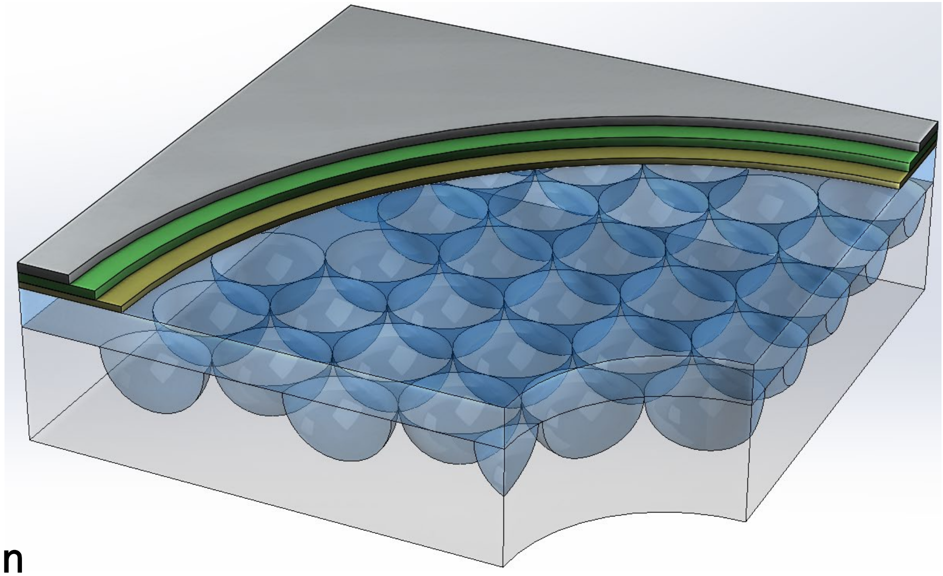
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Eliminating Plasmon Losses in High Efficiency White Organic Light Emitting Devices for Light Applications



University of Michigan

Stephen R. Forrest, Professor / Principal Investigator

Tel: (734) 647-1147; stevefor@umich.edu

Contents

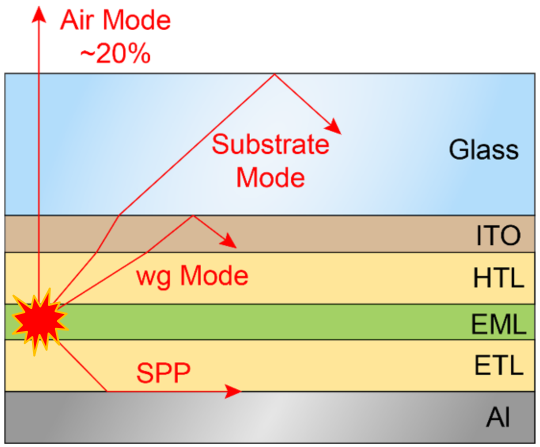
OLED Lighting

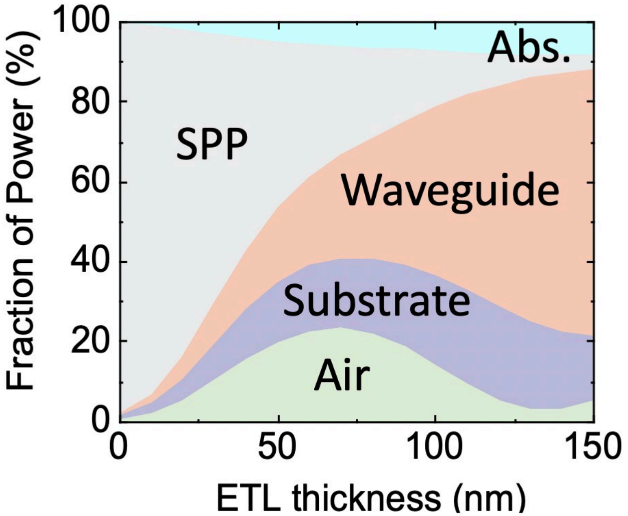
Reference. Luflex, LG Display

Where does the Light Go?

- Internal quantum efficiencies (η_{IQE}) ~100%
- But extraction efficiency (η_{out}) is a major limit
- $\eta_{EQE} = \eta_{IQE} \times \eta_{out} \approx$ 20% (TIR and other losses)

- Refractive index change at interfaces lead to trapped light
  – At glass / air interface, "Glass modes"
  – At high-index ITO / organic layers, "Waveguide modes"
  – Trapped at the metal cathode interface, "Surface plasmons"





Approach Principles

Approaches:

Acceptable solutions must have the following properties

- ✓ **Low cost**
- ✓ **Viewing angle and wavelength independence**
- ✓ **Non-invasive of the OLED structure**

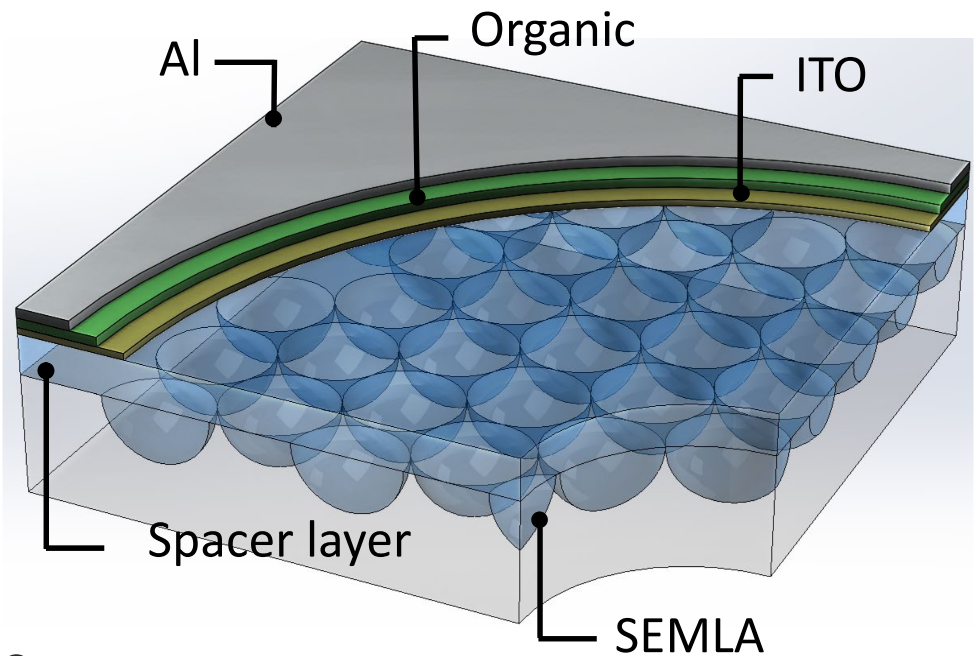
- Solutions that outcouple > 70% of the emitted light
- Demonstrate scalability of the methods investigated

