Enhancement of Light-Outcoupling Efficiency in OLEDs

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Content Talk 3

• Basics of Dipole Emission model
• Tuning the OLED stack
  – dipole orientation, birefringence, refractive index...
• Scattering enhancement tricks
  – scatter particle film
  – interface textures
  – microlenses
Setfos Software Modules:

Organic Solar Cells

Light-scattering (adv. optics)

Absorption module  
Drift-Diffusion module  
Emission module

Light-scattering (adv. optics)

OLEDs
OLED Outcoupling Simulation

- TADF OLED with 100% IQE, 41.5% EQE

Optical simulations by SETFOS:
  - Optimize layer thicknesses
  - Quantify outcoupling efficiency and potential for enhancement (by MLA structure)
  - Determine emitter properties (molecular orientation s=0.29, emission zone)

Angular PL

Scattering due to hexagonal MLA

Kaji et al. Nature Comm. (2015), DOI: 10.1038/ncomms9476
PAIOS with Angular Spectrometer Module for (O)LED Emission Analysis
OLED R&D Challenges

- Scatter foil improves brightness but changes color & angular dependence.
- 10 cm x 30 cm OLED by LG Chem.
- Metal grid enhances conductivity but shadows light.
- Optical simulation (Setfos).
- Electrical large-area simulation (Laoss).
OLED Panels w/ Light Extraction Foil – LG Chem Example

Angular Luminous Intensity (measured by paios)

Angular Corr. Color Temp. CCT (measured by paios)

Viewing Angle

Scatter foil and OLED stack need to be **jointly** optimized!
Multi-scale, Multi-physics OLED Modeling

- Length Scale:
  - cm
  - mm
  - um
  - nm

- Electrical
- Thermal
- Optical

- Precision:
  - Electro-(thermal) FEM model
  - Drift-diffusion model (1D vertical)
  - Monte-Carlo

- Methods:
  - 3D Ray-tracing
  - Microstructure optics
  - Dipole emission & thin film optics
  - Full-wave
Radiating dipole as harmonic oscillator

The recombination of holes and electrons is assumed to radiate like an oscillating dipole.

We are interested in both the radiation pattern and the dipole dynamics:

\[ \frac{d^2 \vec{p}}{dt^2} + b_0 \frac{d\vec{p}}{dt} + \omega^2 \vec{p} = \frac{e^2}{m} \vec{E}_R(\omega) \]

N. Reinke
Dipole Emission Model Summary

Intrinsic power of dipole in inf. media:

\[ b_0 = q_0b_0 + (1 - q_0)b_0 \]

We can write a dipole in a multilayer:

\[ b = q_0b_0 \cdot F + (1 - q_0)b_0 \]

The dipole lifetime \( \tau \) becomes:

\[ \frac{\tau_0}{\tau} = \frac{b}{b_0} = (1 - q_0) + q_0 \cdot F. \]

(F: Purcell factor)

And with \( u = \frac{\text{kinplane}}{\kappa} = \sin(\theta_e) \) we get

\[ F = \int_0^{\infty} f(u)du, \]

The modes are distinguished

\[ u = 0 \ldots \frac{n_t}{n_e} \quad \text{radiative modes} \]
\[ = \frac{n_t}{n_e} \ldots 1 \quad \text{guided modes} \]
\[ = 1 \ldots \infty \quad \text{evanescent modes} \]

See Setfos Manual section 3.1 «Description of Optical Models»
Most of the internally emitted light is trapped inside the OLED!
Extra outcoupling tricks are needed to get more than 20% of the light!
Different “Emission” simulation modes

- Simulation of emitted radiance and spectrum (Spectral modes)

- Emitted power distribution versus $k_{\text{inplane}}$, $n_{\text{eff}}$ or $u$ (Dissipation power analysis)

- Compute the power emitted in the different modes, dipole lifetime (mode analysis)
Spectral mode: Spectrum vs. Angle

- Green OLED pixel example
- Increased viewing angle: spectrum shifts to blue
Angular OLED Radiance: Exp. vs. Sim.

