Challenges in Achieving Low Cost, Spectrally Broad OLED Outcoupling

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OLEDs: Major Remaining Challenges for Lighting

- **Getting the Light Out**
- Blue PHOLED Lifetime
- Cost & Yield
  - Patterning & Deposition
  - Throughput

80% of Light is Trapped in the OLED

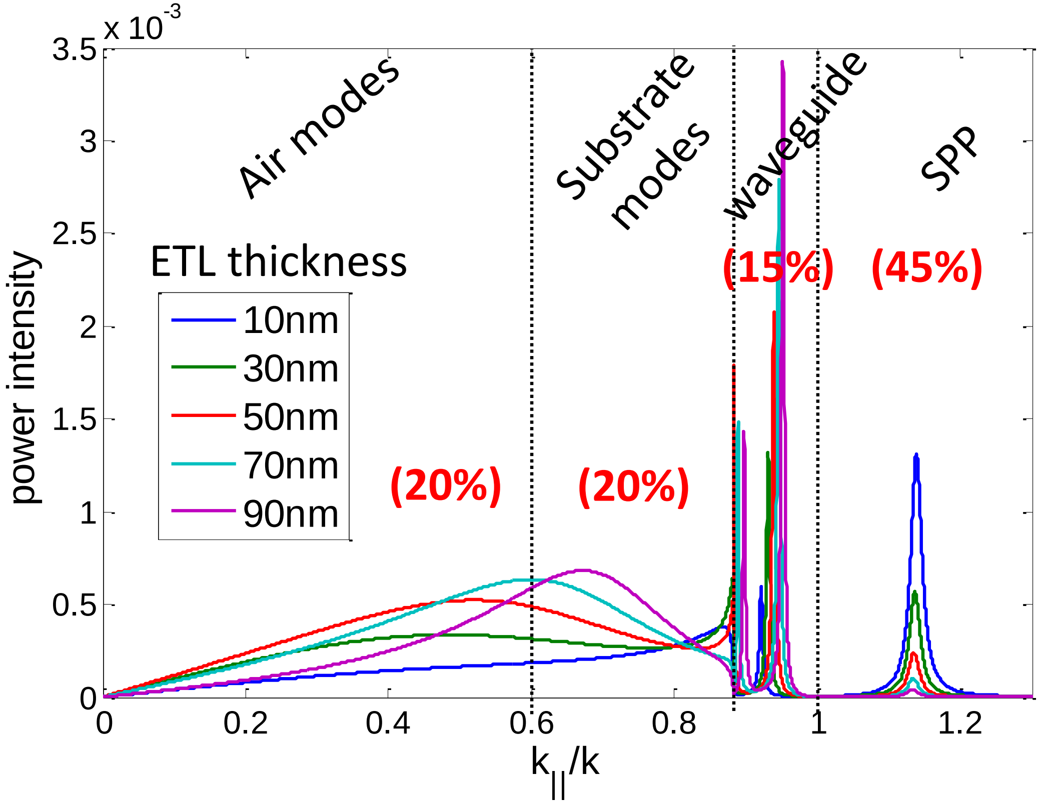
- $\eta_{EQE} = \eta_{IQE}\,(\sim 100\%) \times \eta_{Ext} \approx 20\%$

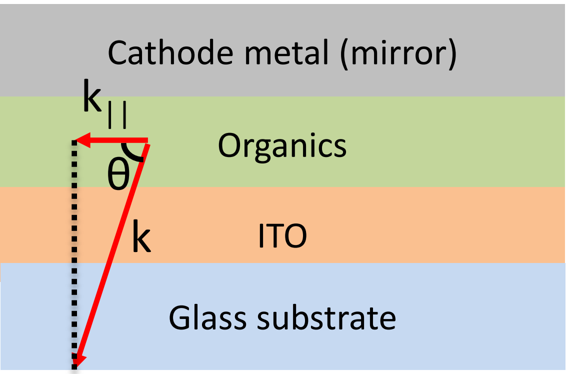
  - Total internal reflection at the air substrate interface — ***substrate modes***

  - Higher refractive indices of organic materials and ITO – ***waveguide modes***

  - Organic metal interface –***surface plasmon modes***

Where do all the photons go?

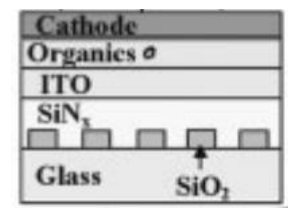


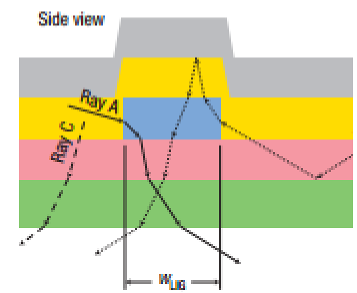


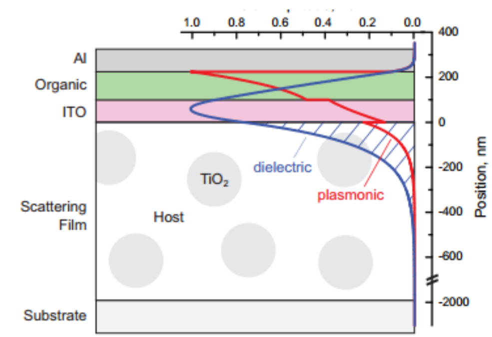
- **Air modes**: EQE first increases, then decreases with ETL thickness
- **Waveguide modes**: Only one waveguide mode TE_0 due to thin ETL (<30nm). TM_0 appears when >50nm.
- **Surface plasmon polariton modes:** Reduced with ETL thickness
- Both waveguide and SPP modes are quantized
- Total energy is the integral of Power Intensity • cos(θ), so SPP not as small as it looks

Getting all the photons out

- **Good solutions**
  - Inexpensive
  - Viewing angle independent
  - Independent of OLED structure
- **Among those things that have been tried**
  - Optical gratings or photonic crystals[1]
  - Corrugations or grids embedded in OLED[2]
  - Nano-scale scattering centers[3]
  - Dipole orientation management



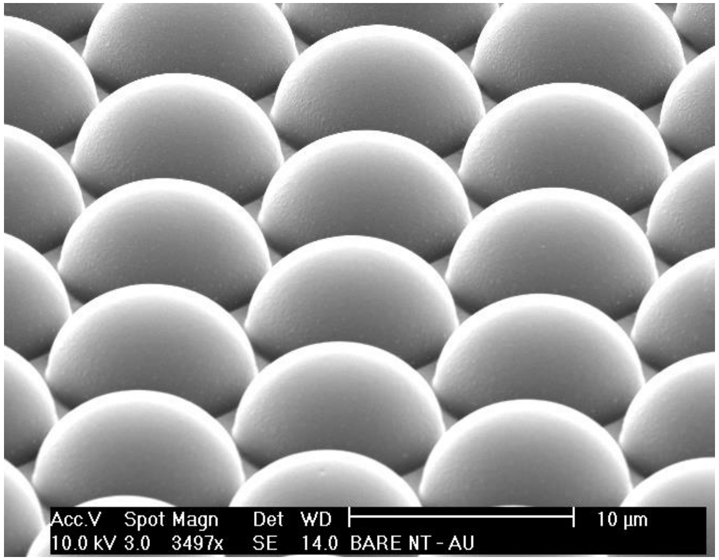




[1]Y .R. Do, et al, *Adv. Mater*. **15**, 1214 (2003).
[2]Y. Sun and S.R. Forrest, *Nat Phot*. **2**, 483 (2008).
[3]Chang, H.-W. *et al*. *J. Appl. Phys.* **113,** - (2013).

