No Photon Left Behind: Challenges in OLED Outcoupling

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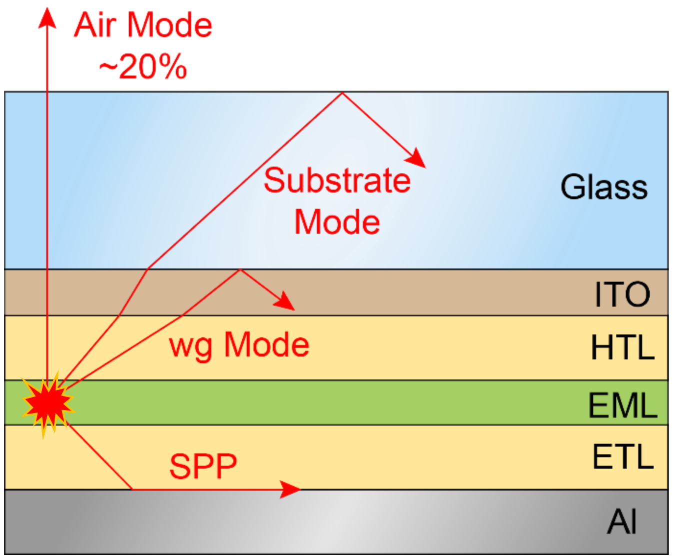
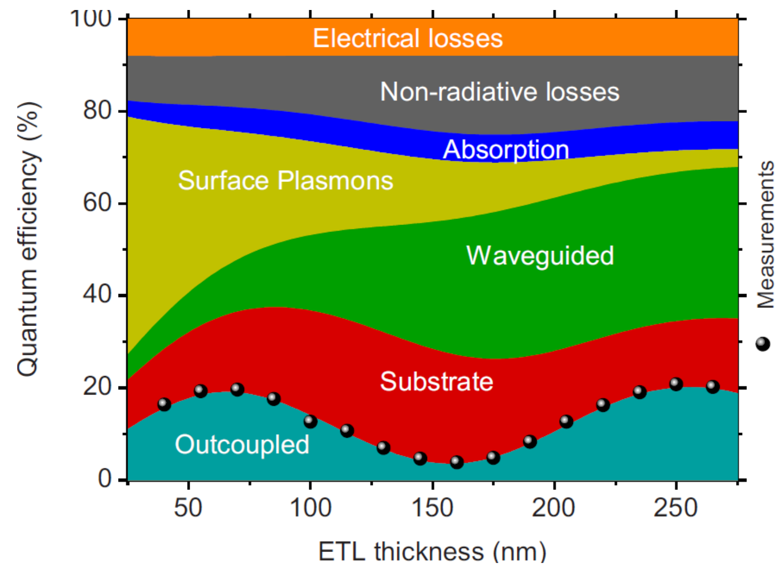
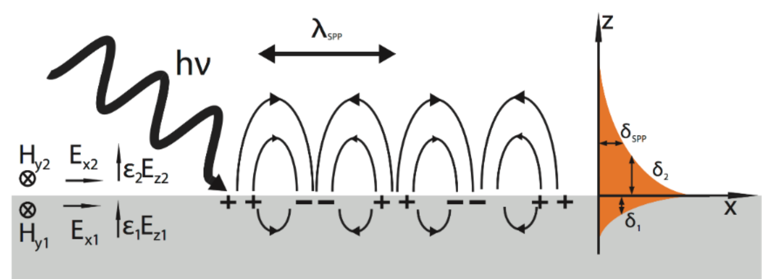
80% of Light is Trapped in the OLED

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



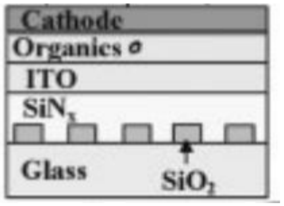


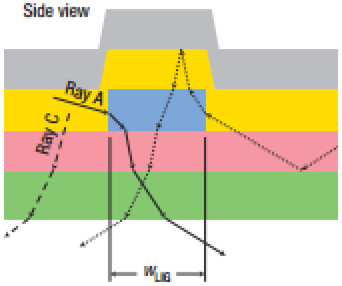


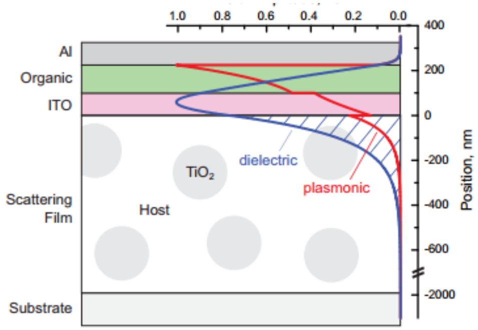
- OLED Loss Channels
  - ➢ Substrate mode
  - ➢ Waveguide mode
  - ➢ **Surface plasmon polariton (SPP)**
  - ➢ **Metal absorption**

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







[1]Y .R. Do, et al, *Adv. Mater*. **15**, 1214 (2003).
[2]Y. Sun and S.R. Forrest, *Nat Phot*. **2**, 483 (2008).
[3]Chang, H.-W. *et al*. *J. Appl. Phys.* **113,** - (2013).

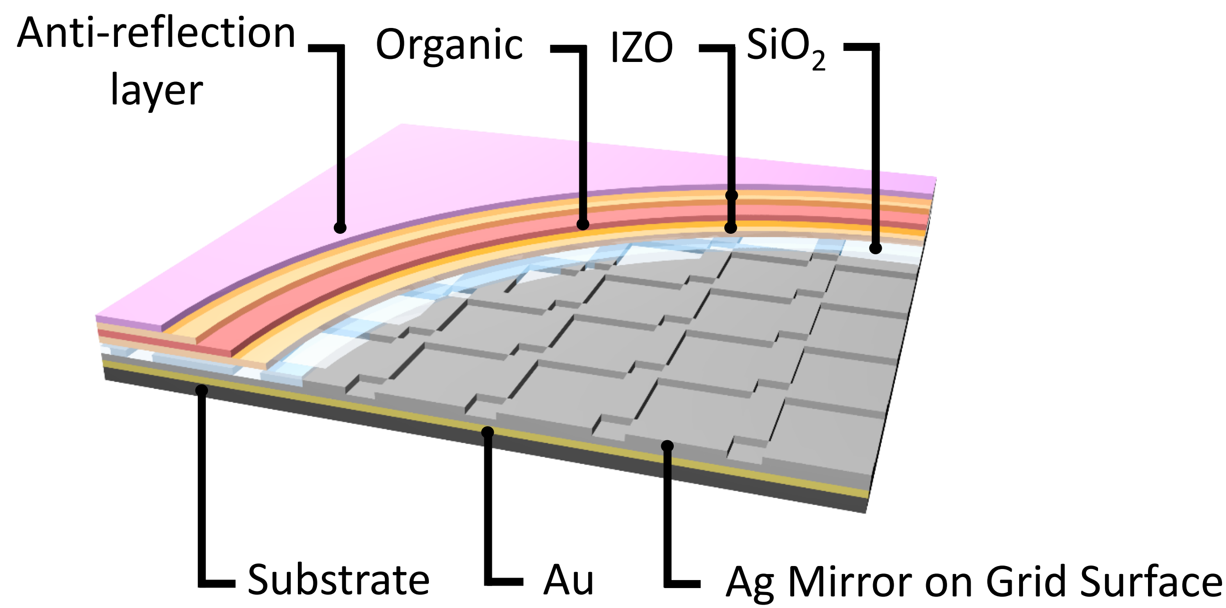
Three solutions explored in SSL

- Sub electrode grids and microlens arrays
  - Harvests most available photons
- Dielectric diffuser
  - Efficient and simple
- Ultrathin, roughened substrates
  - Good for flexible, too.

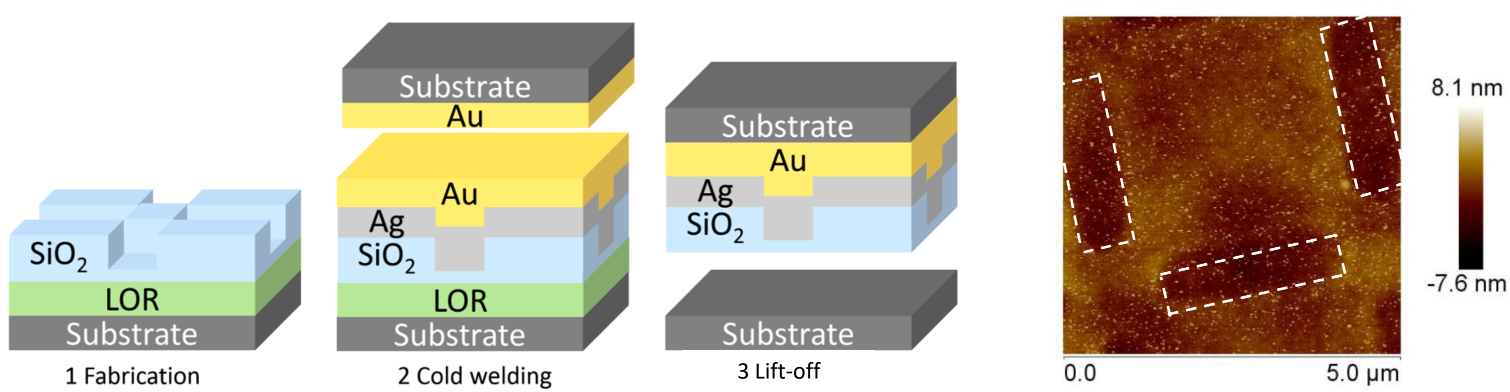
Getting Rid of SPPs Using Sub-Anode Grid + Mirror

