%. Considering that 50% of the light generated by the OLED stack in their case was lost in the substrate, the scattering medium succeeded in extracting. However, the light extraction value that is reported is still much lower than what we observe.

The difference in the values may be caused by the fact that our phosphors do not only scatter, but also get excited and emit. In order to separate the difference between light extraction enhancement due to volumetric light scattering and enhancement due to absorption-reemission mechanism of our OSRAM phosphor, the efficiency enhancement of an orange light-emitting OLED due to the same down-conversion layer described above was compared to the enhancement of the blue PHOLED in our white device. The conversion layer in the orange OLED functions as a volumetric scattering layer as the phosphor does not absorb in the orange. To ensure a fair comparison, the extraction efficiency based on the fraction of light that is lost in the substrate for both OLEDs when uncoated has to be considered.

The emission intensity of the uncoated orange light-emitting OLED and of the uncoated blue PHOLED was measured with a Si photodiode according to the method described by Nakamura [16, Sec. III-D]. The distance between the Si photodiode and the OLED substrate surface was kept at < 0.5 mm. Measurements were carried out alternatively with an air gap and an optical gel whose refractive index was 1.56. When the air gap was filled with gel, total internal reflection at the glass-air interface disappeared, enabling the emitted light of the external and substrate waveguided modes to be measured by the Si photodiode simultaneously. For the orange and for the blue PHOLEDs, about 50% of the light is extracted to air. After applying the same down-conversion layer on the substrate surface of the orange light-emitting OLED, its light output was measured again. The resulting output of the orange OLED was increased by 30% due to light scattering in the conversion layer. Based on our analysis in the previous section, the blue-to-white conversion is 96%. Pure scattering effects would give 125% conversion efficiency which is substantially lower than the 180% observed experimentally. This confirms that pure volumetric scattering cannot account for the light extraction enhancement seen in our white

device. This difference is due to the phosphor particles being excited and re-emit. Re-emission by the phosphor particles is isotropic, while the radiation patterns of scattering media is not. Furthermore, previous work has shown a dependence of the light extraction enhancement on the radiation pattern of the particles [6], [20]. Thus, in the case of the down-conversion layer presented here, we propose, that a larger light extraction enhancement is due to the isotropic emission/scattering due to the conversion layer.

V. CONCLUSION

In summary, we have demonstrated molecular dye dispersed solution processable blue emitting devices and found that the device efficiency is a strong function of both charge balance in the devices as well as the exact location of the carrier recombination zone and hence the device architecture. By the tuning the electron transporting moiety in the devices, the device efficiency could vary from 3 to 25 cd/A.

In addition, white emitting devices have been fabricated based on the blue-emitting devices with a down-conversion phosphor layer. White emitting devices with peak efficiency of 39 cd/A and power efficiency of 25 lm/W have been achieved. The high blue-to-white conversion efficiency has been due to a combination of efficient down-conversion efficiency and due to light extraction enhancement caused by the phosphor particles at the substrate surface.

Furthermore, a simple methodology to determine the light extraction efficiencies of OLED devices has been presented. The optical modeling presented and the proposed methodology allow study of the effects of device geometry and accordingly the location of the emission zone on spectral output and light out-coupling. In addition to the experimental data, results of optical modeling indicate that the light out-coupling efficiency of devices is a strong function of the device structure and emission spectral characteristics which are in good agreement consistent with our data. Estimate of device internal quantum efficiency based on external quantum efficiencies without considering the device architecture could lead to overestimations of device efficiencies.

Finally, we have demonstrated for a given light extraction scheme the enhancement in light extraction is strongly dependent on device architecture. It should be cautious to generalize the extraction efficiency for a particular light extraction scheme without considering the device architecture. We further demonstrated the *net* out-coupling efficiency for a particular light extraction scheme is independent of the device architecture.

REFERENCES

- [1] M. A. Baldo, S. Lamansky, P. E. Burrows, M. E. Thompson, and S. R. Forrest, "Very high-efficiency green organic light-emitting devices based on electrophosphorescence," *Appl. Phys. Lett.*, vol. 75, p. 4, 1999.
- [2] G. Gu, D. Z. Garbuzov, P. E. Burrows, S. Venkatesh, S. R. Forrest, and M. E. Thomson, "High-external-quantum-efficiency organic light-emitting devices," *Opt. Lett.*, vol. 22, p. 396, 1997.
- [3] C. Adachi, M. A. Baldo, M. E. Thompson, and S. R. Forrest, "Nearly 100% internal phosphorescence efficiency in an organic light-emitting device," *J. Appl. Phys.*, vol. 90, no. 10, 2001.
- [4] S. Moeller and S. R. Forrest, "Improved light out-coupling in organic light emitting diodes employing ordered microlens arrays," *J. Appl. Phys.*, vol. 91, p. 3324, 2002.