Substrate Modes: ~2X Improvement

η_{ext}~40%



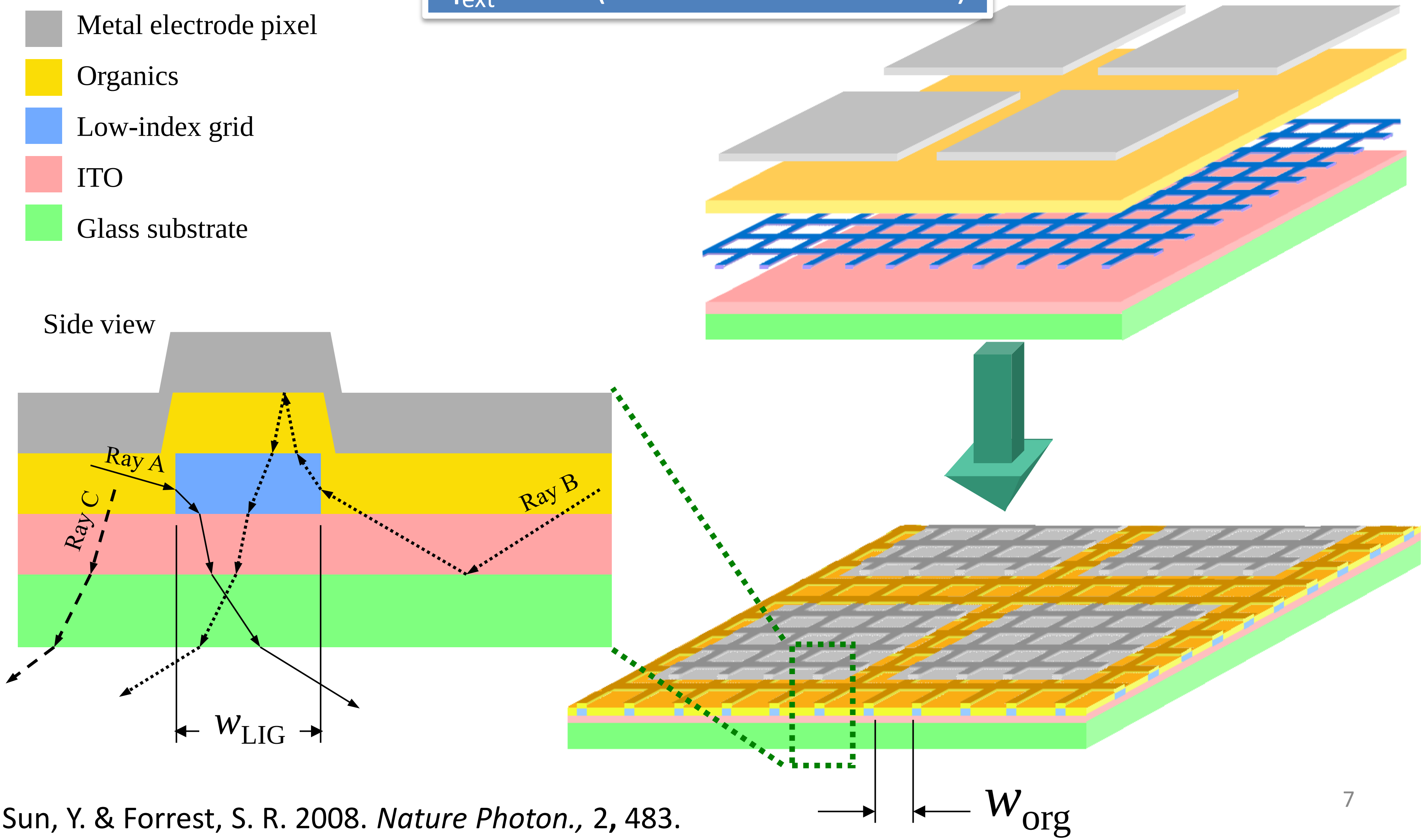
Microlens arrays
- Polymer hemispheres
- Much smaller than pixel

Möller, S. & Forrest, S. R. 2001. *J. Appl. Phys.,* 91**,** 3324.

Several adequate solutions exist today

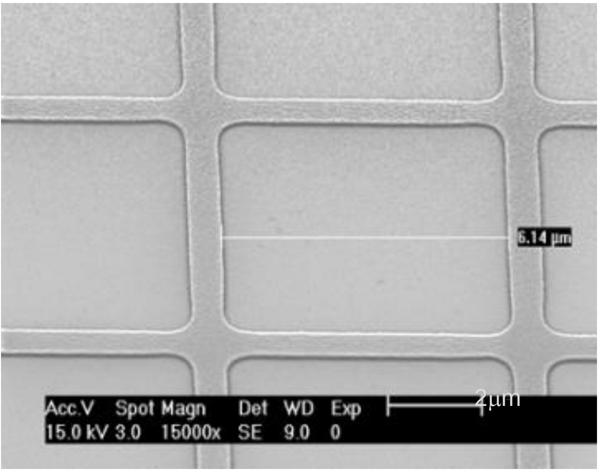
Waveguide Modes
Embedded Low Index Grid

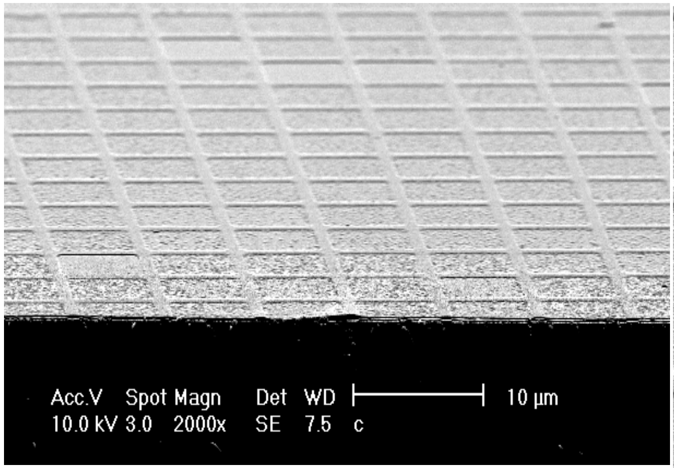
η_{ext}~60% (incl. substrate modes)

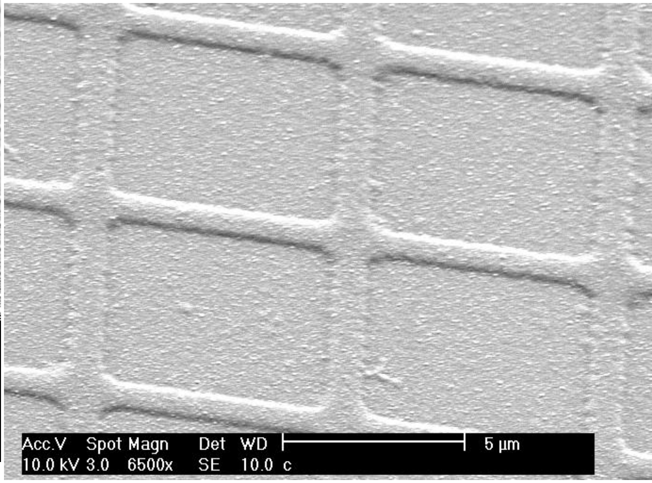


Sun, Y. & Forrest, S. R. 2008. *Nature Photon.*, 2, 483.