Contents

SEMLA on a U of M Logo

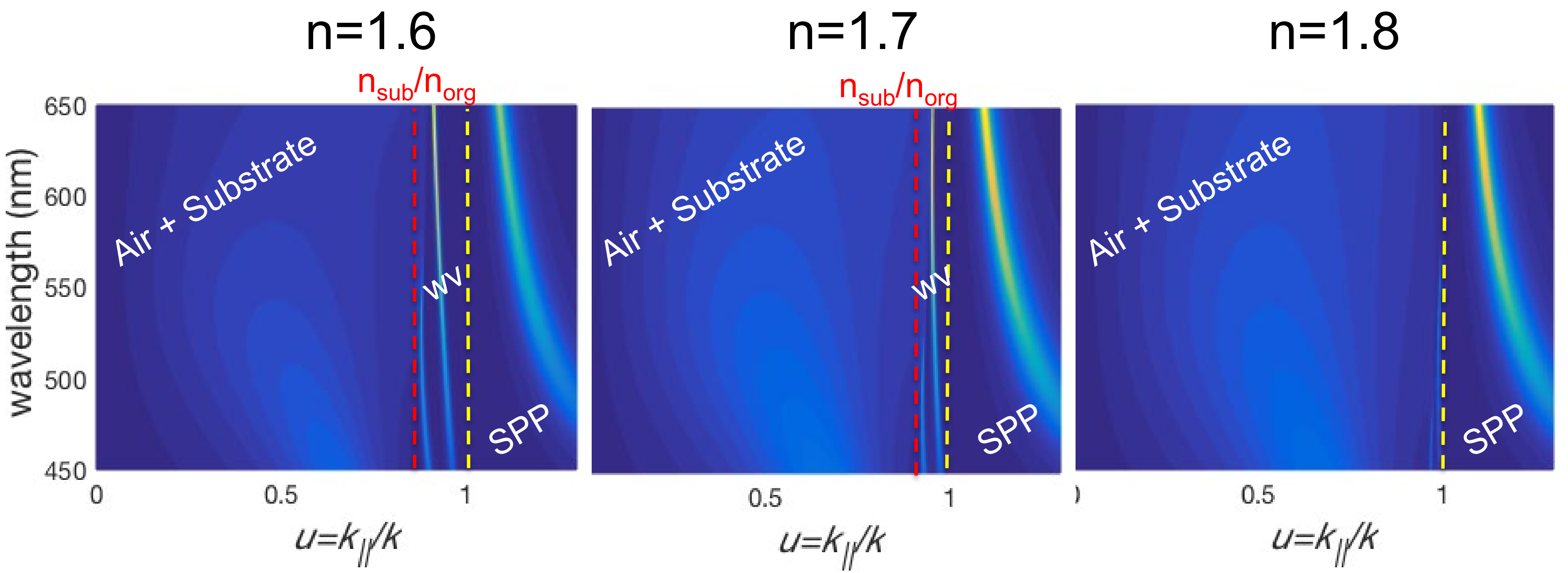
Design Scheme

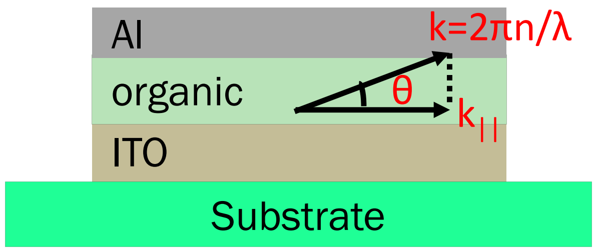
- Micron-scale lens array between the bottom electrode and the glass substrate
- Flat spacer layer
- High refractive index
- Microlens array embedded into glass



T Komoda et al, Dig. Tech. Pap. - Soc. Inf. Disp. Int. Symp. 2012, 43 (1), 610– 613