Bottom (through glass) and top emission due to semitransparent electrodes

Device: Al(15 nm)/PEDOT(60 nm)/ [76% PVK + 19% PBD + 5% CGR-Red(x nm)] / Ba(1 nm)/Al (15 nm)

d=115 nm

Emitted angular radiance well reproduced with SETFOS!
White OLEDs with Color Filter
(Arbitrary Layer Sequences)

Example: Thickness variation of green color filter

Hybrid model tackles thin & thick layers!
e.g. encapsulation layers
Dipole location matters

Bi-layer thickness sweep

Layer structure

ETL

HTL

Luminance

Emitted color
Different “Emission” simulation modes

- Simulation of emitted radiance and spectrum (Spectral modes)

- Emitted power distribution versus k_inplane (Dissipation power analysis)

- Compute the power emitted in the different modes, dipole lifetime (mode analysis)
«Dissipation power analysis» - in depth analysis of modes

- Single wavelength
- Scans «angle»:
  - $k_{\text{in plane}}$
  - $n_{\text{eff}}$
  - $u_{\text{inplane}}$
- Dipole couples strongly to «resonant modes»
- Discrete dipole location inside a PLED

(example: disspow1.par)
Power outcoupled into glass, to air
Guided mode
Evanescent mode

\[ n_{\text{eff}} = n \cdot \sin(\theta) \]
(Relative) dipole location matters!

Larger separation of dipole from electrode:
smaller evanescent coupling and larger waveguided mode!

\[ u_{\text{inplane}} = \sin(\theta) \]
Now the dissipated power, emitted in different «u directions», is integrated.

**OC**: outcoupled into upper medium  
**GM**: Guided mode  
**EC**: Evanescently coupled  
**BT**: Bottom emission  
**AL**: Absorption losses  
**NR**: non-radiative
Emitter Orientation Matters!

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al (200nm)</td>
<td></td>
</tr>
<tr>
<td>TPBi (0-350nm)</td>
<td></td>
</tr>
<tr>
<td>TPBi:Ir(MDQ)$_2$(acac) (5nm)</td>
<td></td>
</tr>
<tr>
<td>TCTA (30nm)</td>
<td></td>
</tr>
<tr>
<td>ITO (120nm)</td>
<td></td>
</tr>
</tbody>
</table>

Glass

<table>
<thead>
<tr>
<th>Orientation</th>
<th>$\eta_{\text{sub}}$ (%)</th>
<th>$\eta_{\text{air}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random</td>
<td>48</td>
<td>25</td>
</tr>
<tr>
<td>$\alpha=80%$</td>
<td>53</td>
<td>28</td>
</tr>
<tr>
<td>$\alpha=100%$</td>
<td>67</td>
<td>35</td>
</tr>
</tbody>
</table>

- $\alpha=80\%$ enhancement = 1.10 - 1.12
- $\alpha=100\%$ enhancement = 1.4
OLED Emitter Orientation Analysis

Setfos Emission module is used to extract the dipole orientation from angular PL data!

Figure 3. (a) Dependence of light intensity at 530 nm in TM mode on the emission angle in 15 nm thick 6 wt % PXZ-TRZ:mCBP films deposited on glass substrates at $T_{\text{deposition}} = 200$, 250, and 300 K. The estimated values of the dipole ratio ($p_z/p_x$) are summarized in Table 1.

Emitter Orientation Fitting (by EL)

angular, polarized EL spectra (\textit{paios})

**setfos** analysis:
orientation changes polarization & angular intensity

Fitted orientation distribution

\[\text{M. Flämmich et al., Org. Elec. 11 1039, (2010)}\]
\[\text{or also:}\]
\[\text{P. Liehm et al., Appl. Phys. Lett. 101 253304 (2012)}\]
Emitter Orientation Fitting (by EL)

Angular (TM) spectra

Angular Radiance

Wavelength [nm]

Spectral intensity ppol [a.u.]

Measurements: paios

Simulations: setfos

by Markus Regnat, ZHAW

Good agreement with literature value for dipole orientation of Irppy2(acac) in CBP ≈ 77%, see Liehm et al. Appl. Phys. Lett. 101, 253304 (2012)
Dipole orientation fitted from angular PL considering birefringence

We have to account for anisotropic optical refractive index \((n_o, n_e)\) of EML host (and transport layers)

Efficiency in birefringent OLED stacks

ETL & HTL birefringent

Outcoupling to substrate is increased from **54%** to **74%** for random dipole orientation

*Original study: M. Callens, D. Yokoyama & K. Neyts Opt. Ex. 23 No. 6 (2015)*
TADF OLED with low-index ETL

tris-[3-(3-pyridyl)mesityl]borane (3TPYMB) has a low $n$ of 1.65 (at 550 nm)

(birefringent layers can have similar effect)

What is Emission-Zone Fitting?