The Real Things



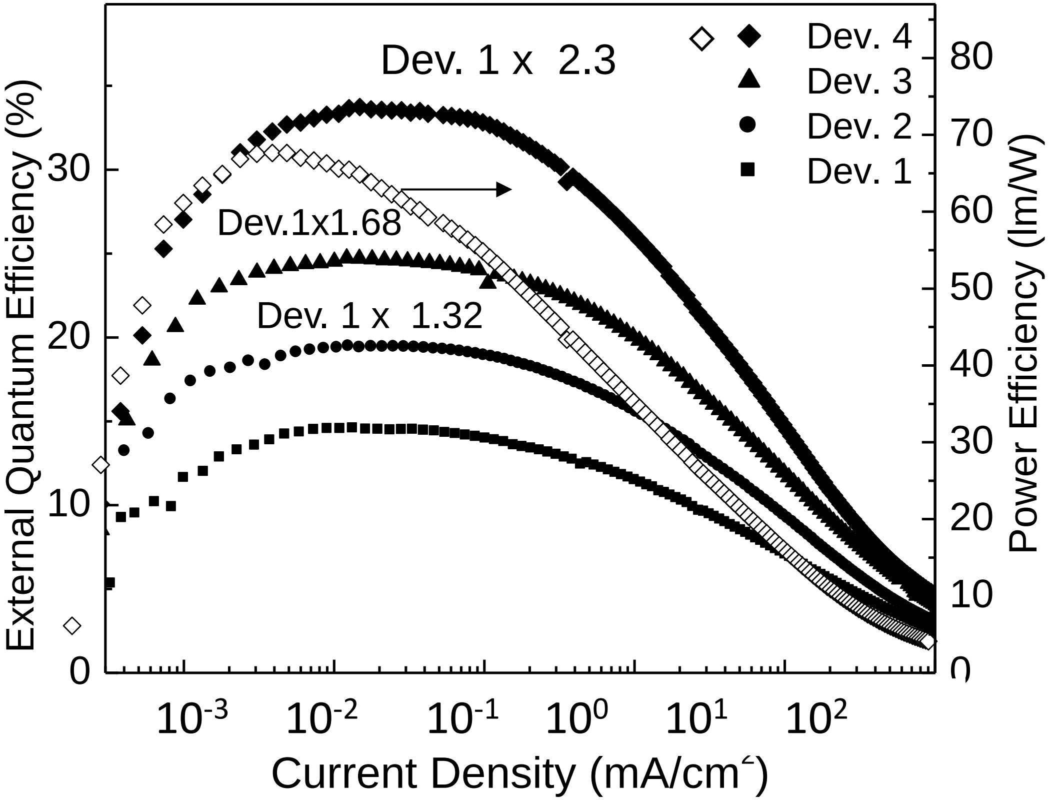


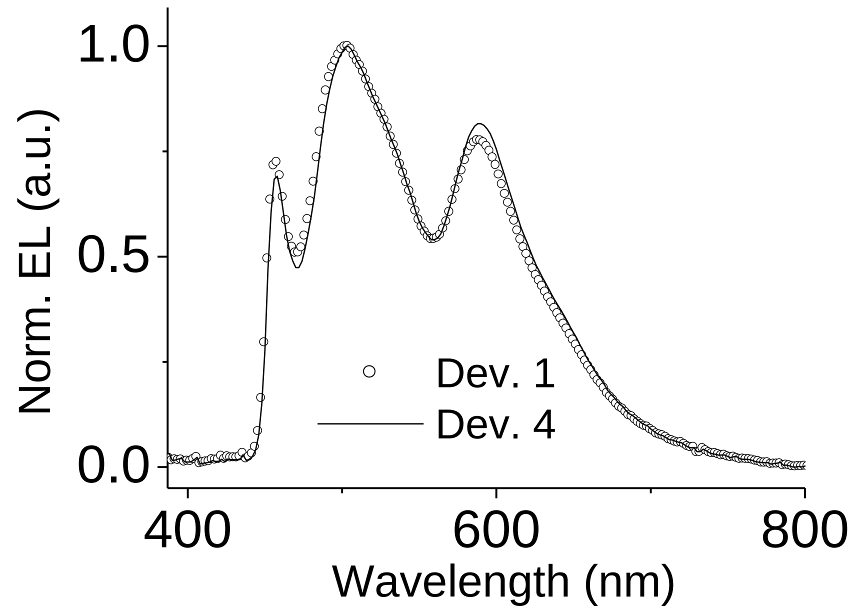


- OLED >> Grid size >> Wavelength
- Embedded into OLED structure
- May partially decouple waveguide mode from SPPs

These solutions often interfere with OLED structure

Device Performance Using Embedded Grids + Microlens





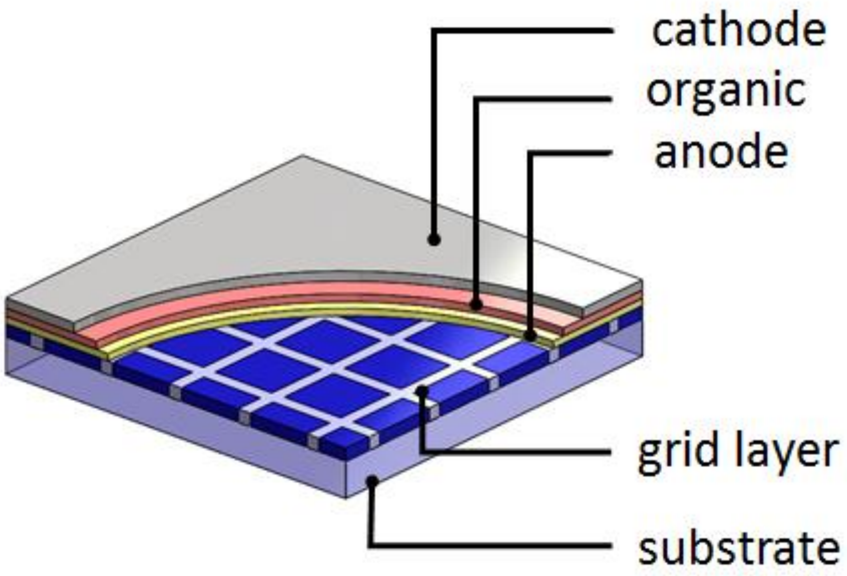
Device 1: Conventional
Device 2: LIG only
Device 3: Microlenses only
Device 4: LIG + Microlenses

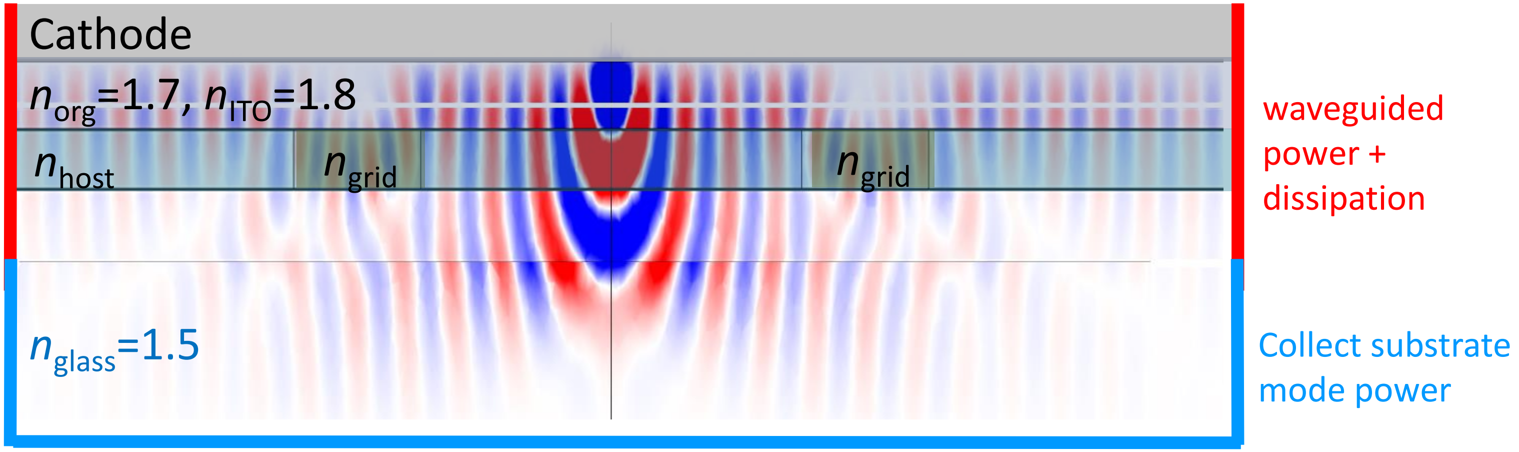
Method is Wavelength Independent

Sun, Y. & Forrest, S. R. 2008. *Nature Photon.,* 2**,** 483.

A better approach: Sub-Anode Grid

- Multi-wavelength scale dielectric grid between glass and transparent anode (sub-anode grid)
- <u>The grid is outside of the OLED active region</u>
- Waveguided light is scattered into substrate and air modes





Qu, Slootsky, Forrest, *Nature Photonics* (2015)