Qu, et al. ACS Photonics, 2017

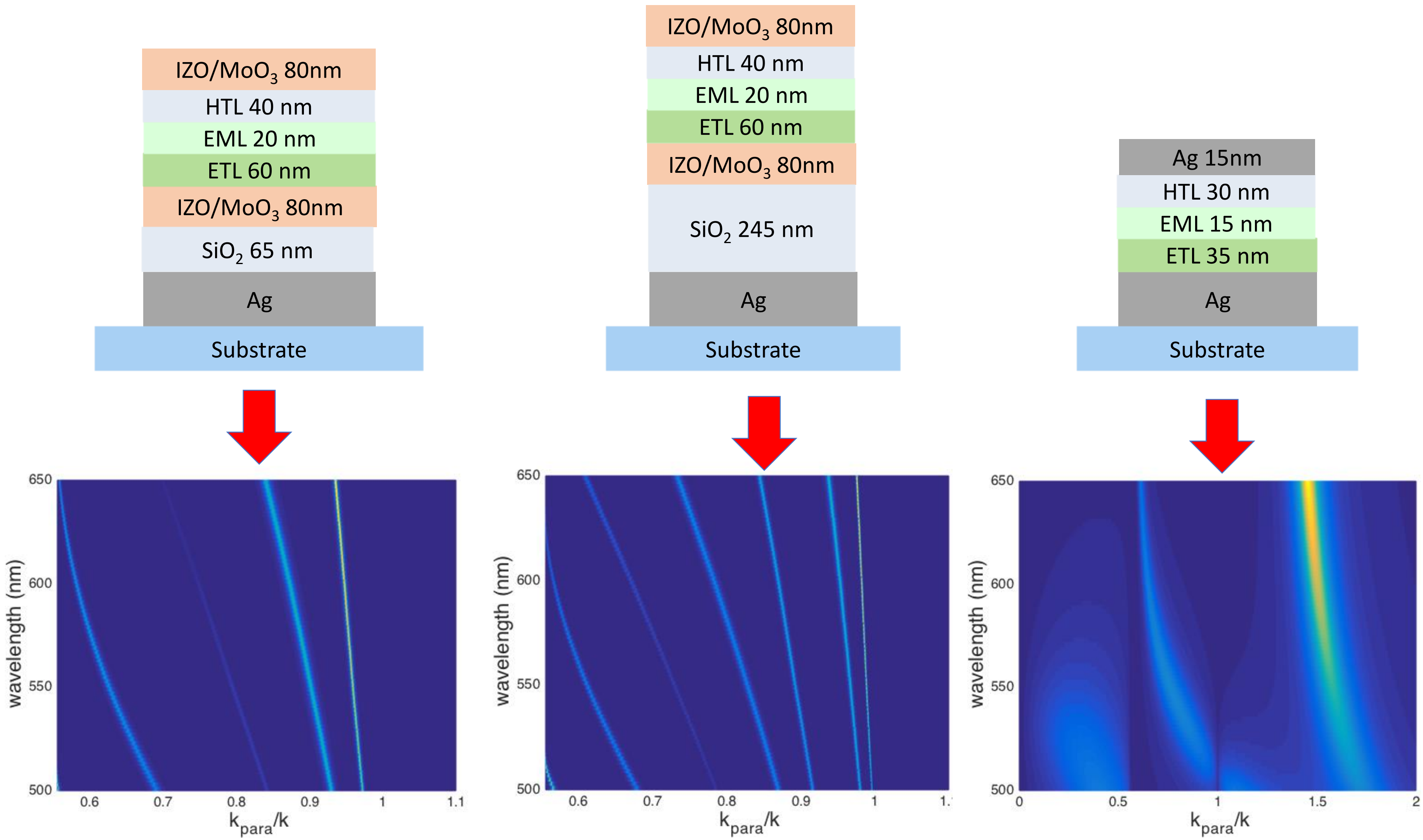
Top Emitting OLED



Substrate Fabrication

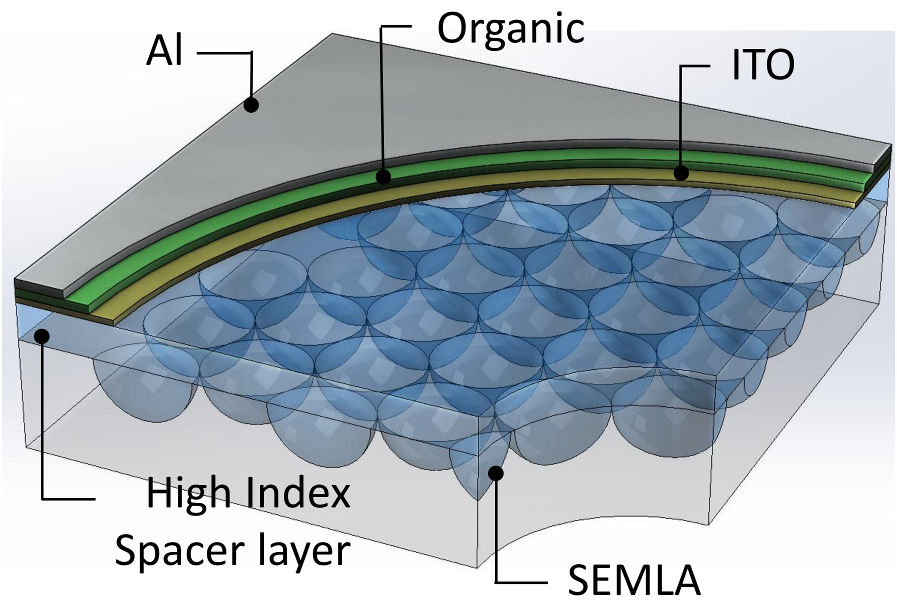


Sub-electrode grid modeling



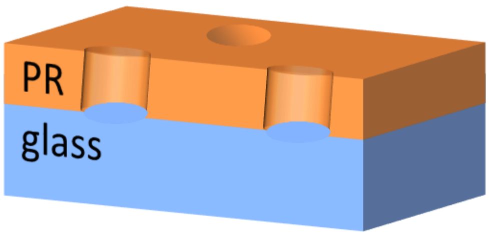
Variable Waveguide Widths Prevent Mode Propagation

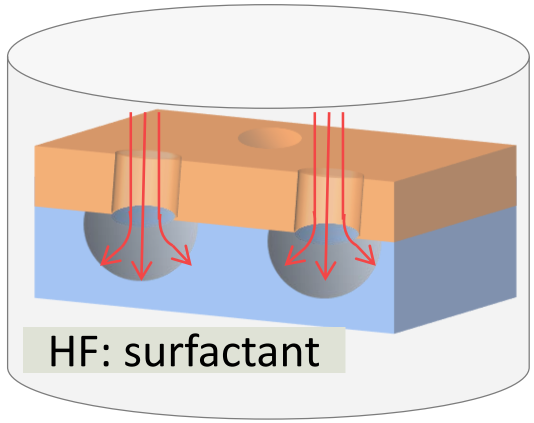
Getting All the Light Out: Sub-Electrode Microlens Array (SEMLA)

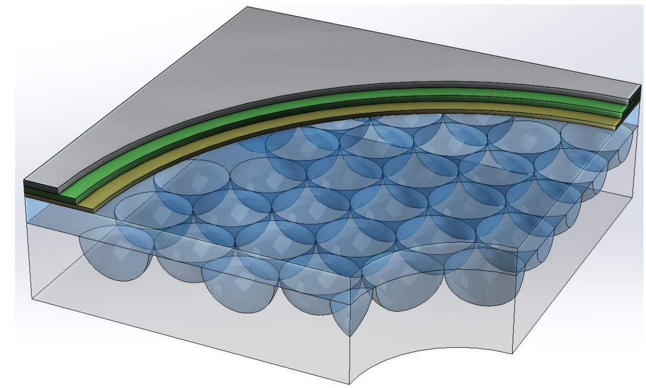


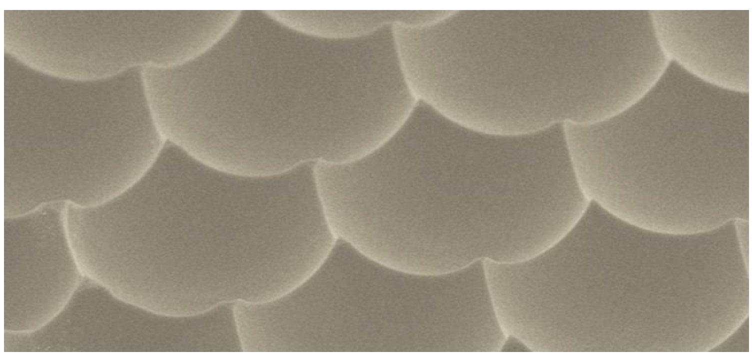
- Micron-scale lens array between the bottom electrode and the glass substrate
- Flat spacer layer
- High refractive index
- Microlens array imbedded into glass