Measurement of spectral emission (one or more angles)

Emission Zone Fitting

Dipole Distribution

Dipole Spectrum

Motivation:
Monitor charge balance, recombination in fresh and degraded OLED state

About our methods in Setfos and applications:
B. Perucco et al., Optics Express, 18 S2 (2010)
B. Perucco et al., Organic Electronics, 13 (2012)
Validation with artificial data

Fitted dipole distribution

Radiative density [m^-3s^-1]

Relative position [\( \ell \)]

Glass  ITO  MTDATA  gelNaPD  BAiq  TPBi  LiF-Al  air

Emission Zone Fit

Ref
Our hybrid optical modeling approach... 

...bridges the gap between two worlds

Nano/wave-optics:
• Small scale (\sim \lambda)
• Coherence
• Interference

Ray-optics:
• large scales (>\lambda)
• Incoherence
SETFOS 4.4: *Emission and Light-scattering*

- Wave nature of light considered in thin-film layer stack.
- Light intensity is considered in incoherent layers.
- Fully integrated and fast implementation in SETFOS
- BSDF hybrid approach: Different simulation models can be plugged in

→ SETFOS allows the combination of optical models on different length scales
Design Challenges for Scattering OLEDs

- Scattering properties?
- What is the ideal **haze**? (def. as ratio of scattered to incident light)
- How **broad** should scattering be?
- OLED stack properties?
- Should the OLED be highly **reflective**?
- How about **absorption** in OLED layers?

Combined optimization is necessary!
Impact of Substrate Haze on Emitted Power

- In real devices, **haze** (def. as ratio of scattered light) will be smaller than 100%!
- Thus we varied the **haze** of the scattering layer and we look at the evolution of the emitted power.
- We assume that the scattered part of the light is a **Lambertian function** ($\cos(\theta)$)

![Diagram showing layers of a device]

- The emitted power in air increases with the Haze.
- Even with 50% haze the emitted power almost doubles!
Impact of Haze on the Emitted Spectrum

→ Using a scattering layer the emission at 550 nm is enhanced.
   In order to keep the same color, the OLED structure must be tuned.
→ The emitted color almost does not change with the angle.
Top-emitting flexible OLED with thin film encapsulation & scat. foil

- Optional (commercial) outcoupling foils from Dupont Tejin Films with embedded particles were applied.
- Foils with different haze (9% vs. 59%) were used.

Excellent Agreement between Experiment (Holst) and Simulation (Setfos)

- Angular luminance increases with haze
- Blue color (no scatter foil) turns into white (with scatter foil)

S. Altazin (Fluxim), S. Harkema (Holst Centre)

Optimization of the PET Scatter Foil

→ Easily sweep the particle parameters to optimize the device.

→ Maximum of luminance for a particle concentration = 2.75 E-3
→ The luminance and emitted color can be optimized at the same time
→ Maximum because of backscattering and absorption by the particles

Joint optimization of stack + particle concentration

- Enhanced brightness: factor 1.9
- 1\textsuperscript{st} and 2\textsuperscript{nd} maximum shift when scattering
- Improved angular colour stability
**Key Concept for Describing Scattering**

**Bi-Directional Scattering Function:**
- black box description of scattering (layer/interface)
- relates input to output angle, for all wavelengths
- transmission and reflection, top to bottom and vice versa

Example:
rough glass/air interface @570 nm
Rough surface scattering (BSDF)

- SETFOS can compute the BSDF of rough surfaces for both I. E. I., and E. E. I.
- Less scattering for I. E. I. because of smaller index difference.
Simulation of White OLED with Rough Interfaces

Using two rough interfaces increases the emitted lumens by 2.1.
The emitted color remains white with the scattering interfaces.
→ Easy outcoupling efficiency calculation even with “scattering” OLEDs
→ No $I_{sg}$ when scattering is present, EC mode and GM remain

OLED Mode-Analysis with Scattering

Microlens Array (MLA)

OLED without MLA

- evanescently coupled (EC)
- guided mode (GM)

- 32% substrate-guided mode!
- 21%

OLED with MLA

- more absorption loss in electrodes
- 38%

Higher Air Mode!
Summary of Simulation Workflow

Scattering structure

Bi-directional Scattering Function (BSDF)

Design & optimize the OLED structure

Examples: textures, particle scattering, micro- and nano-structures

Experiment or simulation

Haze=1

Wavelength (nm)
Summary

• All-in-one modeling of OLEDs with light-scattering enhancement structures with Setfos
• Get extra efficiency from OLED by stack tuning (low-index, dipole orientation, birefringence...)

Setfos Software demo?

Thank you for your attention!