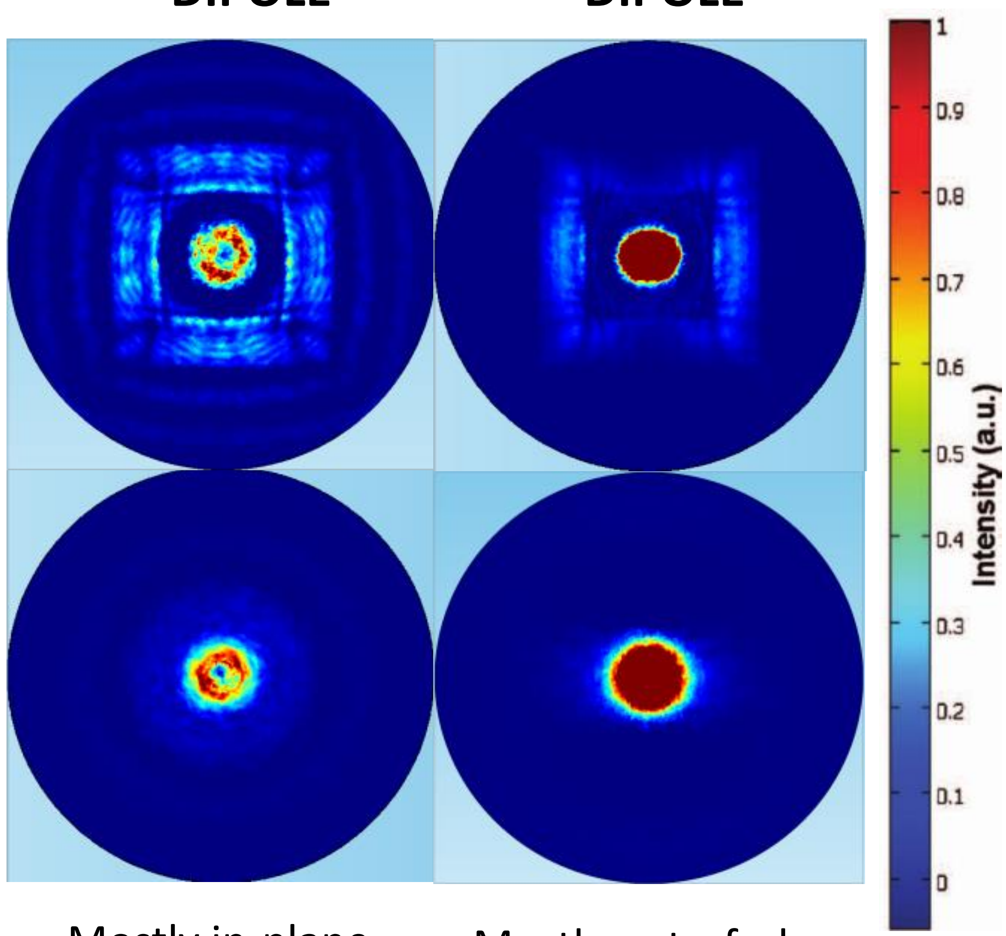
Emission fields

VERTICAL DIPOLE

HORIZONTAL DIPOLE

WITH GRID

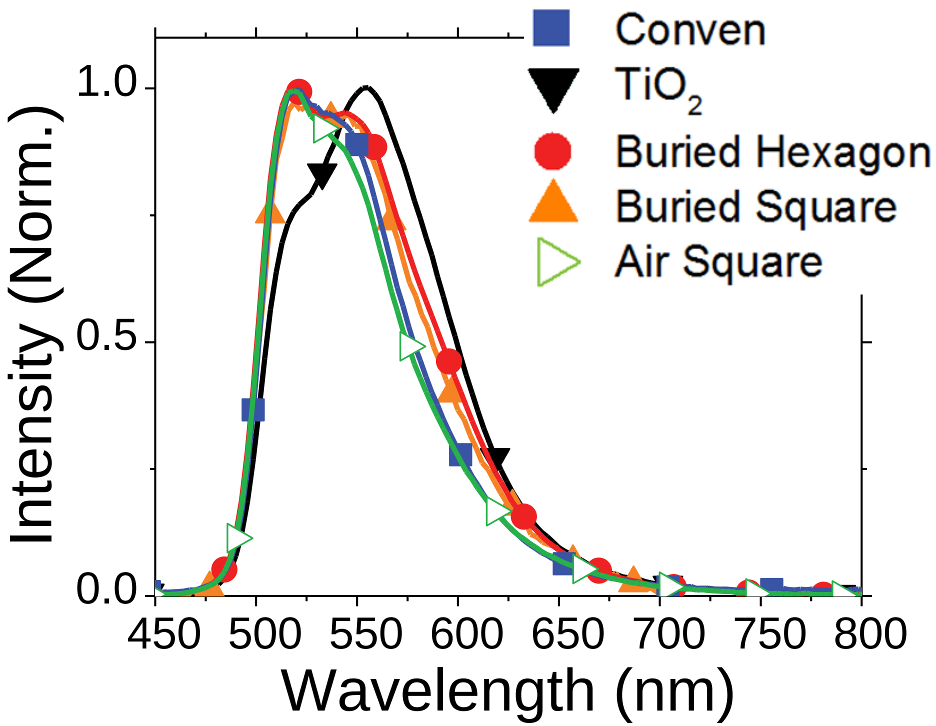
WITHOUT GRID

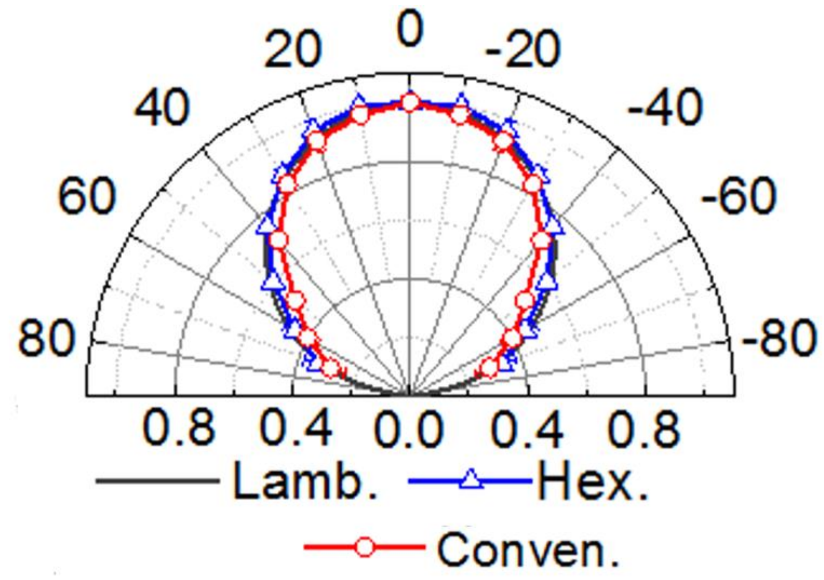


Mostly in-plane (Waveguided)

Mostly out-of-plane (Glass + air)