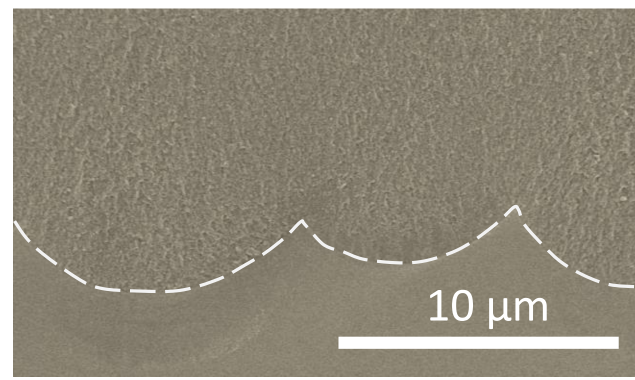
SEMLA Fabrication





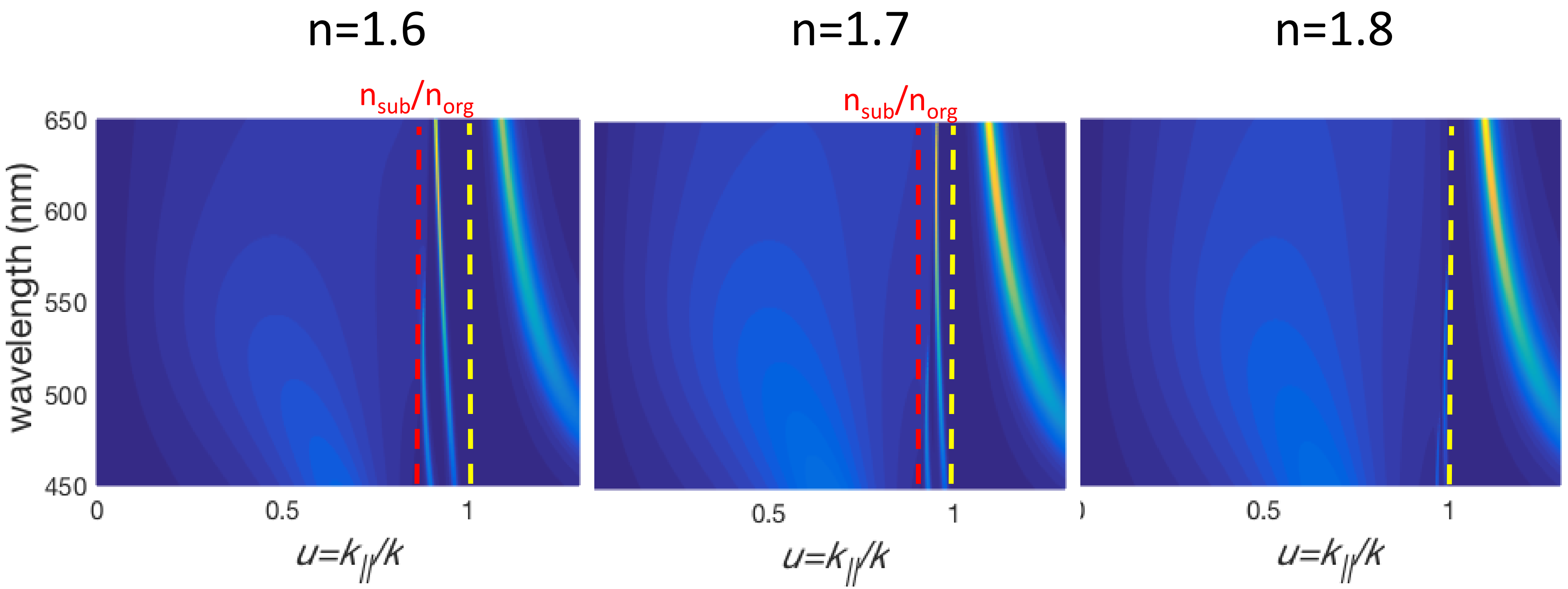






Photoresist 0.8 µm openings with a 10 µm pitch

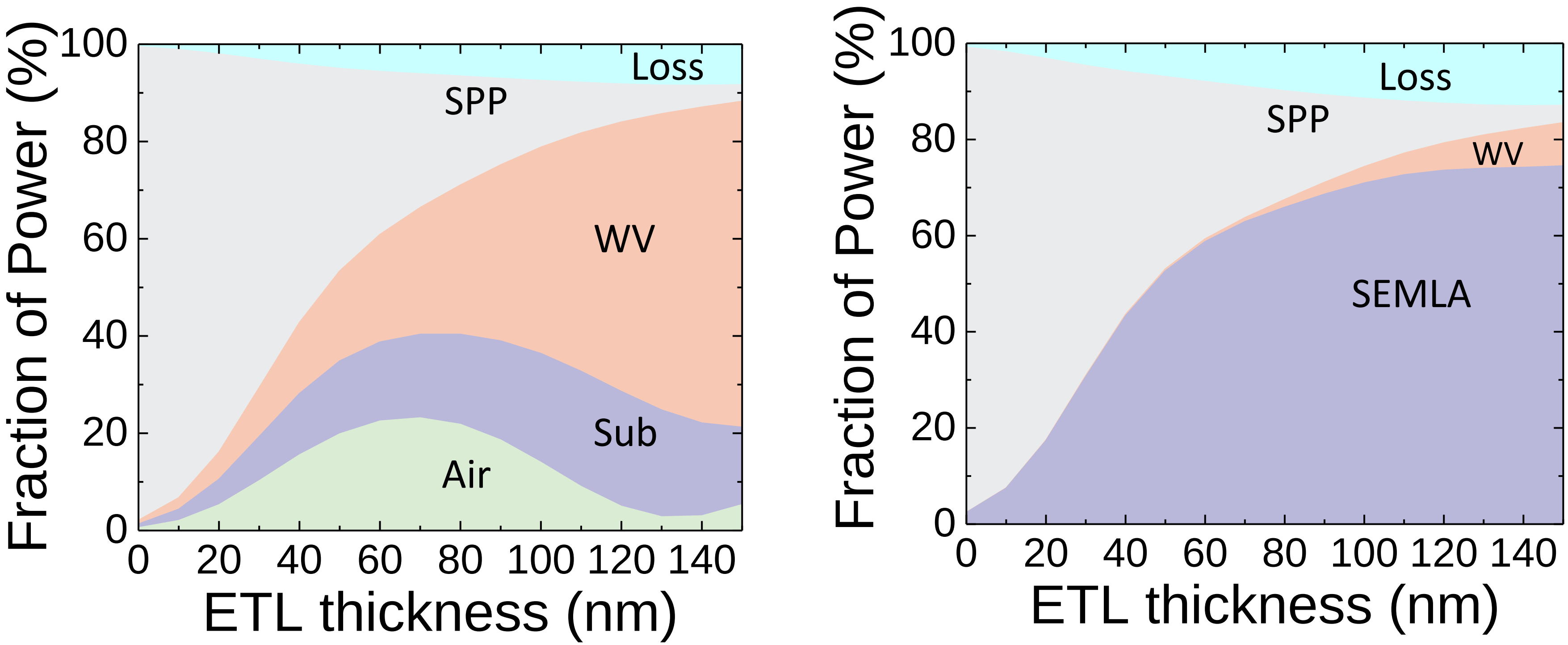
Refractive Index of SEMLA



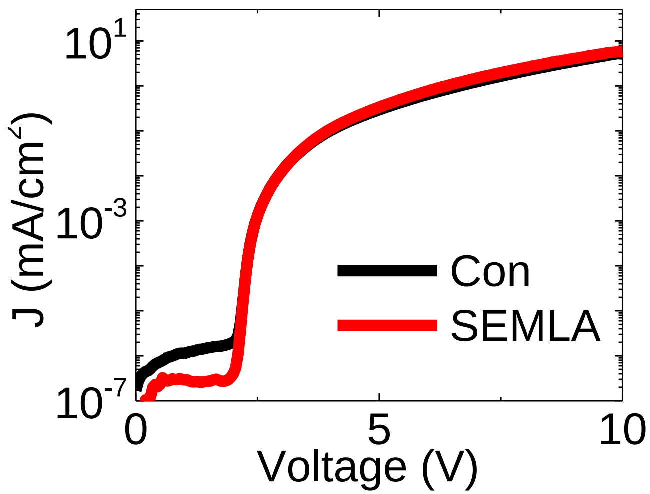
As n_{sub}/n_{org} goes up, more waveguided light is squeezed out