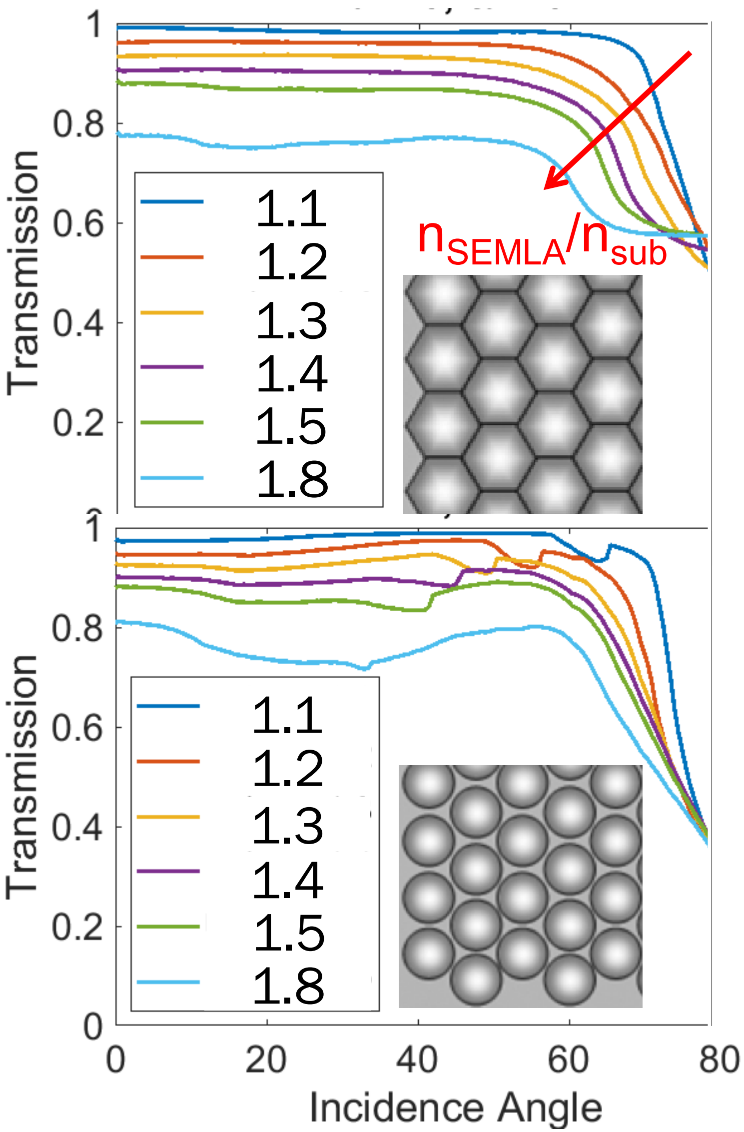
Optical Design *– Organic wg → SEMLA*





As n_{sub}/n_{org} goes up, more waveguided light is squeezed out

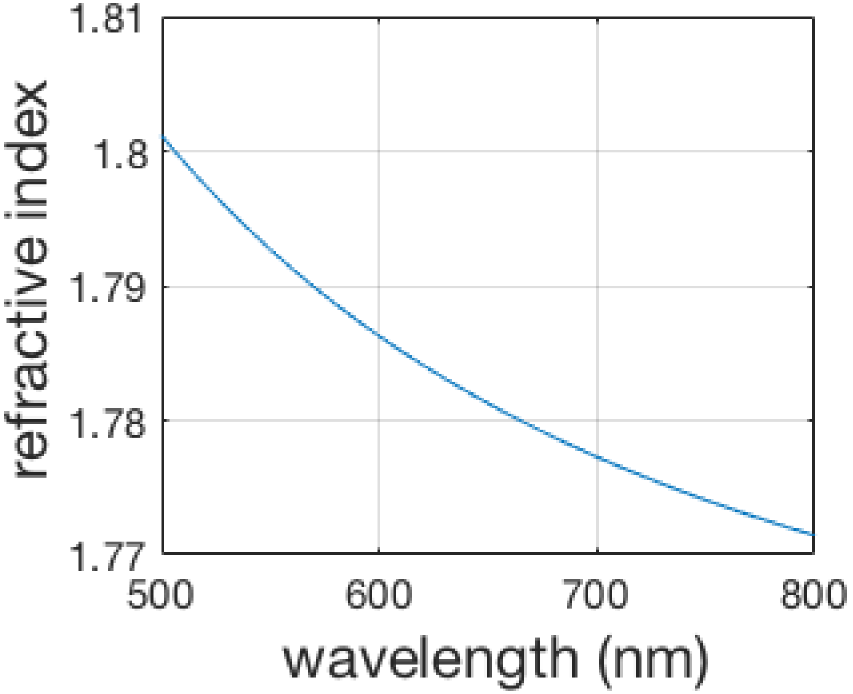
Optical Design *– SEMLA→ Glass Substrate*

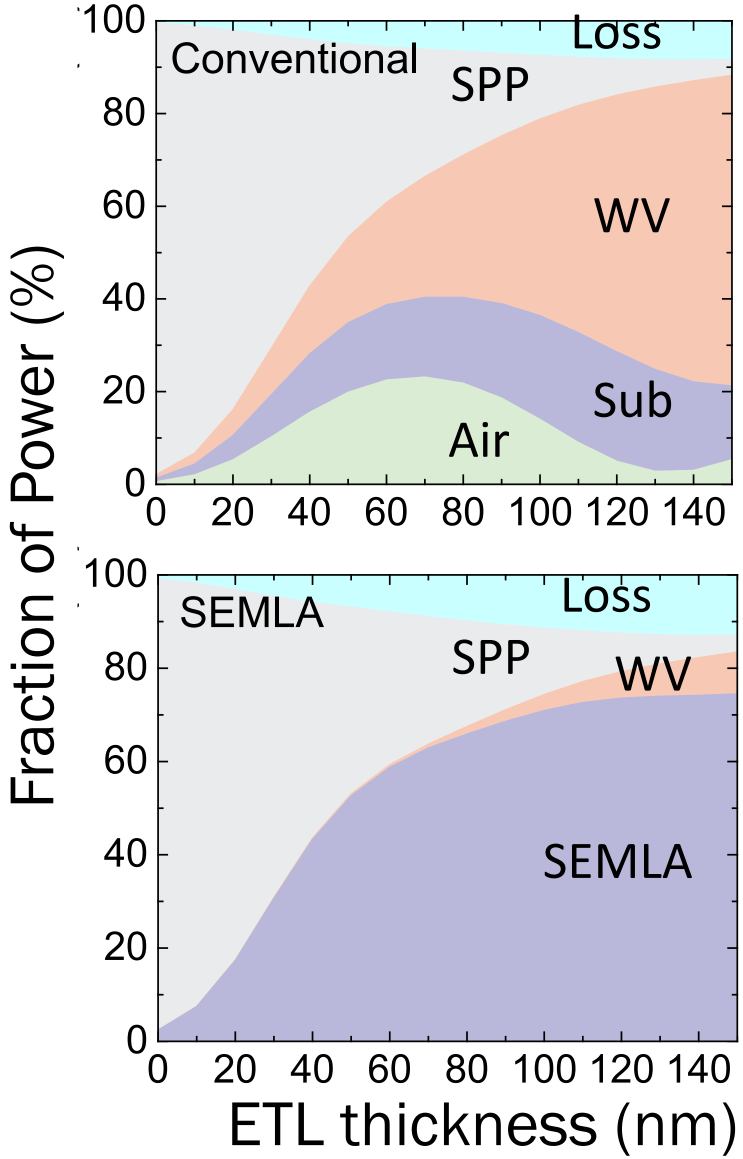


- **As n_{SEMLA}/n_{sub} goes up, both transmission and escaping angle decrease**
- **$n_{SEMLA}/n_{sub} = 1.8/1.5 = 1.2$**

Optical Design *– High Refractive Index Spacer*

NOA 170, Norland Products Inc.





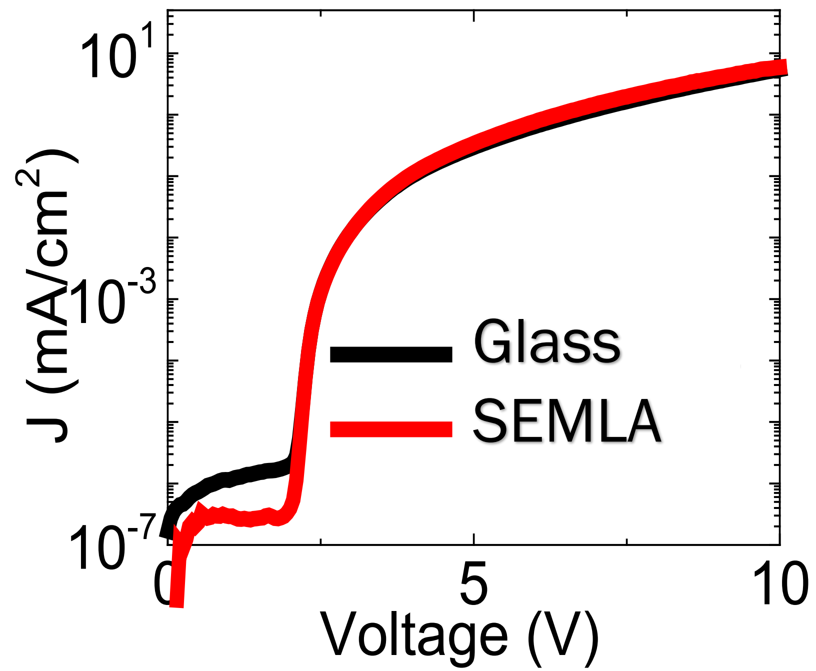
Device Performance *– Measurement*

Internal Extraction

- The SEMLA
- Conventional glass (n=1.45)
- Sapphire (n=1.77)