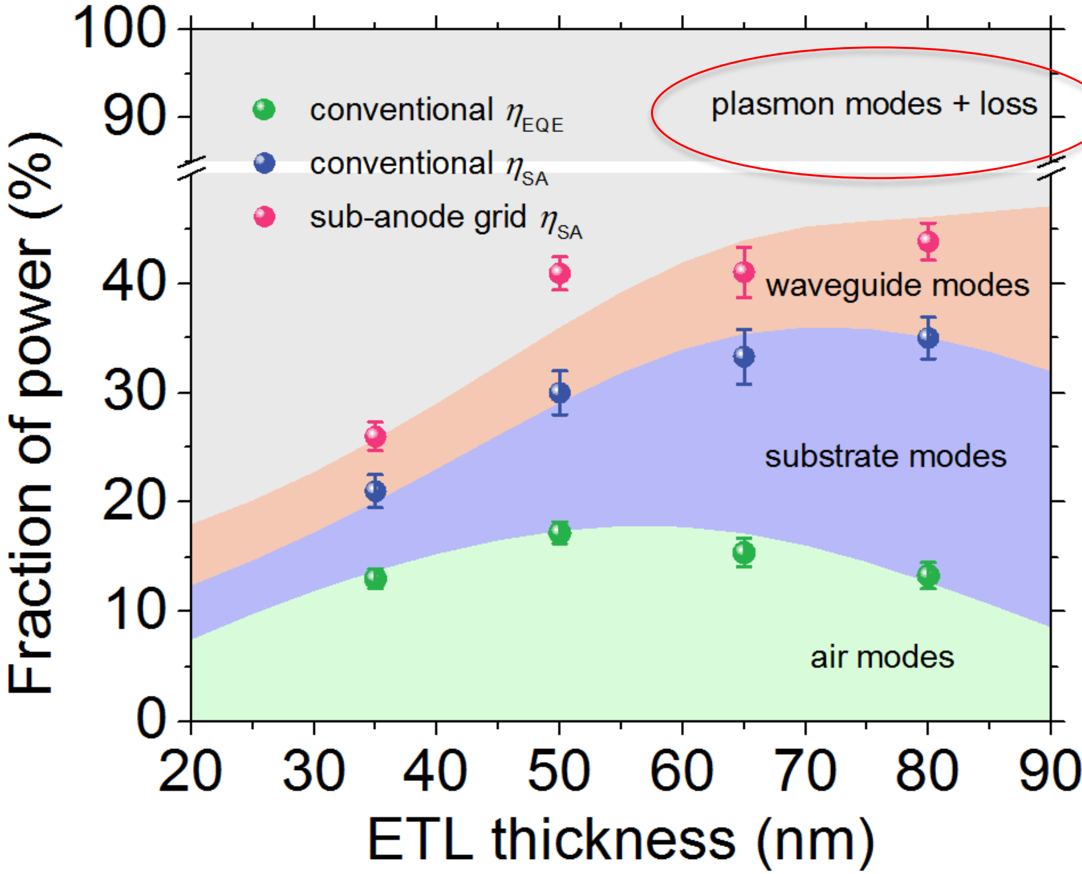
Optical Characteristics

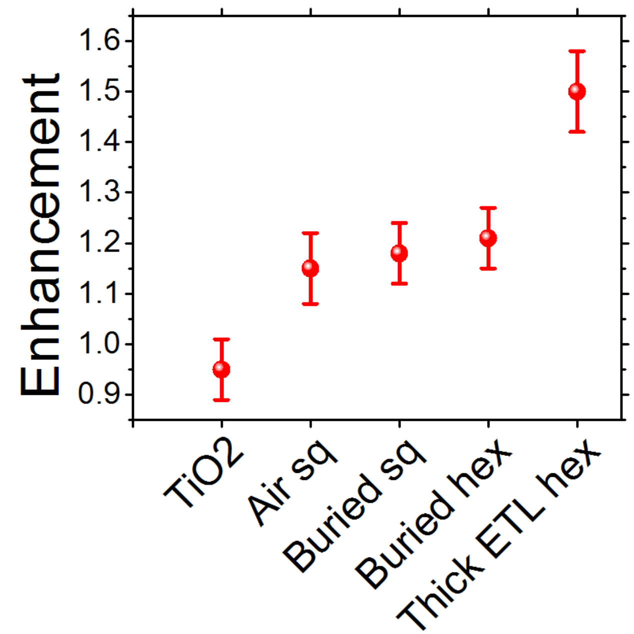




Little or no impact on emission characteristics of the OLED

Optical Power Distribution





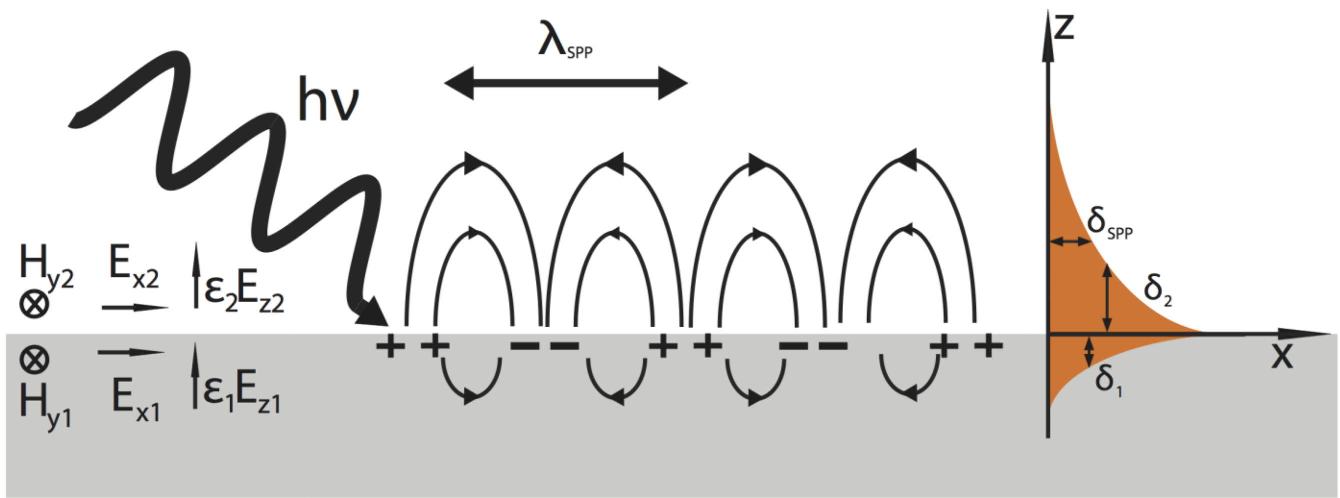
Thick-ETL organic structure:

340nm grid/70nm ITO/2nm MoO_3/40nm TcTa/15nm CBP: $Ir(ppy)_3$/10nm TPBi/230nm Bphen:Li/Al

2nm MoO_3/40nm CBP/15nm CBP:$Ir(ppy)_3$/xnm TPBi/1nm LiF/Al

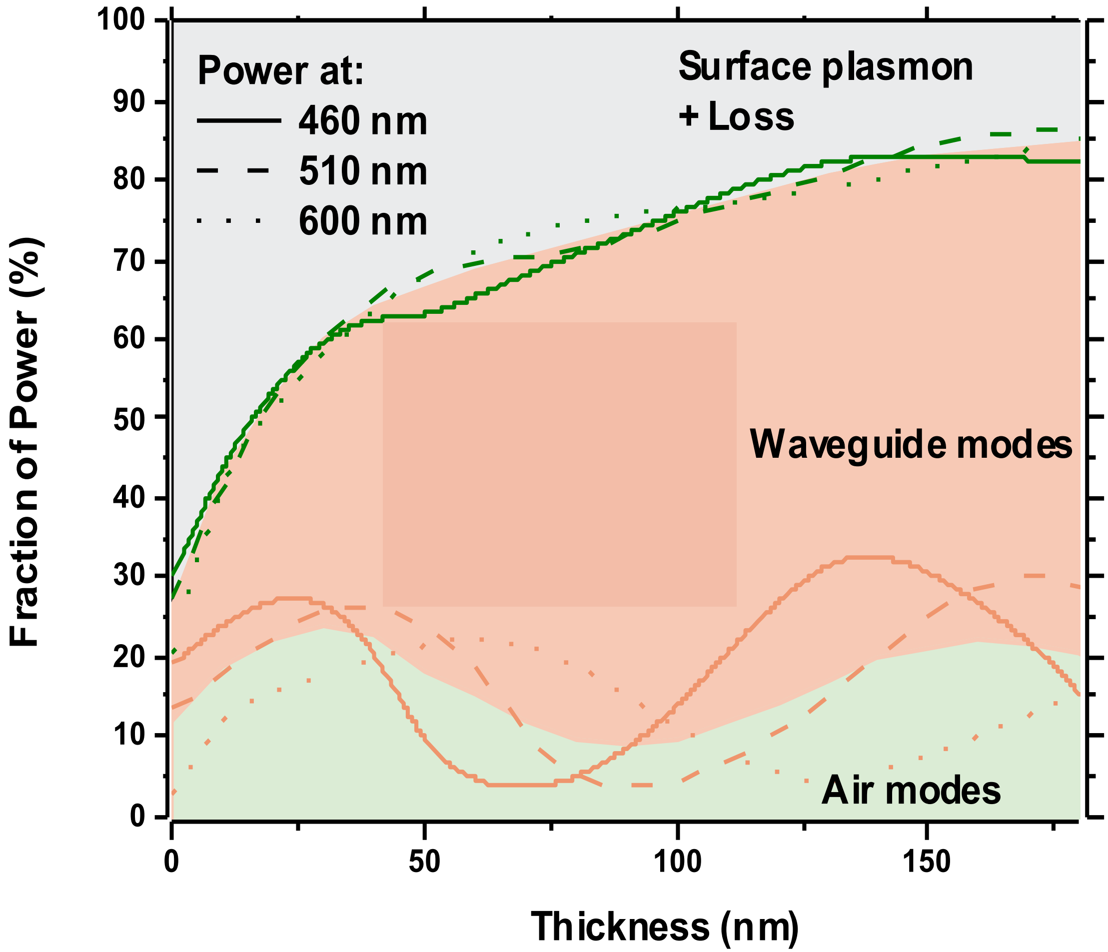
The Last Frontier: Surface Plasmon Polariton (SPP) Modes

η_{ext} > 80% (incl. substrate + waveguide modes)



- Waveguided light excites lossy SPPs in metal cathode
- Major loss channel partially eliminated by rapid outcoupling of waveguide modes
- Most difficult to eliminate cost-effectively without impacting device structure

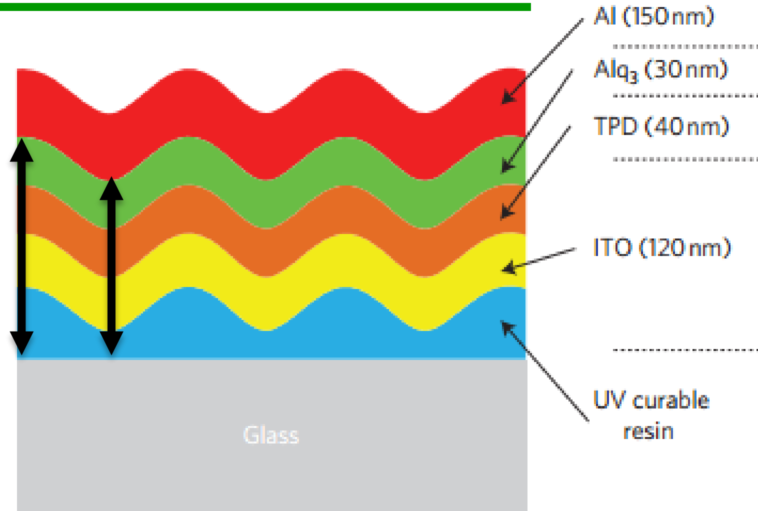
How Much Light Can We Realistically Hope to Extract?



- Simple design that does not interfere with OLED structure
- Only substrate processing
- Extracts all wavelengths approximately equally
- 80-90% extraction within reach!