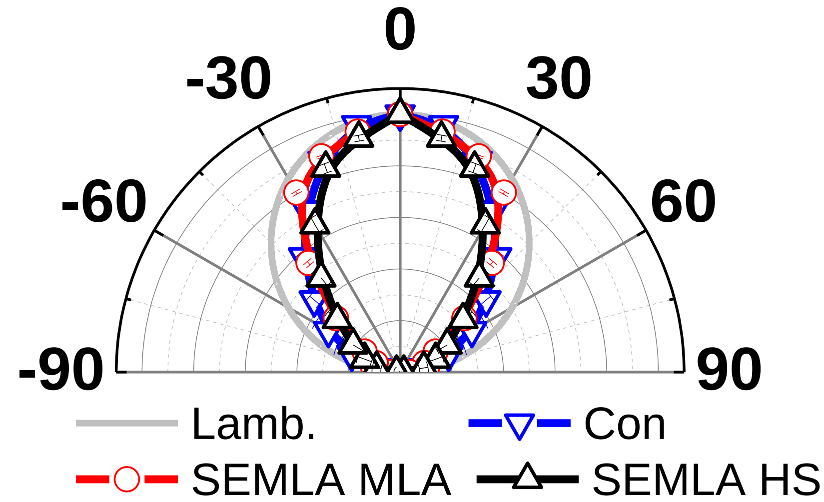
Structure: 70nm ITO/ 40nm TAPC/ 20nm CBP/ 65nm Bphen/Al