- [5] V. Bulovic, V. B. Khalfin, G. Gu, P. E. Burrows, D. Z. Garbuzov, and S. R. Forrest, "Weak microcavity effects in organic light-emitting devices," *Phys. Rev. B.*, vol. 58, p. 3730, 1998.
- [6] J. Shiang, T. Faircloth, and A. Duggal, "Application of radiative transport theory to light extraction from organic light emitting diodes," *J. Appl. Phys.*, vol. 95, p. 5, 2004.
- [7] M. Scheffel, A. Hunze, J. Birnstock, J. Blässing, W. Rogler, G. Wittmann, and A. Winnacker, "Enhanced light extraction by substrate modification of organic electroluminescent devices," in *Proc. Eur. Conf. on Organic Electronics and Related Phenomena '01*, 2001, vol. 158.
- [8] M.-H. Lu, C. F. Madigan, and J. C. Sturm, "Improved external coupling efficiency in organic light-emitting devices on high-index substrates," in *Int. Electron Devices Meeting Tech. Dig.*, 2000, vol. 600.
- [9] T. Tsutsui, M. Yahiro, H. Yokogawa, K. Kawano, and M. Yokoyama, "Doubling coupling-out efficiency in organic light emitting devices using a thin silica aerogel layer," *Adv. Mater.*, vol. 13, p. 1149, 2001.
- [10] M. Lupton, B. J. Matterson, I. D. W. Samuel, M. J. Jory, and W. L. Barnes, "Bragg scattering from periodically microstructured light emitting diodes," *Appl. Phys. Lett.*, vol. 77, p. 3340, 2000.
- [11] M. G. Salt, W. L. Barnes, and I. D. W. Samuel, "Photonic band structure and emissive characteristics of MEH-PPV textured microcavities," *J. Mod. Opt.*, vol. 48, p. 1085, 2001.
- [12] R. H. Jordan, L. J. Rothberg, A. Dodabalapur, and R. E. Slusher, "Efficiency enhancement of microcavity organic light emitting diodes," *Appl. Phys. Lett.*, vol. 69, p. 1997, 1996.
- [13] H. J. Peng, M. Wong, and H. S. Kwok, "Coupling efficiency enhancement of organic light emitting devices with refractive microlens array on high index glass substrate," in *SID Int. Symp. Dig. Tech. Papers*, 2003, vol. 34, p. 516.
- [14] J.-S. Kim, P. K. H. Ho, N. C. Greenham, and R. H. Friend, "Electroluminescence emission pattern of organic light-emitting diodes: Implications for device efficiency calculations," *J. Appl. Phys.*, vol. 88, no. 2, p. 1073, 2000.
- [15] X. H. Yang and D. Neher, "Polymer electrophosphorescence devices with high power conversion efficiencies," *Appl. Phys. Lett.*, vol. 84, p. 2476, 2004.
- [16] T. Nakamura, N. Tsutsumi, N. Juni, and H. Fujii, "Improvement of coupling-out efficiency in organic electroluminescent devices by addition of a diffusive layer," *J. Appl. Phys.*, vol. 96, p. 6016, 2004.
- [17] M. Matsumura and T. Furukawa, "Properties of organic light-emitting devices with a rubrene sub-monolayer inserted between electron- and hole-transport layers," *Jpn. J. Appl. Phys.*, vol. 41, pt. 1, p. 2742, 2002.
- [18] Z. Wu, L. Wang, G. Lei, and Y. Qiu, "Investigation of the spectra of phosphorescent organic light-emitting devices in relation to emission zone," *J. Appl. Phys.*, vol. 97, p. 103105-1, 2005.
- [19] M. K. Mathai, V.-E. Choong, S. A. Choulis, B. Krummacker, and F. So, "Highly efficient solution processed blue organic electrophosphorescence with 14 lm/W luminous efficacy," *Appl. Phys. Lett.*, vol. 88, p. 243512, 2006.
- [20] C. Gärditz, R. Pätzold, D. Buchhauser, R. Bathelt, G. Gieres, C. Tschamber, A. Hunze, K. Heuser, A. Winnacker, J. R. Niklas, J. Amelung, and D. Kunze, "OLED lighting based on white broadband copolymer emitters," in *SPIE Proc.*, 2006.
- [21] P. Schlöter, R. Schmidt, and J. Schneider, "Luminescence conversion of blue light emitting diodes," *Appl. Phys. A*, vol. 64, p. 417, 1997.
- [22] A. R. Duggal, J. J. Shiang, C. M. Heller, and D. F. Foust, "Organic light-emitting devices for illumination quality white light," *Appl. Phys. Lett.*, vol. 80, p. 3470, 2002.
- [23] A. Duggal, J. Shiang, D. Foust, L. Turner, W. Nealon, and J. Bortscheller, "Large area white OLEDs," in *SID 05 Dig.*, 2005, vol. 28.
- [24] F. Jermann, T. Fiedler, F. Zwaschka, and M. Zachau, "Next generation LED phosphors: From garnets to nitrides," in *Conf. Proc. Intertech's Global Phosphor Summit*, 2004.
- [25] "European Patent Specification," EP 1 238 041 B1, 2005.