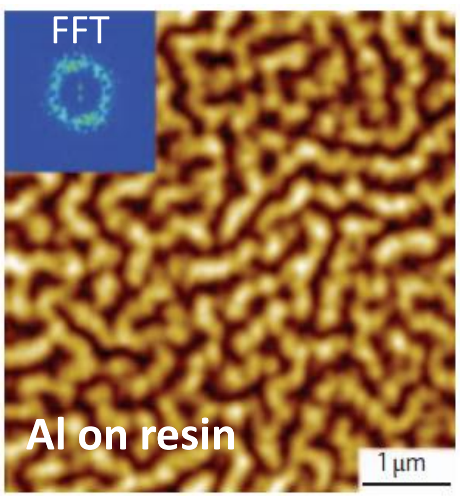
One possible solution: Surface corrugations

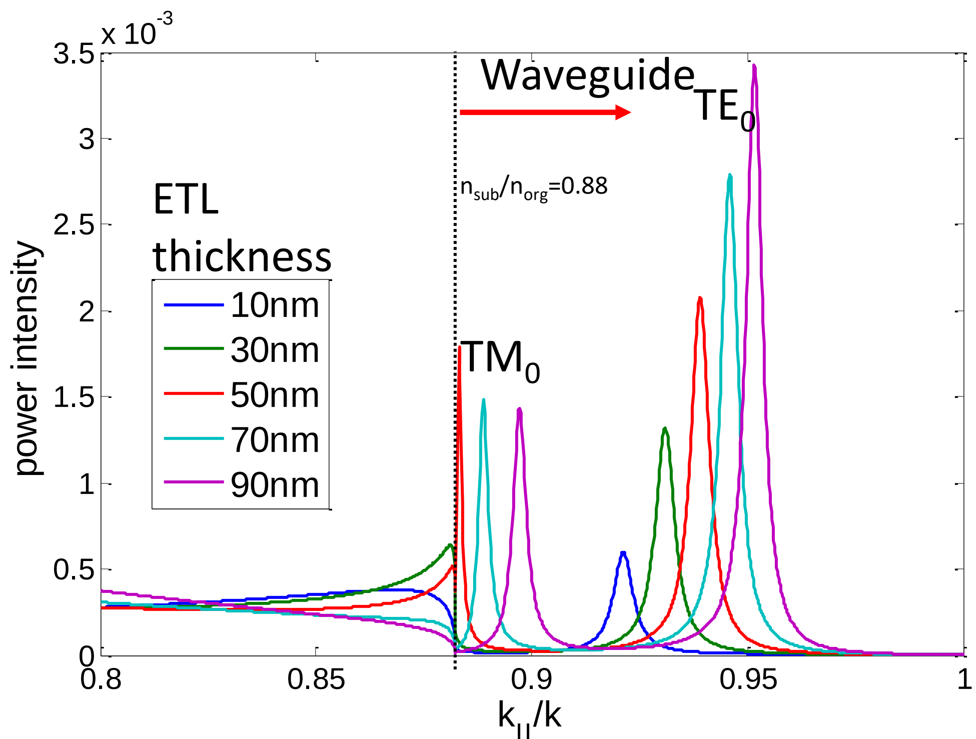
- Waveguide thickness varies due to the corrugation.
- As the thickness changes, the mode distribution changes.
- When the waveguided power travels from thin to thick areas, $\mathbf{k}_{||}$ needs to change direction to keep “being trapped”.
- Otherwise, the light is extracted.



W. H. Koo, et al, *Nat. Photonics* 2010, **4**, 222.

A possible approach: Surface buckling?

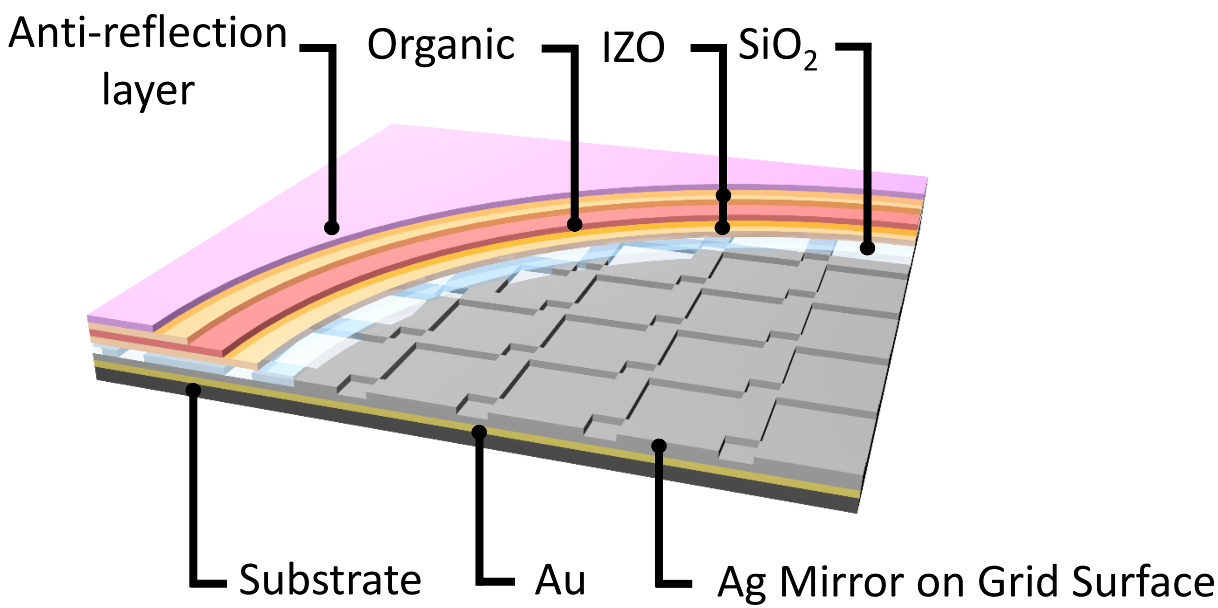




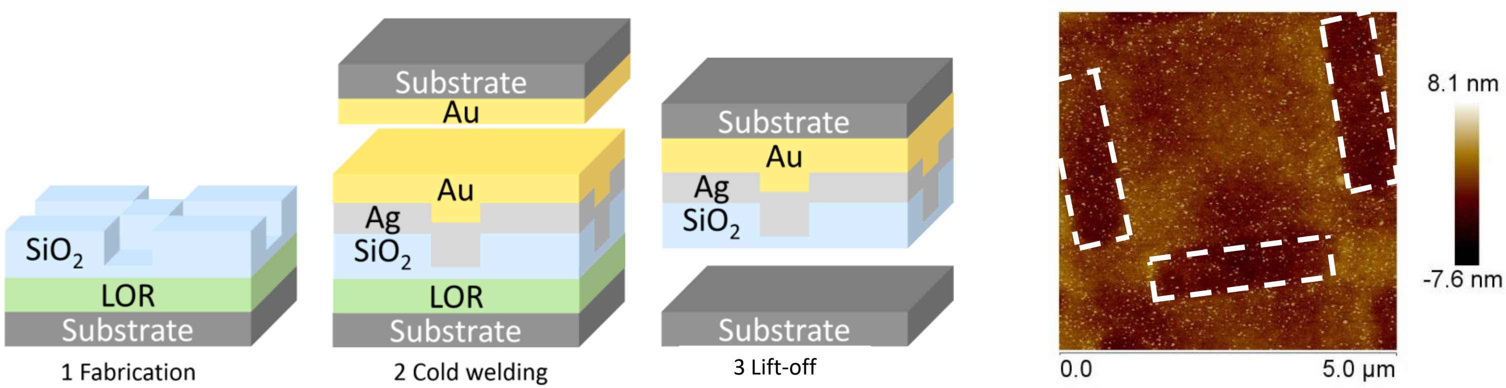
Getting Rid of SPPs Using Sub-Anode Grid + Mirror