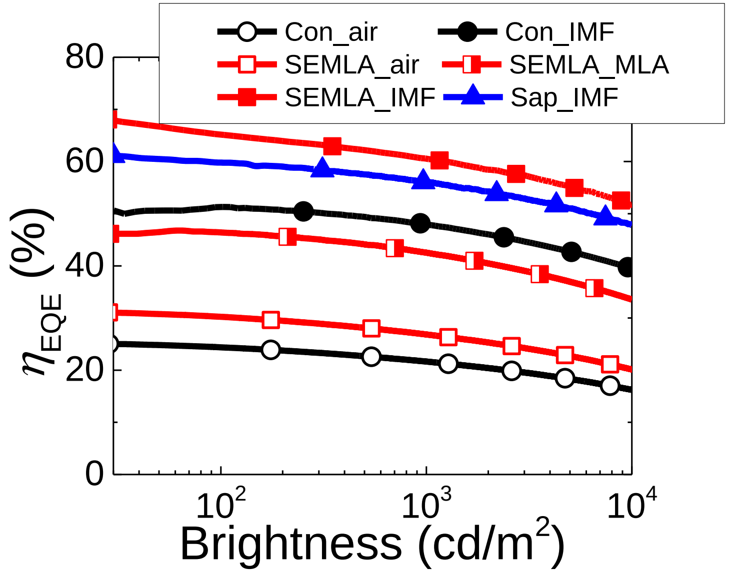
SEMLAs Change the Outcoupling Landscape

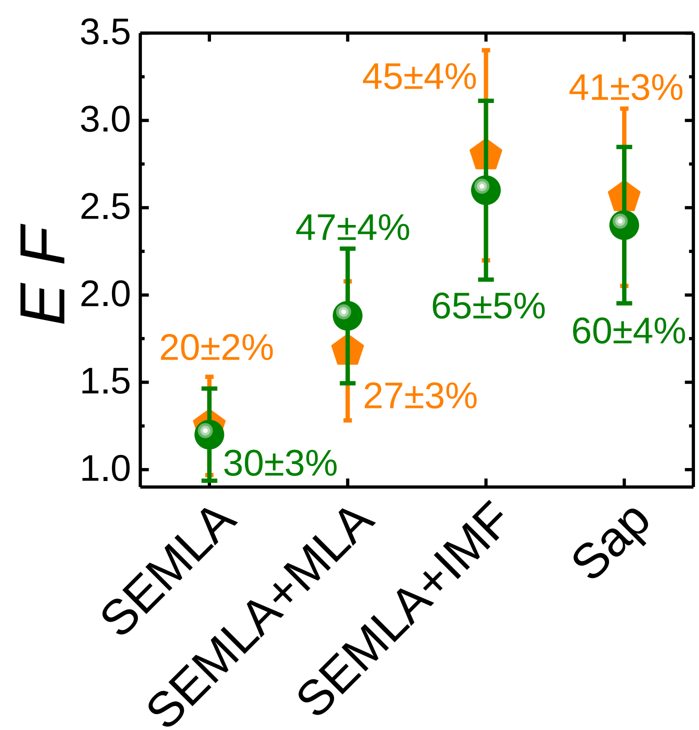


SEMLA Performance



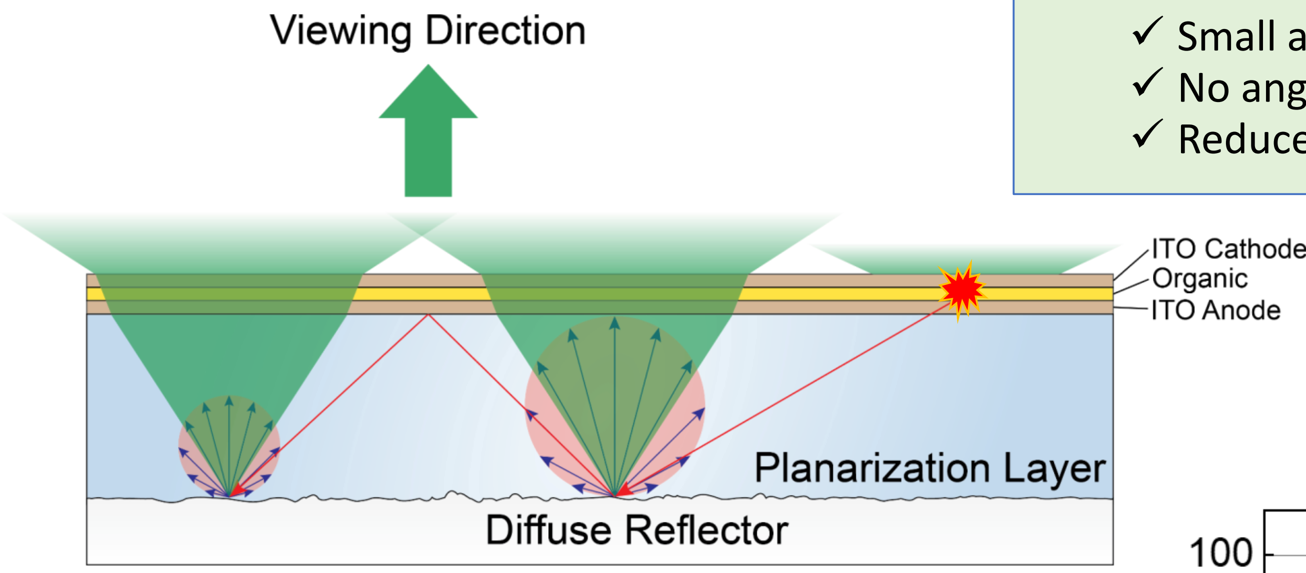


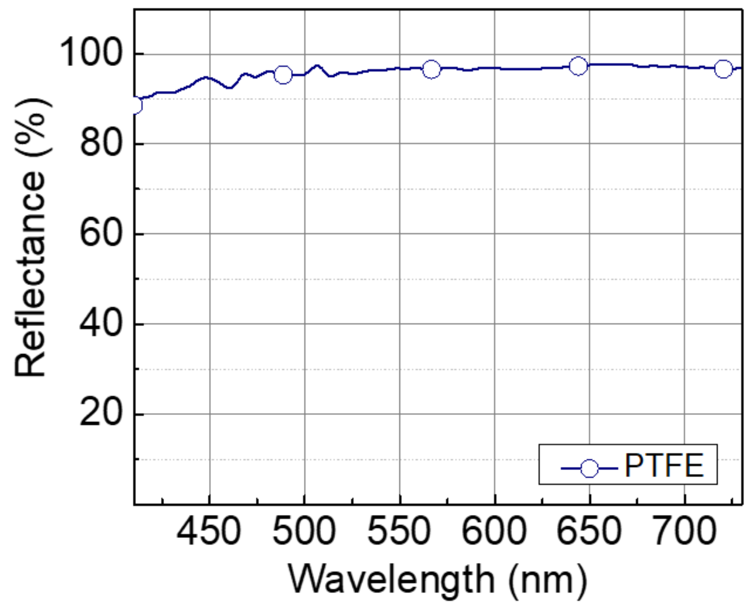




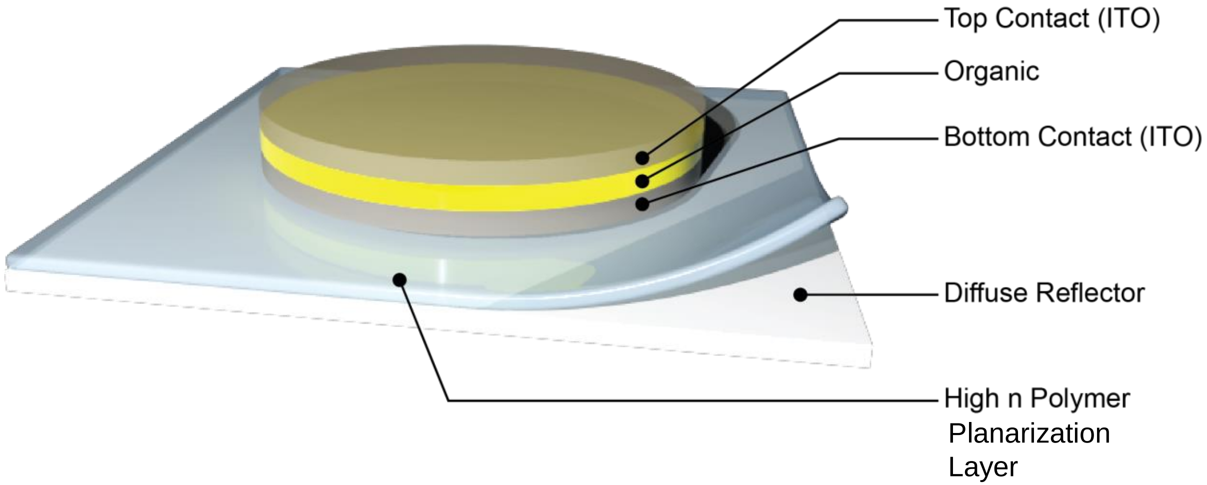
Diffuse Reflectors: Low Cost & Simple

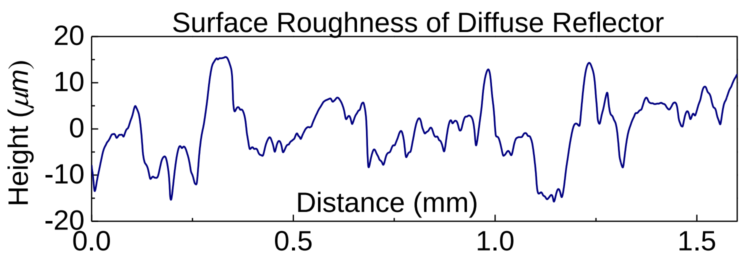
- Dielectric diffusive reflector
  - ✓ No SPP
  - ✓ Small absorption (Reflectance ~98%)
  - ✓ No angle dependence
  - ✓ Reduced w/g mode