External Extraction

- External microlens arrays (MLA)
- Index matching fluid (IMF)

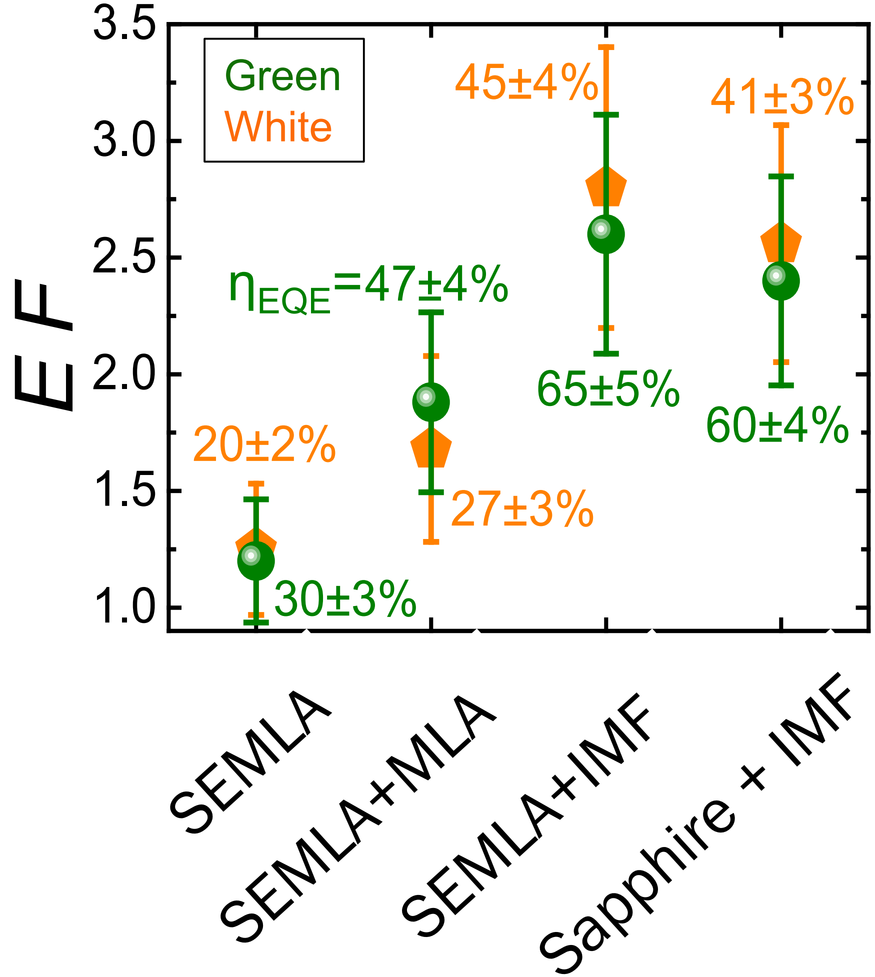


Device Performance *– Efficiency*

- **Control Conventional**
  - Peak EQE ~ 25% (Green)
  - Peak EQE ~ 17% (White)
- **Enhancement factors (*EF*) with EQEs**