Qu, et al. ACS Photonics, 2017

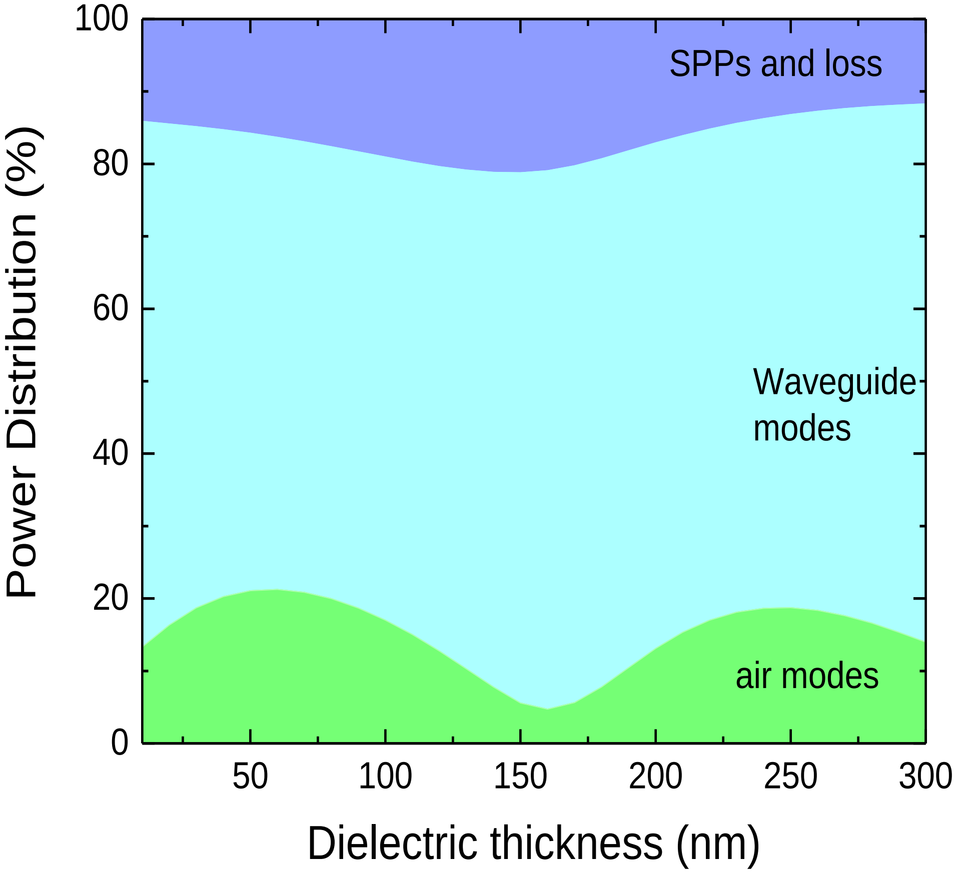
Top Emitting OLED

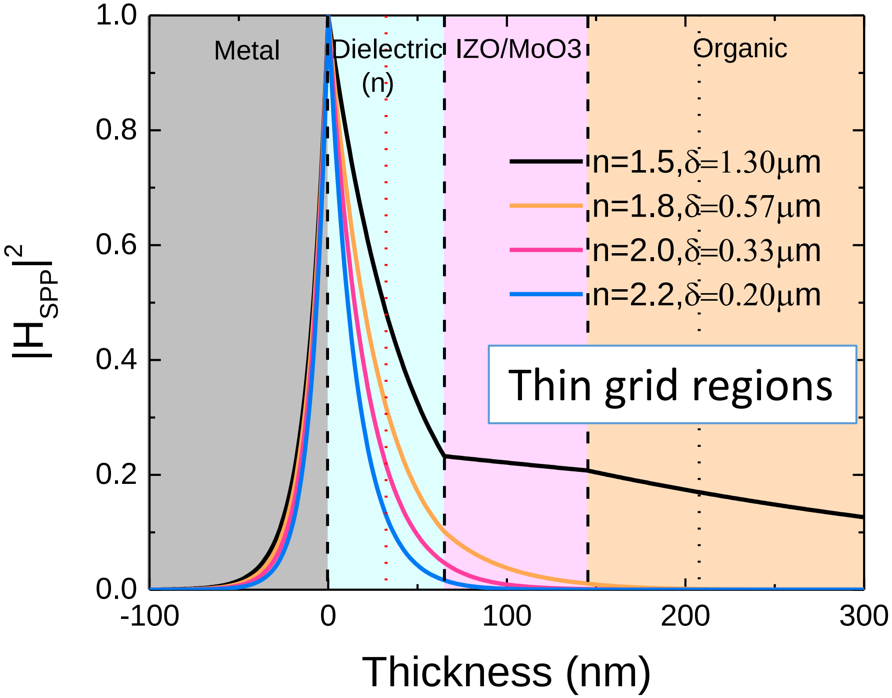


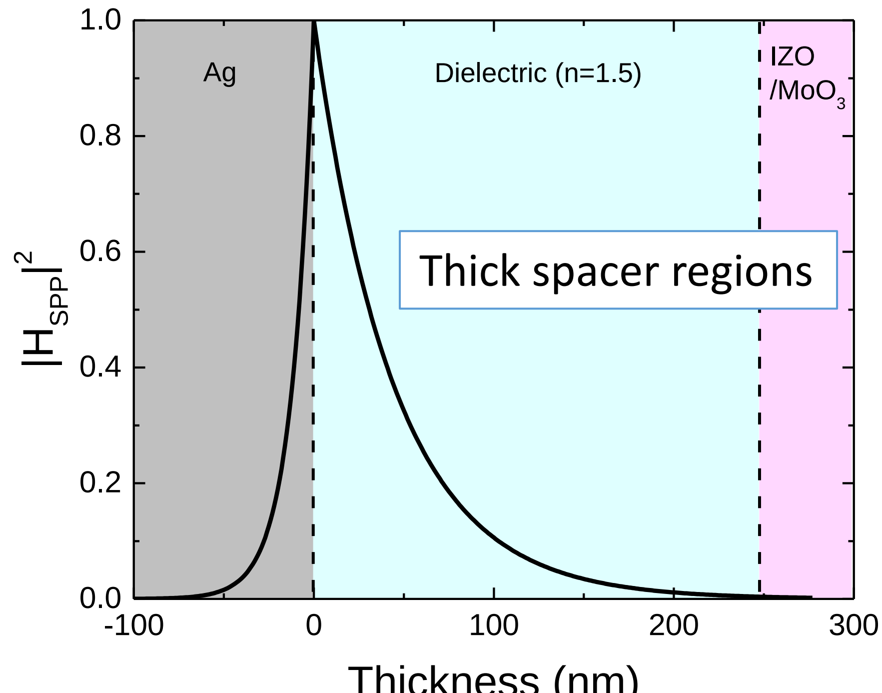
Substrate Fabrication



Decoupling SPPs with Grid + Mirror

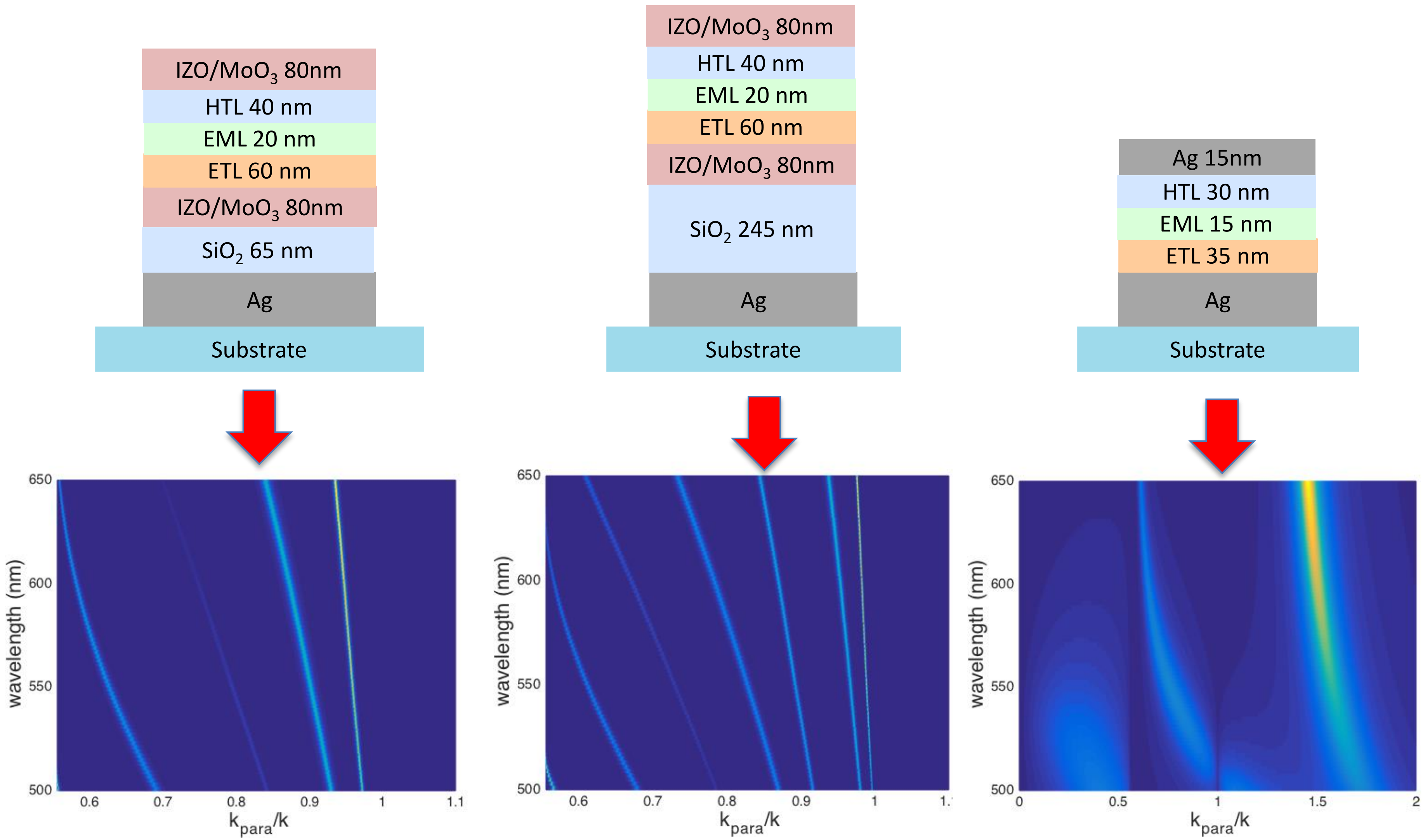






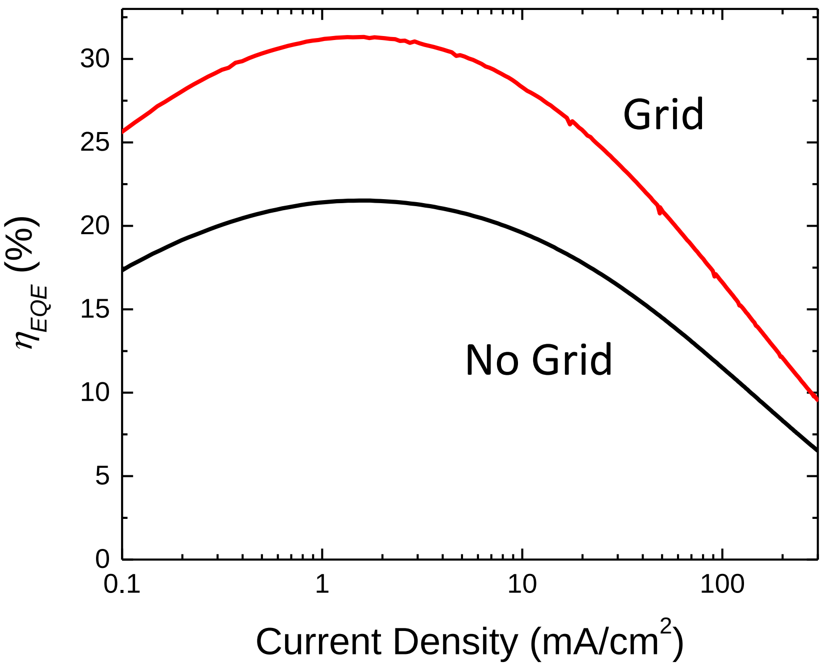
Qu, et al. ACS Photonics, 2017

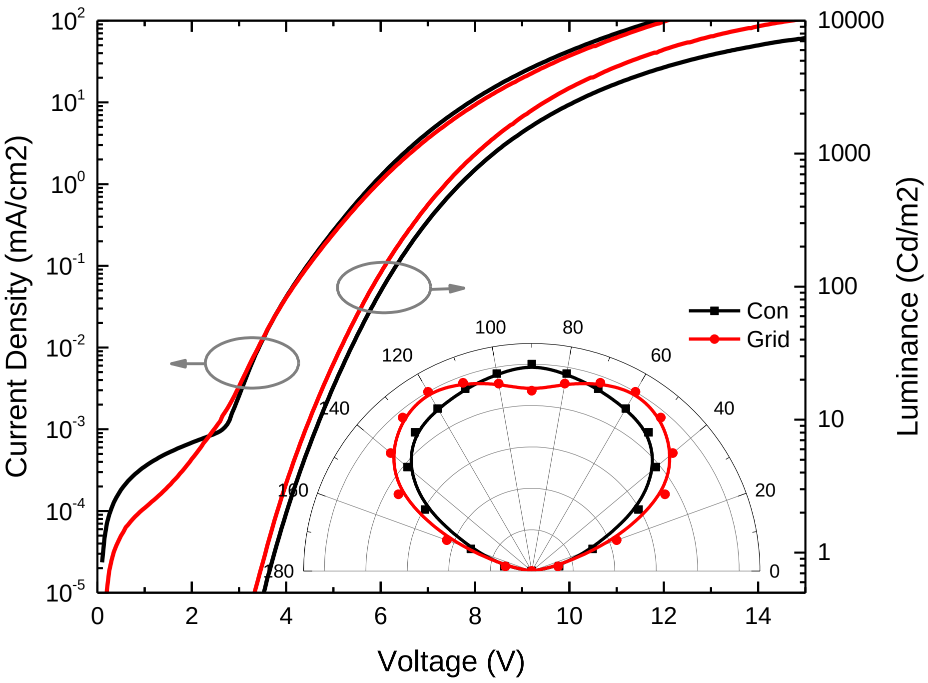