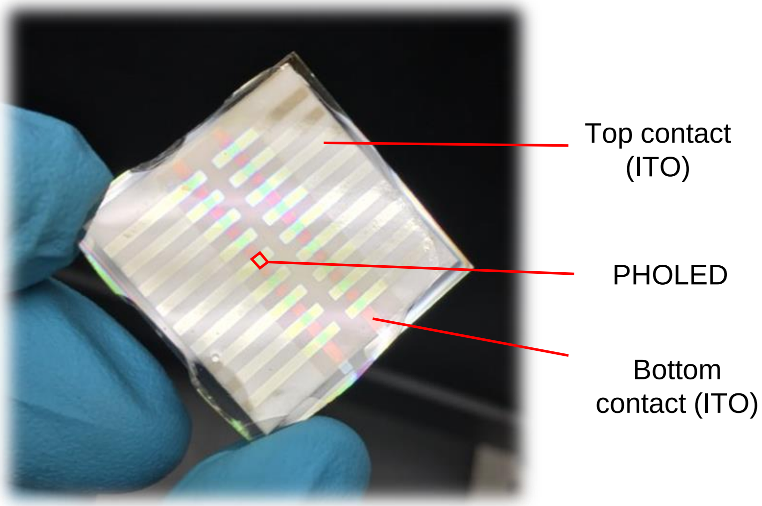




Device Structure

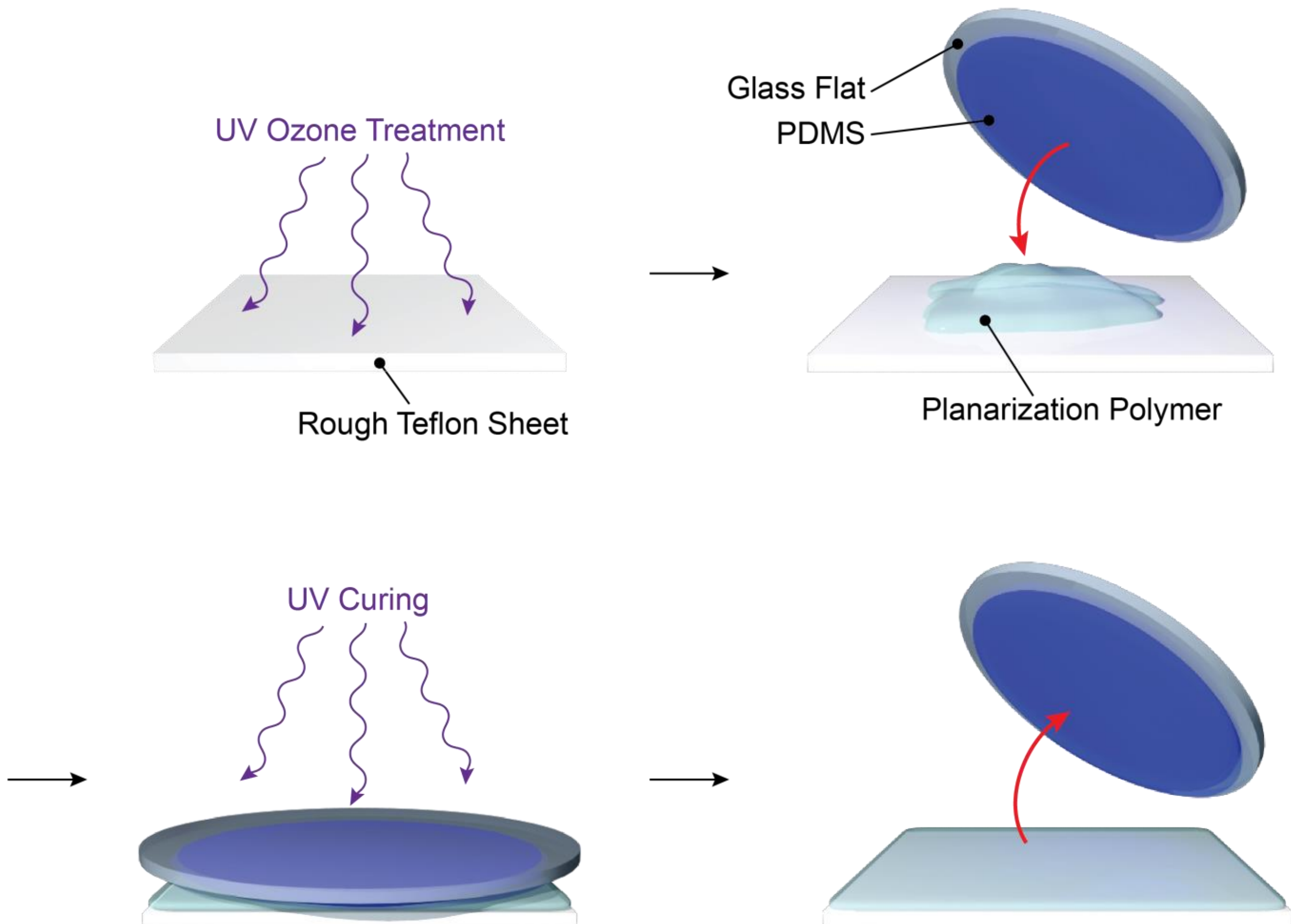






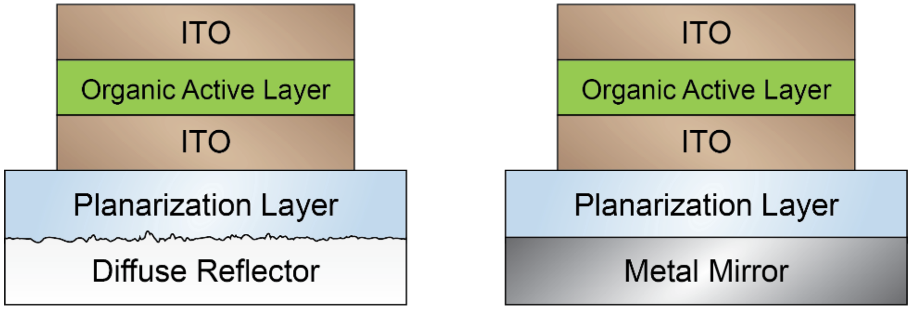
OLED grown on the substrate

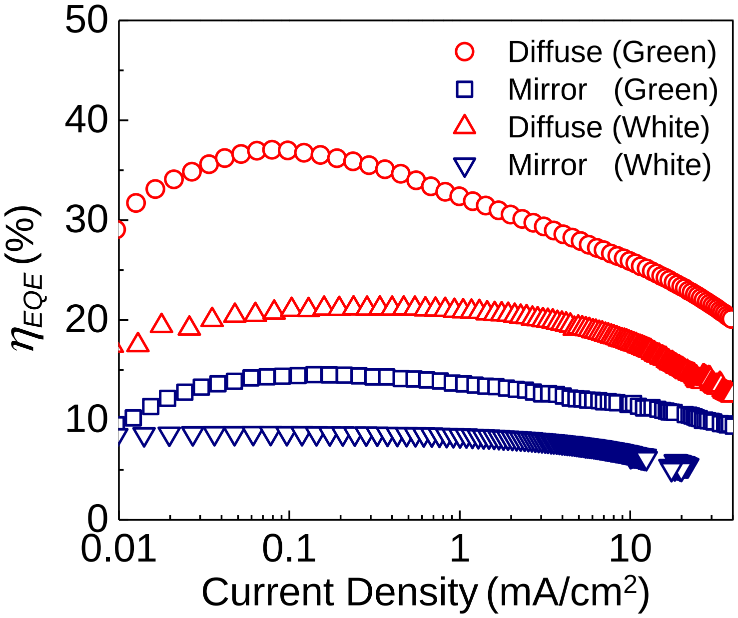
Fabrication Sequence

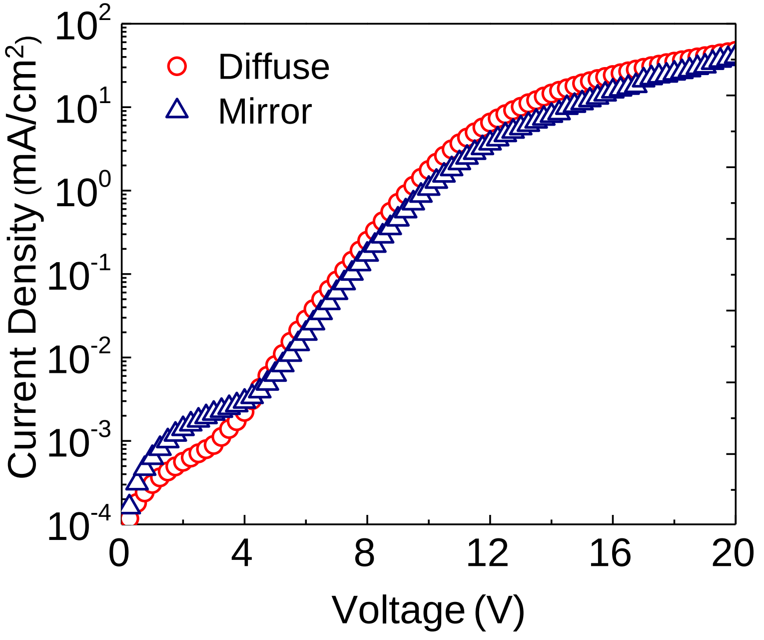


Device Performance – Efficiency

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

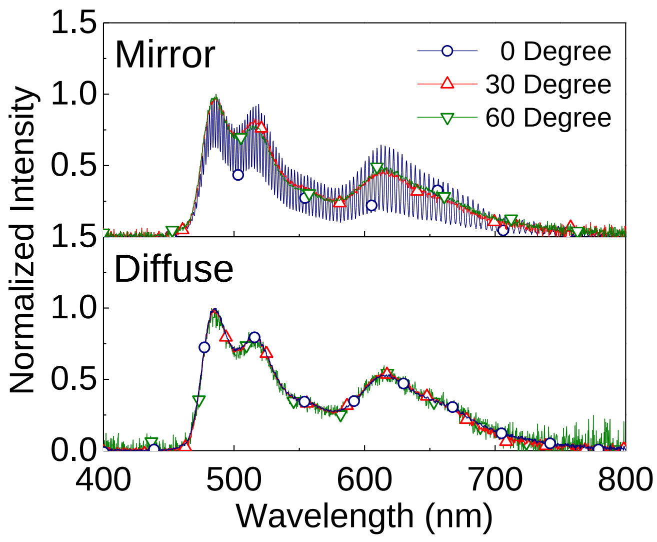


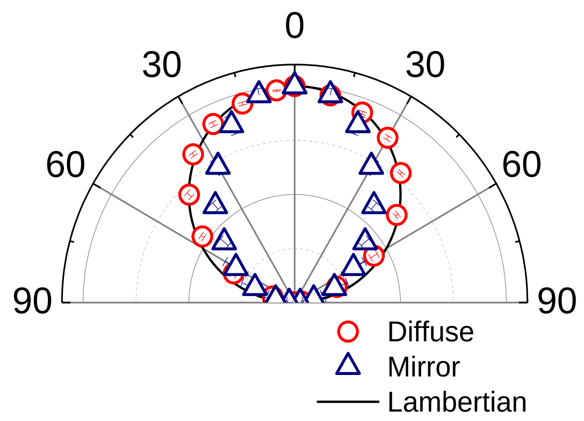


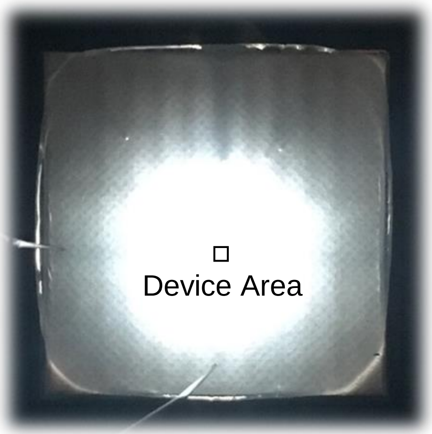


Device Performance – White Spectrum

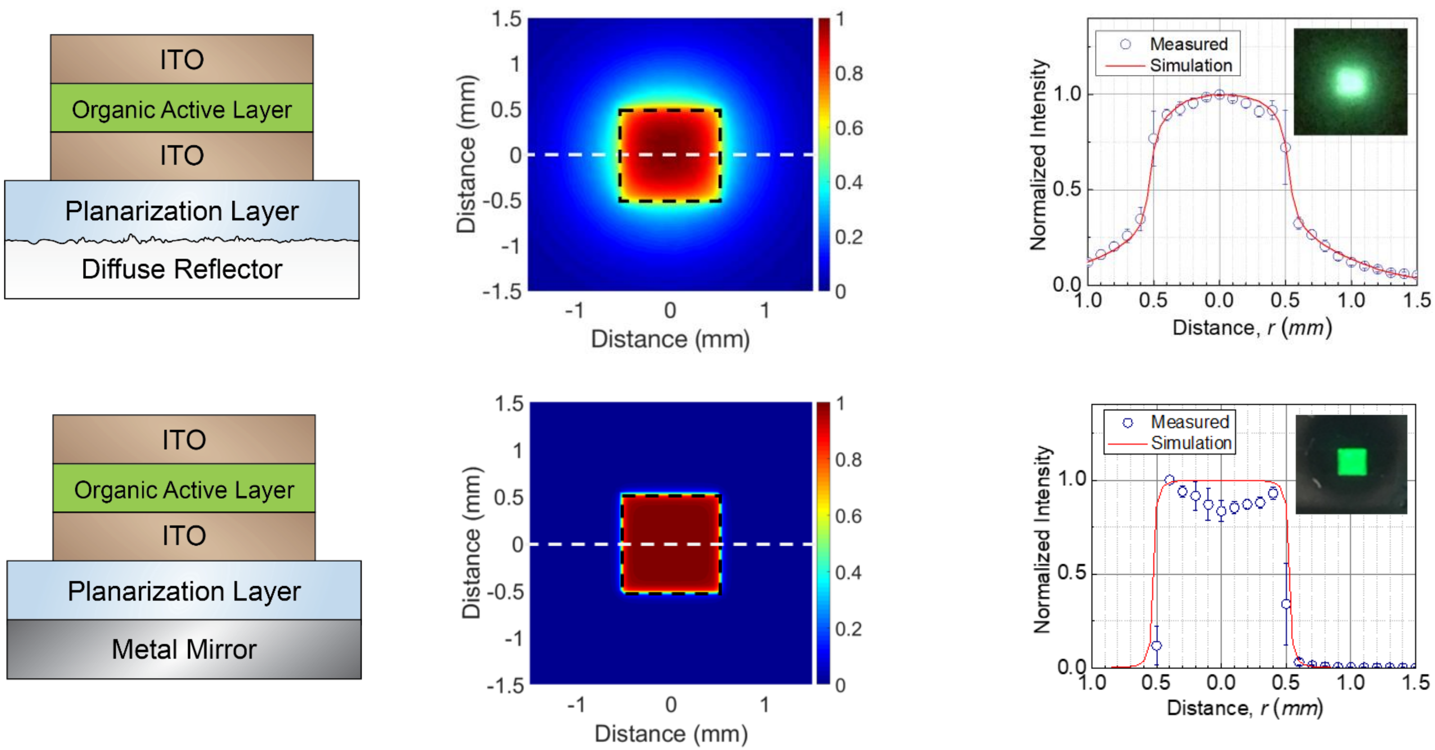
- White OLED
  - ➢ No spectrum shift
    - ✓ Weak optical micro-cavity by high-index planarization layer
  - ➢ Lambertian light source
    - ✓ Scattering via diffuse reflection