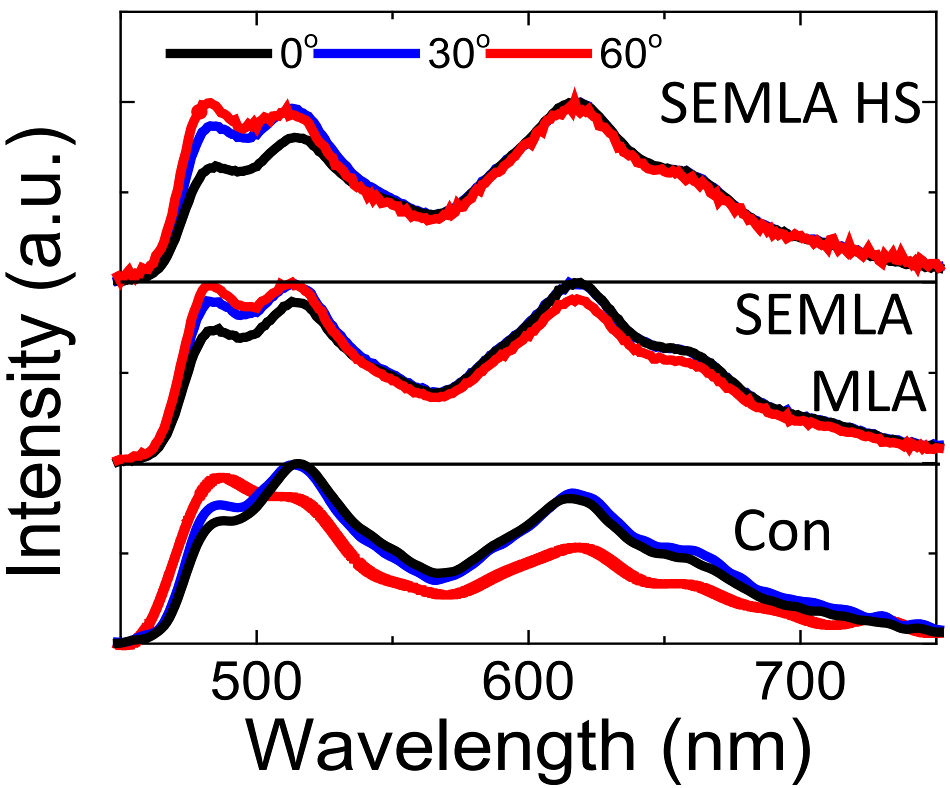
$$EF = \eta / \eta_{glass}$$

- **Independent on emissive wavelengths**



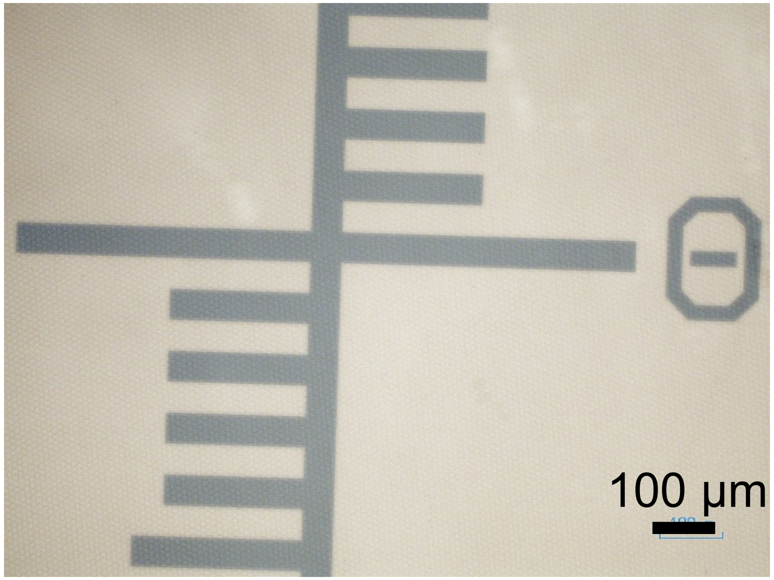
Device Analysis *– Angle Dependence*

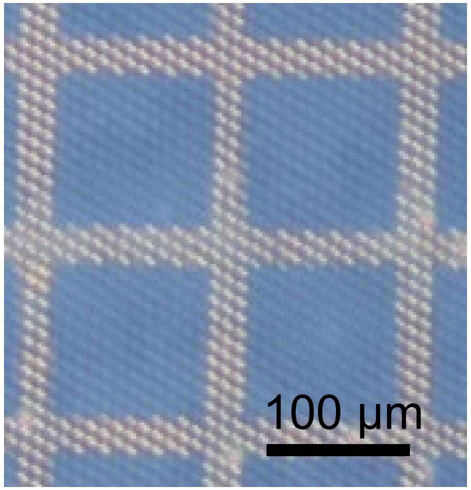
- **SEMLA with MLA and large Hemisphere lens (HS)**
- **no blue shift at large angles (at 60 degree)**



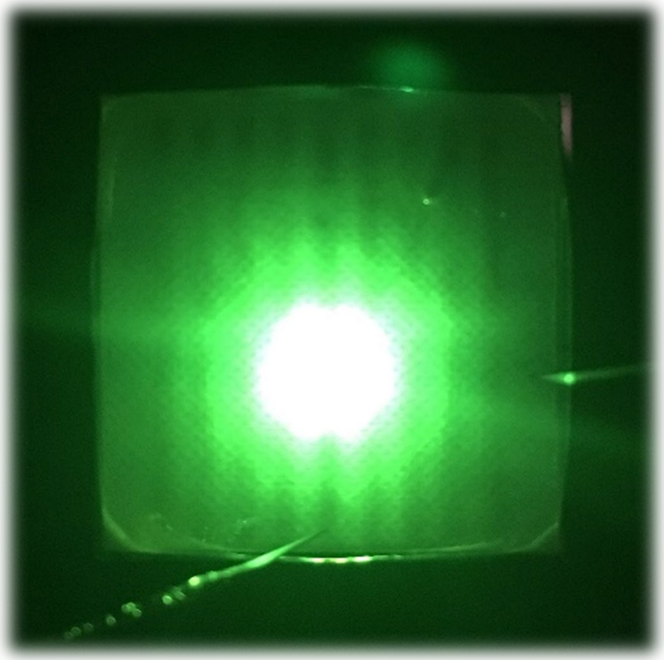
Device Analysis *– Resolution Impact*

- No visible impact on the image resolution
- Patterning of the SEMLA can only be seen under the microscope





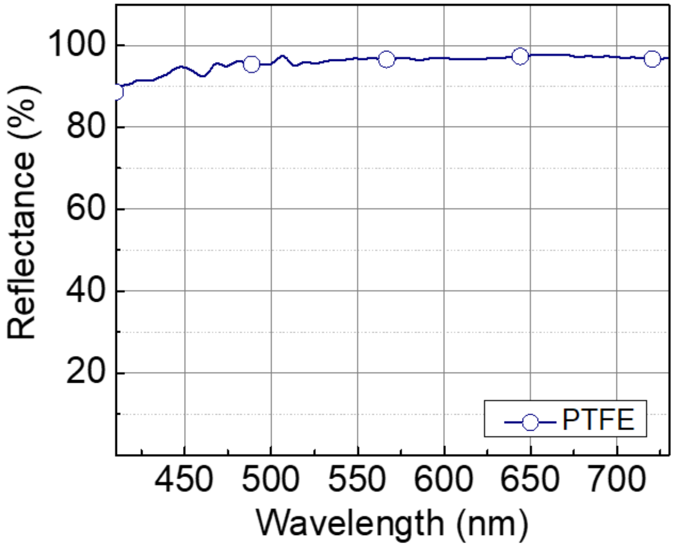
Contents

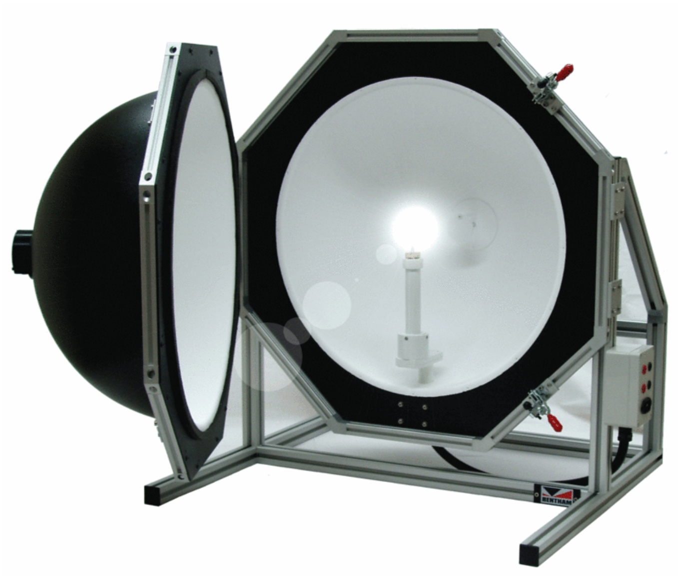


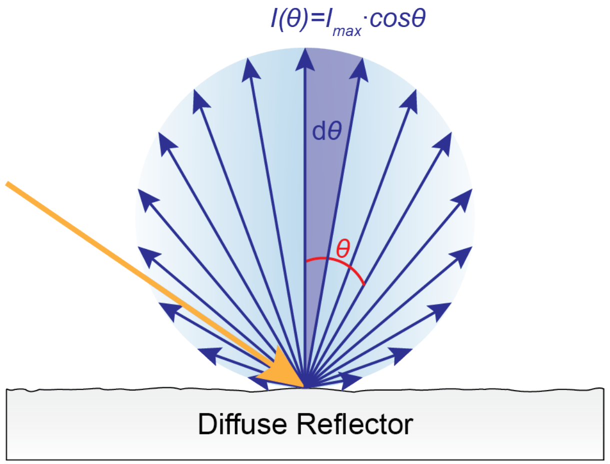
Green OLED on Diffuse Reflector Substrate