Benjamin Krummacker received the Diploma in material science from University of Erlangen-Nuremberg, Germany, in 2003.

In 2004 he joined OSRAM Opto Semiconductors Inc., San Jose, CA, working toward the Ph.D. degree, supervised by Prof. Albrecht Winnacker from University of Erlangen-Nuremberg. Currently he is R&D engineer at the Technology Department of OSRAM Opto Semiconductors GmbH, Regensburg, Germany. His research focuses on light extraction from organic light-emitting diodes and developing white light-emitting light sources by means of phosphor down-conversion.

Mathew Mathai received the B.Eng. degree in polymer engineering from the University of Pune, Pune, India, in 1998, and the M.S. and Ph.D. degrees in polymer science from the University of Connecticut, Storrs, in 2001 and 2004, respectively, where he researched chemical and morphological factors limiting the lifetime performance of organic light emitting diodes.

He joined Osram Opto Semiconductors Inc., San Jose, CA, as a Device Scientist where he was part of the Materials and Devices team developing solution processed PHOLEDs for solid-state lighting. In December 2005, he joined Plextronics Inc. where he currently leads the Device Analysis group involved in high performance hole injection layer development for OLEDs and active layers for organic photovoltaic applications.

Franky So received the B.A degree in physics from Hamilton College, the M.S. degree in materials science from MIT, Cambridge, and the Ph.D. degree in electrical engineering from the University of Southern California, Los Angeles.

After his graduation in 1991, he was a research scientist at Hoechst Celanese Research Division working on high speed polymer electro-optical modulators. In 1993, he joined the Motorola Phoenix Corporate Laboratories and became a Program Manager responsible for the OLED technology development. In 2001, he joined OSRAM Opto-Semiconductors and became the Head of OLED Materials and Devices Research. In 2005, he joined the faculty in the Department of Materials Science and Engineering at the University of Florida. He is now currently an Associate Professor in the Department. Dr. So holds more than 50 issued patents.

Stelios A. Choulis received the B.Sc. degree in physics from University of Patras, Patras, Greece, in 1995, the M.Sc. and Ph.D. degrees in semiconductor material and device physics from the University of Surrey, Surrey, U.K., in 2001.

Following three years post-doctoral research positions at the Advanced of Technology Institute, University of Surrey, Surrey, U.K. (2001–2002) and at the Center of Electronic Materials and Devices at Imperial College London, London, U.K., (Prof. Donal Bradley group, 2002–2004), he joined OSRAM Opto-Semiconductor Inc (San Jose, CA, 2004), as a R&D scientist, working on organic light emitting diodes for flat panel displays and solid-state lighting. In January 2006, he joined Konarka Technologies, Nurnberg, Germany). He is currently the device group leader of the polymer photovoltaics R&D worldwide activities at Konarka Technologies. He has authored and co-authored more than 40 refereed publications and filed over 7 patents in the area of organic and inorganic semiconductor material and devices.

Vi-En Choong received the B.S. degree in physics from Allegheny College, Meadville, PA, the M.A. degree in physics and the Ph.D. degree in condensed matter physics from the University of Rochester, Syracuse, NY.

After graduation in 1997, he joined the Phoenix Applied Research Center of Motorola as a Staff Scientist where he was primarily involved in research and development of OLED technology. He later joined the Biochip Advanced Technologies group in the Lifescience division of Motorola as Principal Staff Scientist where he worked on new detection concepts and biosensor devices. In 2002, he joined OSRAM Opto-Semiconductors as Manager of OLED Display Testing for advancement of testing instrumentation and became Project Manager for materials research for OLED Lighting and later became the Department Head of Materials and Devices Research. In 2006, he joined the Corporate Research Laboratories of Invitrogen Corp. where he is primarily focused in the area of bio-marker discovery and diagnostics. He holds over 10 issued patents and over 40 publications.