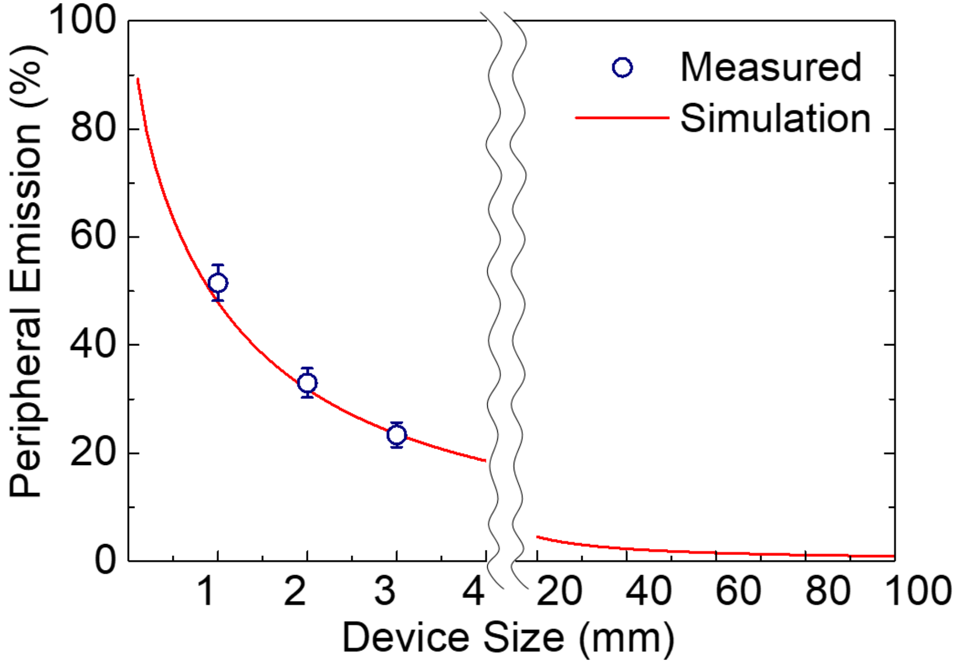




Device Analysis(I) *– Peripheral Emission*



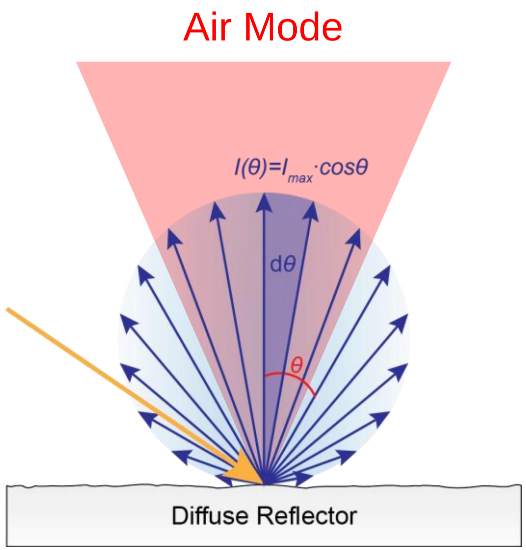
Device Analysis_ *Peripheral Emission*

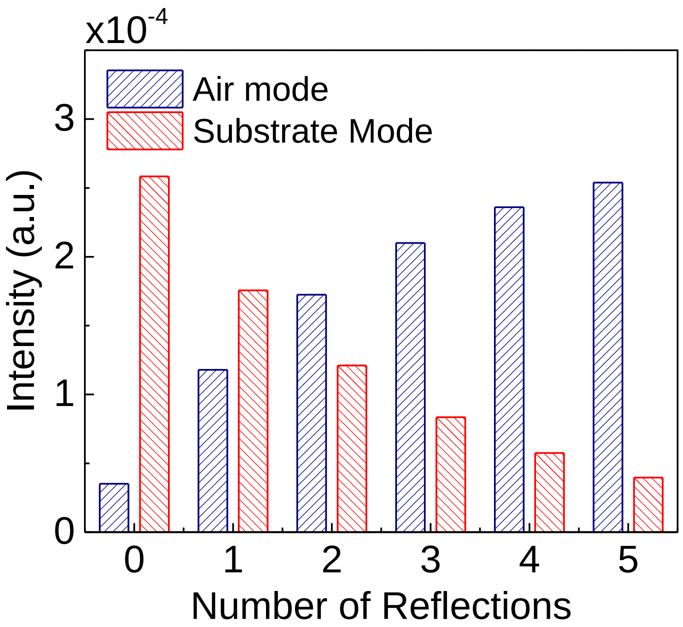


- Light emitted outside the defined active area : Peripheral Emission
- Device area ↑ → peripheral emission ↓
- Planar. layer thickness ↓ → peripheral emission ↓, EQE ↑ (68%, ×3.4 @50um)

Device Analysis_ *Number of Reflections*

- Diffuse reflection
  - Redirect light uniformly
  - R_S = 30% → air mode
  - 5 scattering → ~80% escape





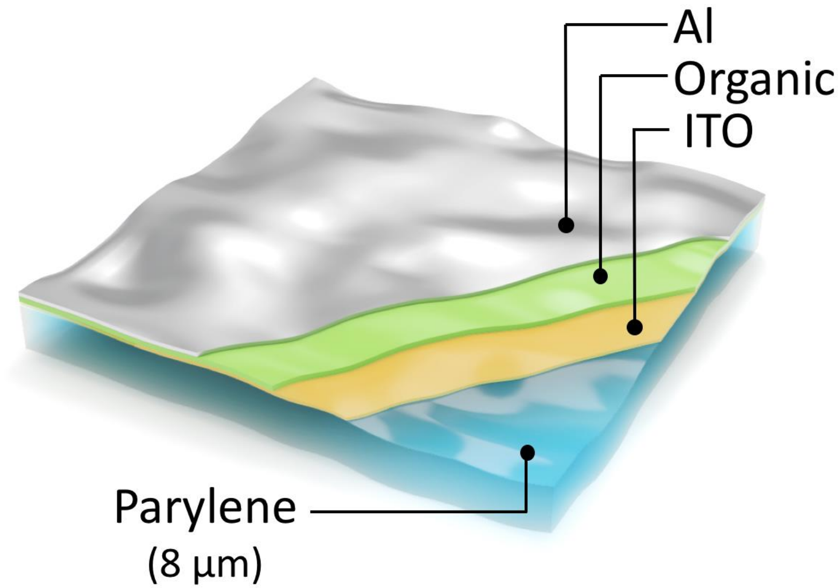
$$\eta_{out} = \eta_{TA} + \eta_D \eta_S$$

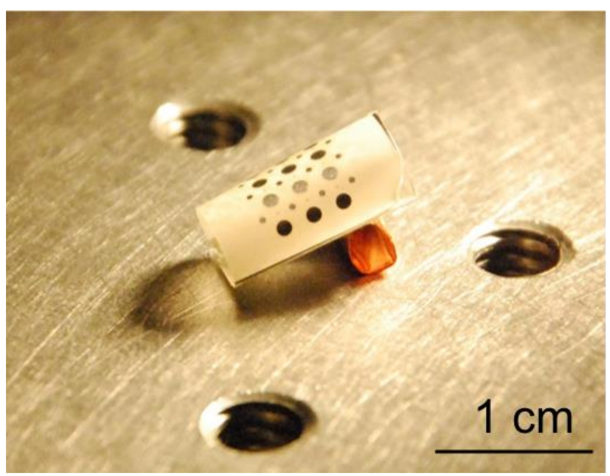
η_{TA} : Light power fraction to top surface

η_D : Planarization layer efficiency

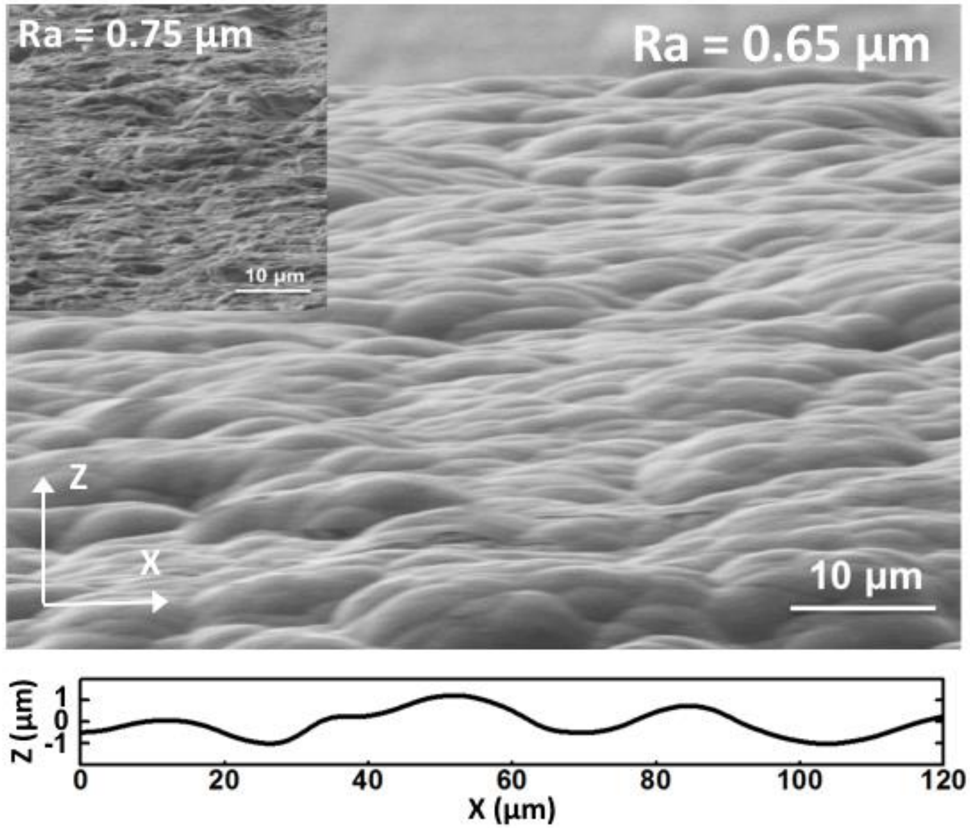
η_S : Light power fraction into planarization layer