Metal reflectors are lossy

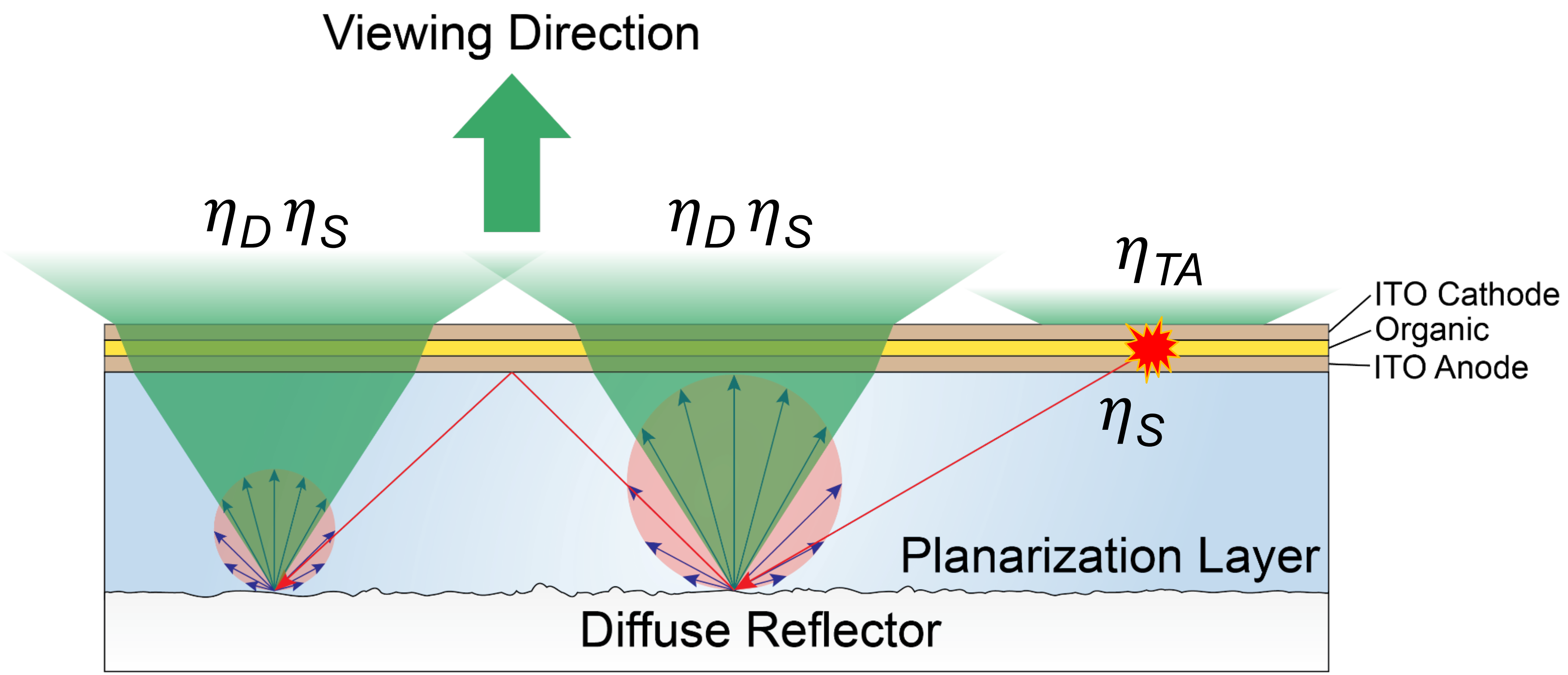
- **Dielectric diffusive reflector**
  - ✓ No SPP
  - ✓ Small absorption (Reflectance ~98%)
  - ✓ No angle dependence
  - ✓ Reduced micro-cavity effect







Device Scheme



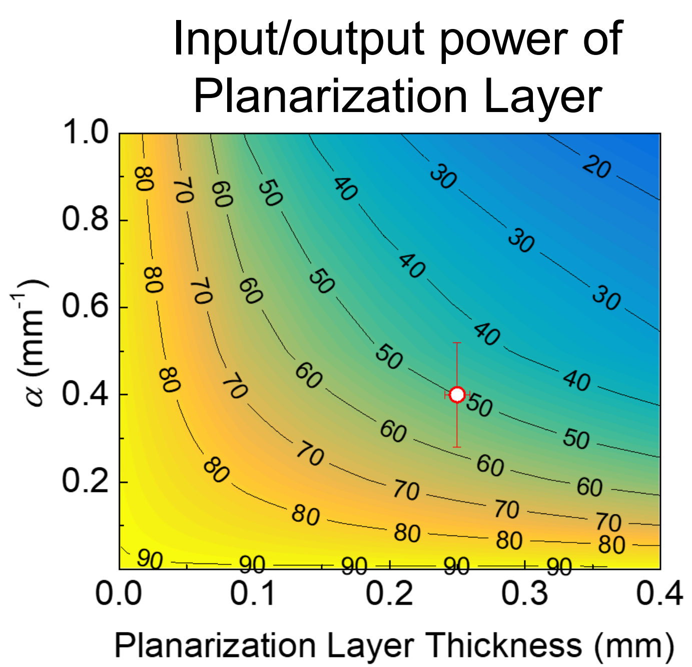
$$\eta_{out} = \eta_{TA} + \eta_D \eta_S$$

η_{TA} : Light power fraction to top surface
η_D : Light extracted / Light fraction into planarization layer
η_S : Light power fraction into planarization layer

