No Photon Left Behind: Challenges in OLED Outcoupling

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80% of Light is Trapped in the OLED

- $\eta_{\text{EQE}} = \eta_{\text{IQE}} (\sim 100\%) \times \eta_{\text{Ext}} \approx 20\%$

- **OLED Loss Channels**
  - Substrate mode
  - Waveguide mode
  - Surface plasmon polariton (SPP)
  - Metal absorption
Getting all the light out, or “no photon left behind”

• Good solutions
  ▪ Inexpensive
  ▪ Viewing angle & wavelength independent
  ▪ Independent of OLED structure

• Examples
  ▪ Optical gratings or photonic crystals\(^1\)
  ▪ Corrugations or grids embedded in OLED\(^2\)
  ▪ Nano-scale scattering centers\(^3\)
  ▪ Molecular dipole orientation management


Three solutions explored in SSL

• Sub electrode grids and microlens arrays
  • Harvests most available photons
• Dielectric diffuser
  • Efficient and simple
• Ultrathin, roughened substrates
  • Good for flexible, too.
Getting Rid of SPPs Using Sub-Anode Grid + Mirror

Top Emitting OLED

Anti-reflection layer
Organic
IZO
SiO₂
Substrate
Au
Ag Mirror on Grid Surface

Substrate Fabrication

Qu, et al. ACS Photonics, 2017
Sub-electrode grid modeling

Variable Waveguide Widths Prevent Mode Propagation
Getting All the Light Out: Sub-Electrode Microlens Array (SEMLA)

- Micron-scale lens array between the bottom electrode and the glass substrate
- Flat spacer layer
- High refractive index
- Microlens array imbedded into glass
SEMLA Fabrication

Photoresist 0.8 μm openings with a 10 μm pitch
As $n_{\text{sub}}/n_{\text{org}}$ goes up, more waveguided light is squeezed out

Structure: 70nm ITO/ 40nm TAPC/ 20nm CBP/ 65nm Bphen/Al
SEMLAs Change the Outcoupling Landscape

The diagrams show the fraction of power (%) as a function of ETL thickness (nm). Different layers (SPP, WV, Sub, Air) and loss mechanisms (Loss) are depicted. As the ETL thickness increases, the fraction of power for each layer changes, reflecting the impact of SEMLAs on the outcoupling landscape.
SEMLA Performance

![Graph showing current density (J) vs. voltage (V) with curves for Con and SEMLA.]  

![Graph showing EQE (%) vs. brightness (cd/m²) with data points for various conditions.]  

![Polar graph showing lambertian performance with data points for Con, SEMLA MLA, and SEMLA HS.]  

![Bar chart showing efficiency factors (EF) with values for SEMLA, SEMLA+MLA, SEMLA+IMF, and Sap, with error bars indicating ±3% to ±5% for each condition.]
Diffuse Reflectors: Low Cost & Simple

- Dielectric diffusive reflector
  - No SPP
  - Small absorption (Reflectance ~98%)
  - No angle dependence
  - Reduced w/g mode
Device Structure

[Diagram of device structure showing layers and contacts]

- Top Contact (ITO)
- Organic
- Bottom Contact (ITO)
- Diffuse Reflector
- High n Polymer Planarization Layer

[Graph showing surface roughness of diffuse reflector]

- Surface Roughness of Diffuse Reflector

[Image of OLED grown on the substrate]

- Top contact (ITO)
- PHOLED
- Bottom contact (ITO)

OLED grown on the substrate
Fabrication Sequence

UV Ozone Treatment

Rough Teflon Sheet

Glass Flat PDMS

Planarization Polymer

UV Curing

UV Curing
Device Performance – Efficiency

- External Quantum Efficiency (EQE)
  - Mirror 15 ± 2%
  - Diffuser 37 ± 4% (×2.5)
- Comparable J-V
  - No influence on device structure
Device Performance – White Spectrum

- **White OLED**
  - No spectrum shift
    - Weak optical micro-cavity by high-index planarization layer
  - Lambertian light source
    - Scattering via diffuse reflection

![Graph showing normalized intensity vs. wavelength for Mirror and Diffuse](image1)

![Diagram showing angular intensity distribution](image2)
Device Analysis(I) – Peripheral Emission
Device Analysis – Peripheral Emission

- Light emitted outside the defined active area: Peripheral Emission
- Device area $\uparrow$ $\rightarrow$ peripheral emission $\downarrow$
- Planar layer thickness $\downarrow$ $\rightarrow$ peripheral emission $\downarrow$, EQE $\uparrow$ (68%, $\times 3.4$ @50um)
Device Analysis - Number of Reflections

- Diffuse reflection
  - Redirect light uniformly
  - $R_s = 30\% \rightarrow$ air mode
  - 5 scattering $\rightarrow$ $\sim 80\%$ escape

\[ \eta_{out} = \eta_{TA} + \eta_D \eta_S \]

$\eta_{TA}$: Light power fraction to top surface

$\eta_D$: Planarization layer efficiency

$\eta_S$: Light power fraction into planarization layer
Ultrathin, Ultra-flexible OLEDs With High Outcoupling
Corrugations by Deposition on Rough Sapphire
Ultrathin, Ultra-Flexible OLED Performance
Conclusions

• Substrates can be modified to extract almost all trapped modes in OLED
  ✓ Waveguide
  ✓ SPP
  ✓ Substrate

• Best solutions do not interfere with OLED structure
  ✓ Wavelength and viewing angle independent
  ✓ Low cost
  ✓ Adaptable to both top and bottom emission

• Practical limit for outcoupling: 70 - 80%
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[Image of a group of people]