Ultrathin, Ultra-flexible OLEDs With High Outcoupling

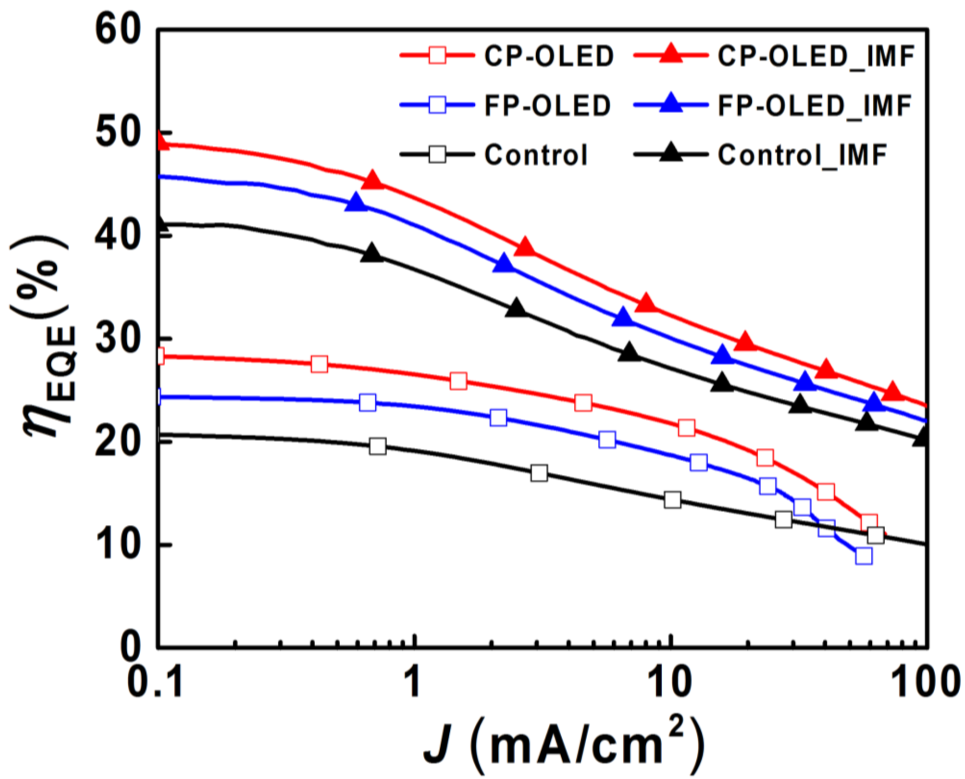


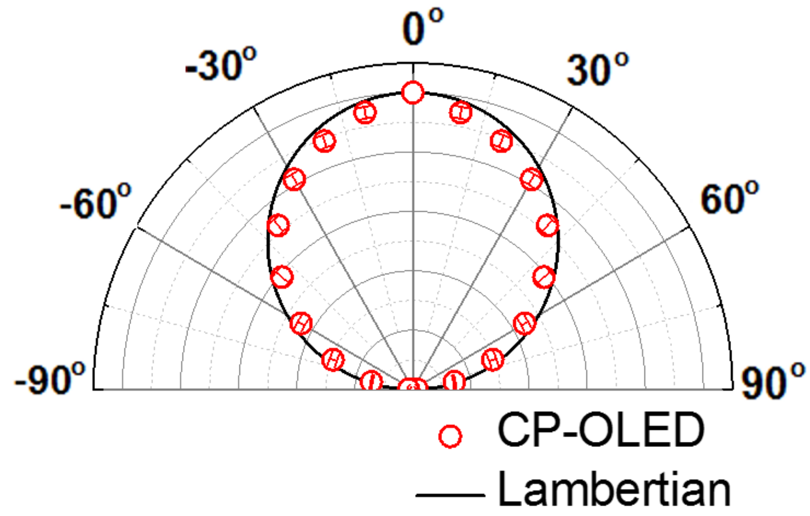


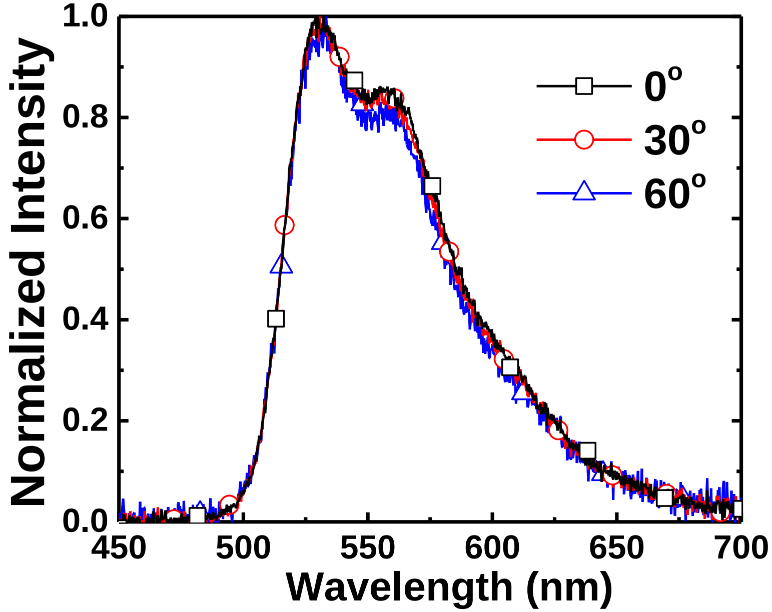
Corrugations by Deposition on Rough Sapphire



Ultrathin, Ultra-Flexible OLED Performance





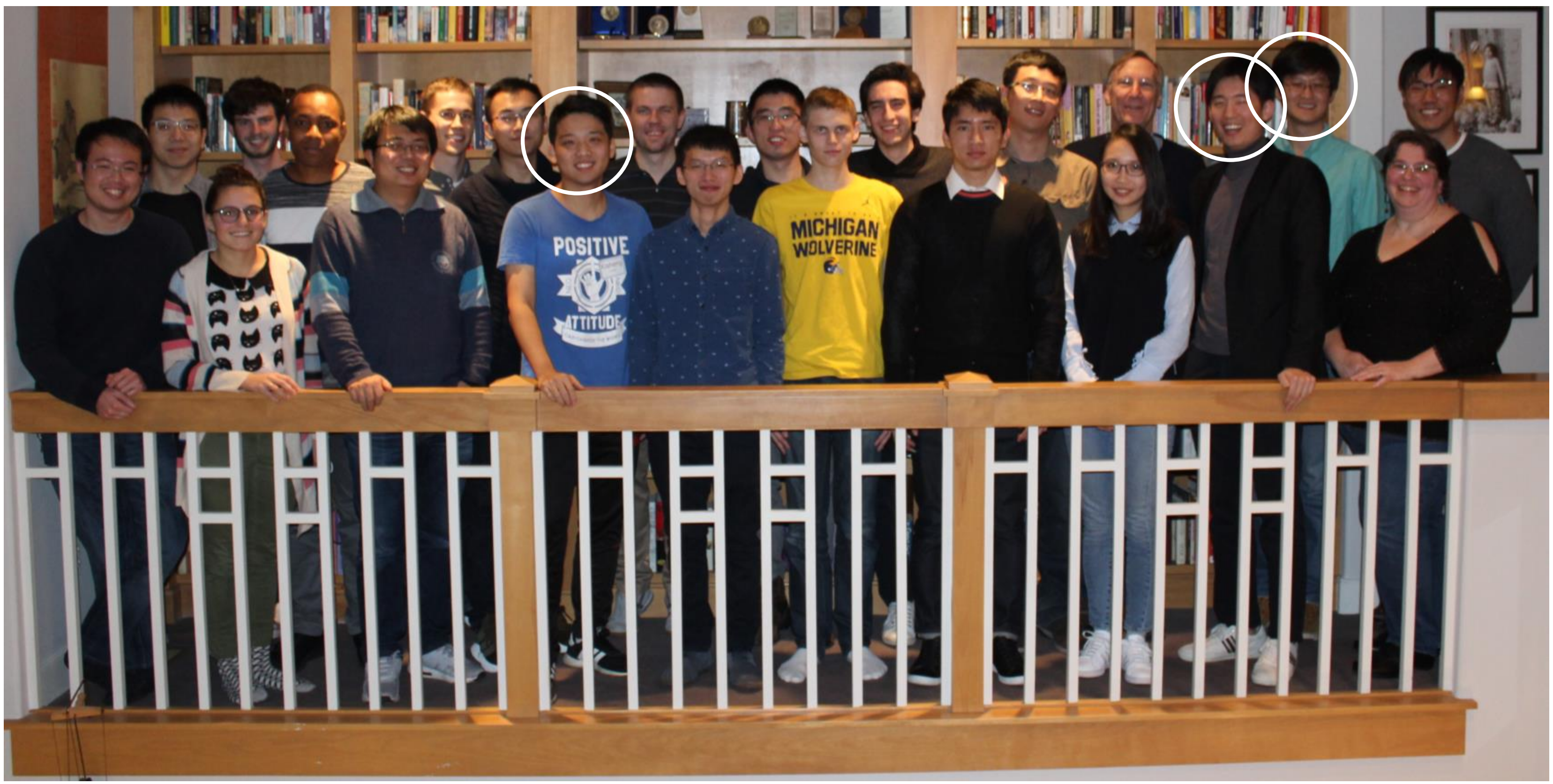


Conclusions

- 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%

Acknowledgements

- Optoelectronic Components and Materials Group @ UM
  - Jonchang Kim
  - Yue Qu
  - Xiaheng Huang



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