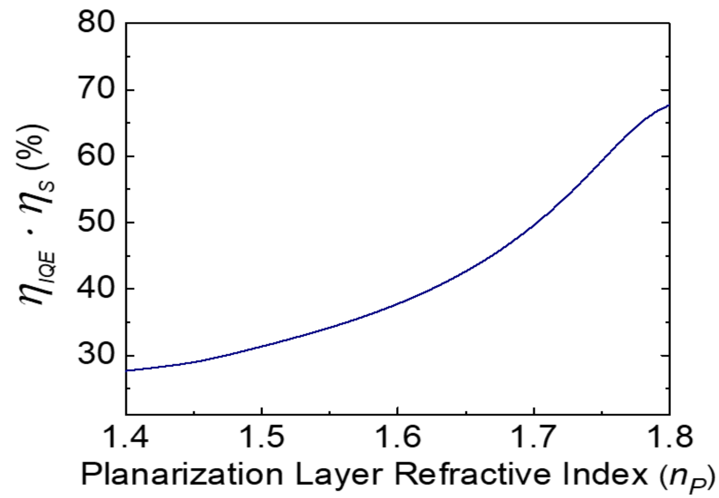
$$\eta_D = R_S + (1 - R_S) \cdot R_S + (1 - R_S)^2 \cdot R_S + \cdots = \sum_{n=0}^{\infty} (1 - R_S)^n \cdot R_S = 1$$

Optical Design _ η_D and η_S

- Outcoupled light from planarization layer (η_D)
  - Thickness, absorption↓ → η_D↑
  - Major loss channel → Planarization layer absorption

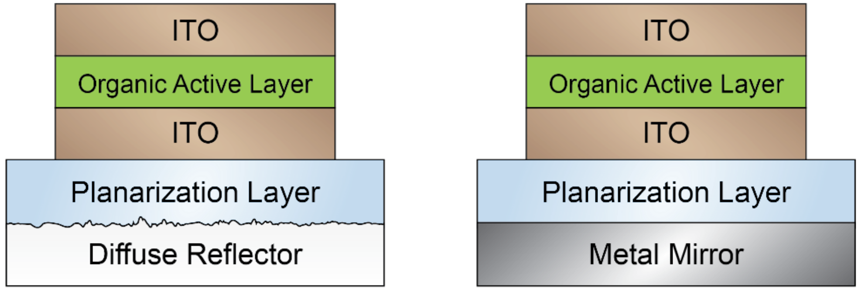


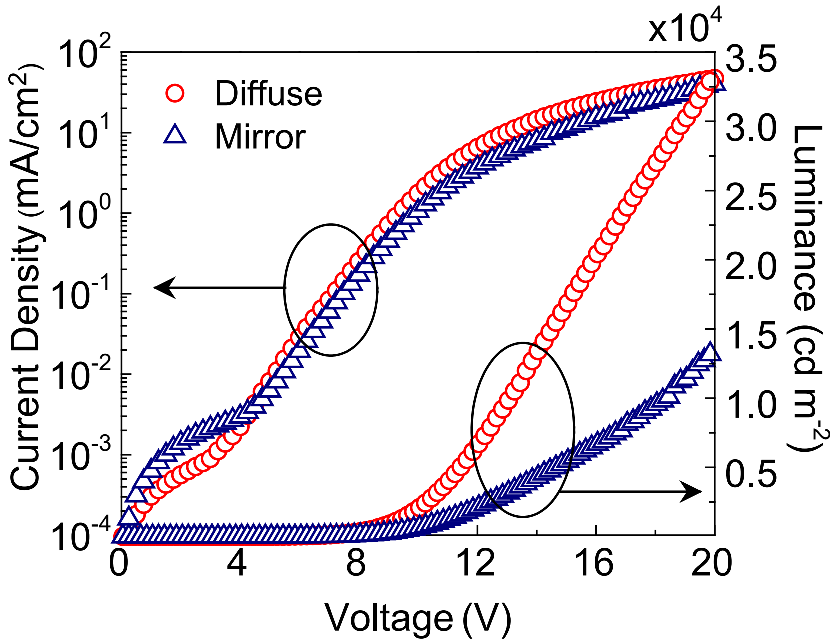
- Coupled light into the planarization layer (η_S)
  - Increase with n_P → n_P = 1.8 wg mode vanish

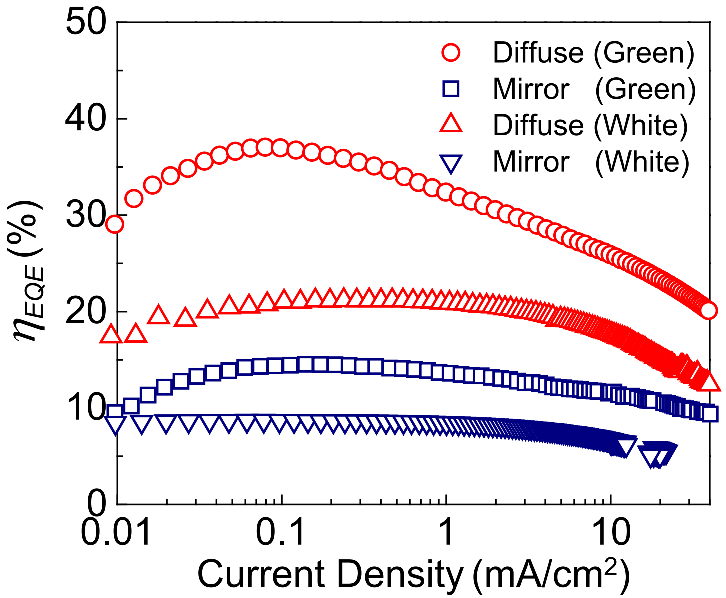


Device Performance *– Efficiency*

- **External Quantum Efficiency (EQE)**
  - Mirror 15 ± 2%
  - Diffuser 37 ± 4% (×2.5)
- **Identical *J-V***
  - No influence on device structure

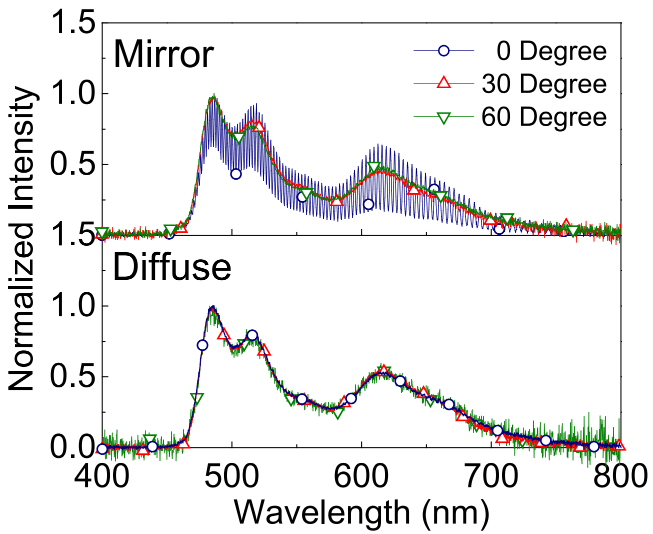


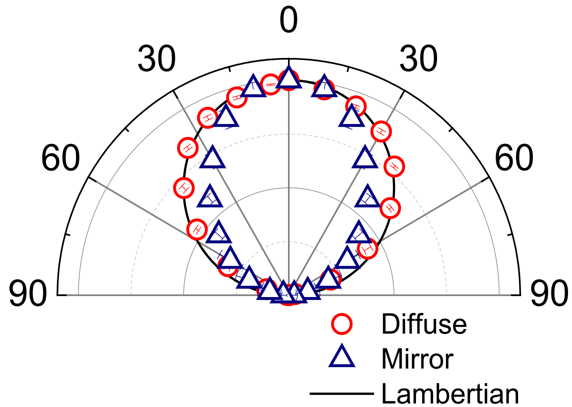


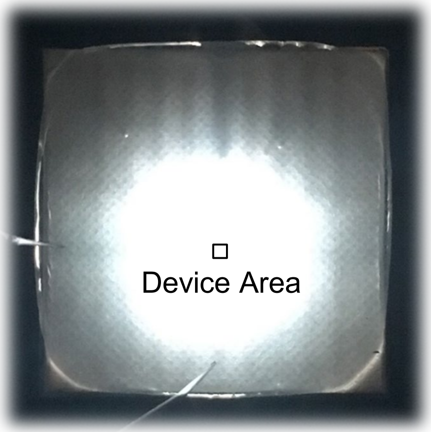


Device Performance *– White Spectrum*

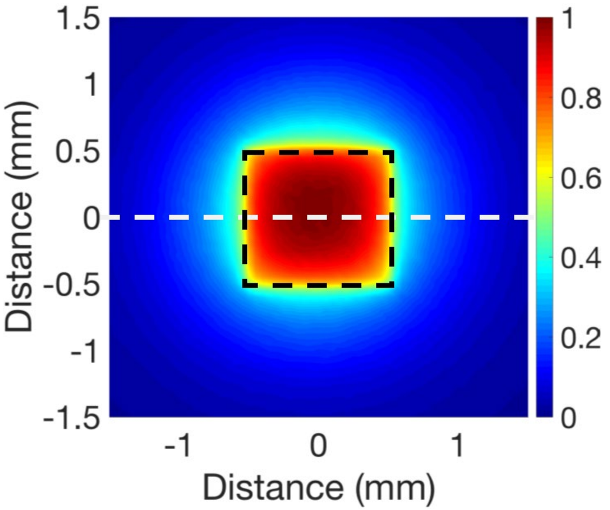
- **White OLED**
  - No spectral shift
    - Weak cavity (high index Planarization layer)
  - Lambertian output pattern
    - Scattering via diffuse reflection

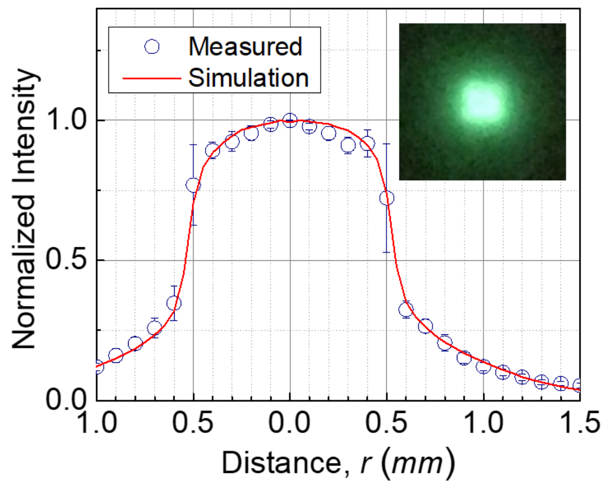


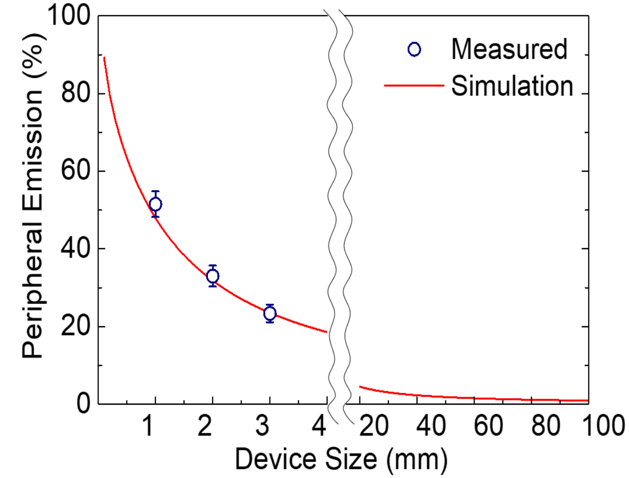




Device Analysis *– Peripheral Emission*







- Light emitted outside the defined active area : Peripheral Emission
- Device area ↑ → peripheral emission ↓
- Planar. layer thickness ↓ → peripheral emission ↓, EQE ↑ (68%, ×3.4 @50um)

Conclusion

- **Outcoupling methods of following features were demonstrated**
  - ✓ Highly efficient
  - ✓ Low-cost
  - ✓ Scalable
  - ✓ Wavelength/viewing angle-independent
  - ✓ No spectrum shift
  - ✓ Non-intrusive into the device structure

- Same enhancement factors for white and monochromatic devices
- No impact on image sharpness (SEMLA)
- No need of external outcoupling, Simple fabrication (Diffuser)

Reference

Y. Qu, J. Kim, C. Coburn and S. R. Forrest, *ACS Photonics* 5, 6, 2453–2458 (2018)
J. Kim, Y. Qu, C. Coburn and S. R. Forrest, *ACS Photonics* 5, 8, 3315–3321 (2018)

Acknowledgements

UNIVERSAL DISPLAY
CORPORATION™

- **Optoelectronic Components and Materials Group (UM)**
  - Xiaheng Huang
  - Jongchan Kim
  - Yue Qu
  - Caleb Coburn
- **Department of Energy**
- **Universal Display Corp.**

Thank You

University of Michigan
Stephen R. Forrest, Professor / Principal Investigator
Tel: (734) 647-1147   email: stevefor@umich.edu