Sub-electrode grid modeling



Variable Waveguide Widths Prevent Mode Propagation

Performance with and without grid + mirror



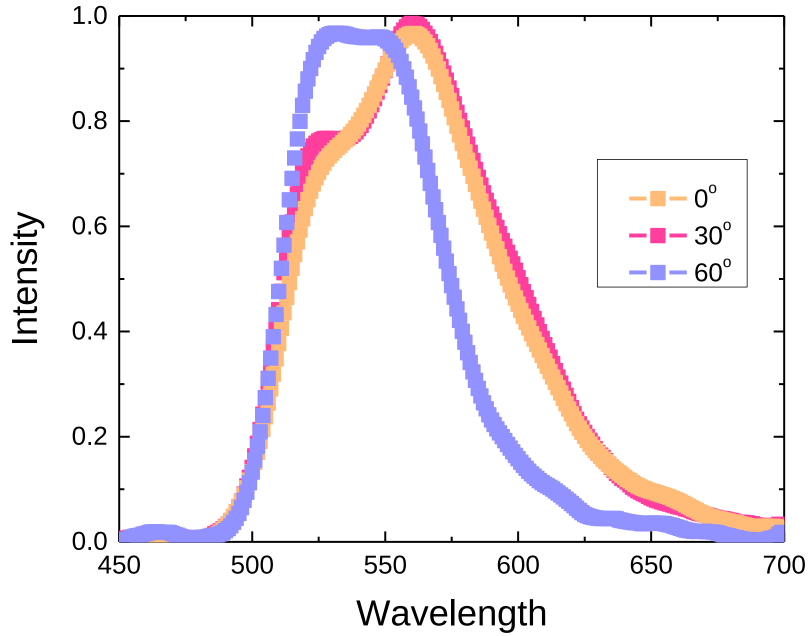


Qu, et al. ACS Photonics, 2017

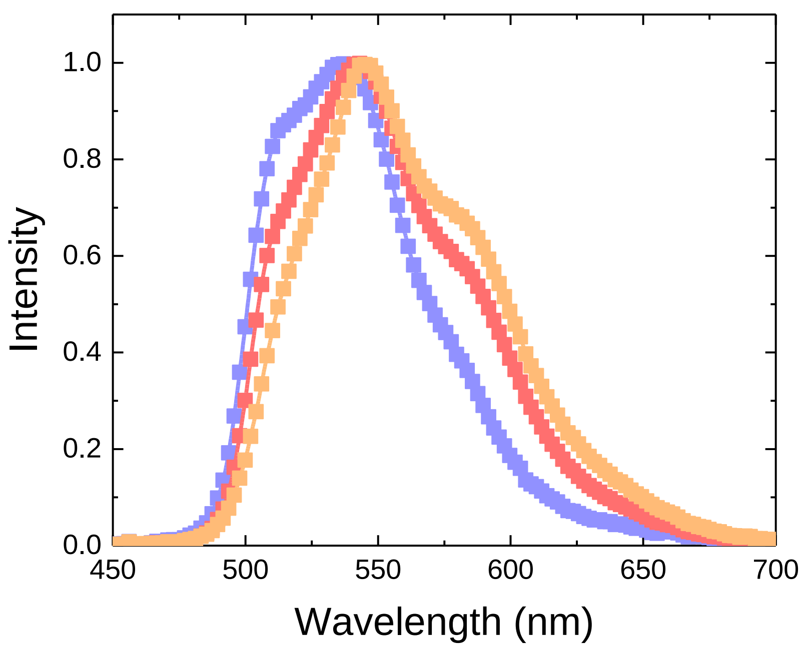
Top emission spectra

All top emitting OLEDs show microcavity effects
Effects minimized by AR coatings, diffusers, µlenses, etc.

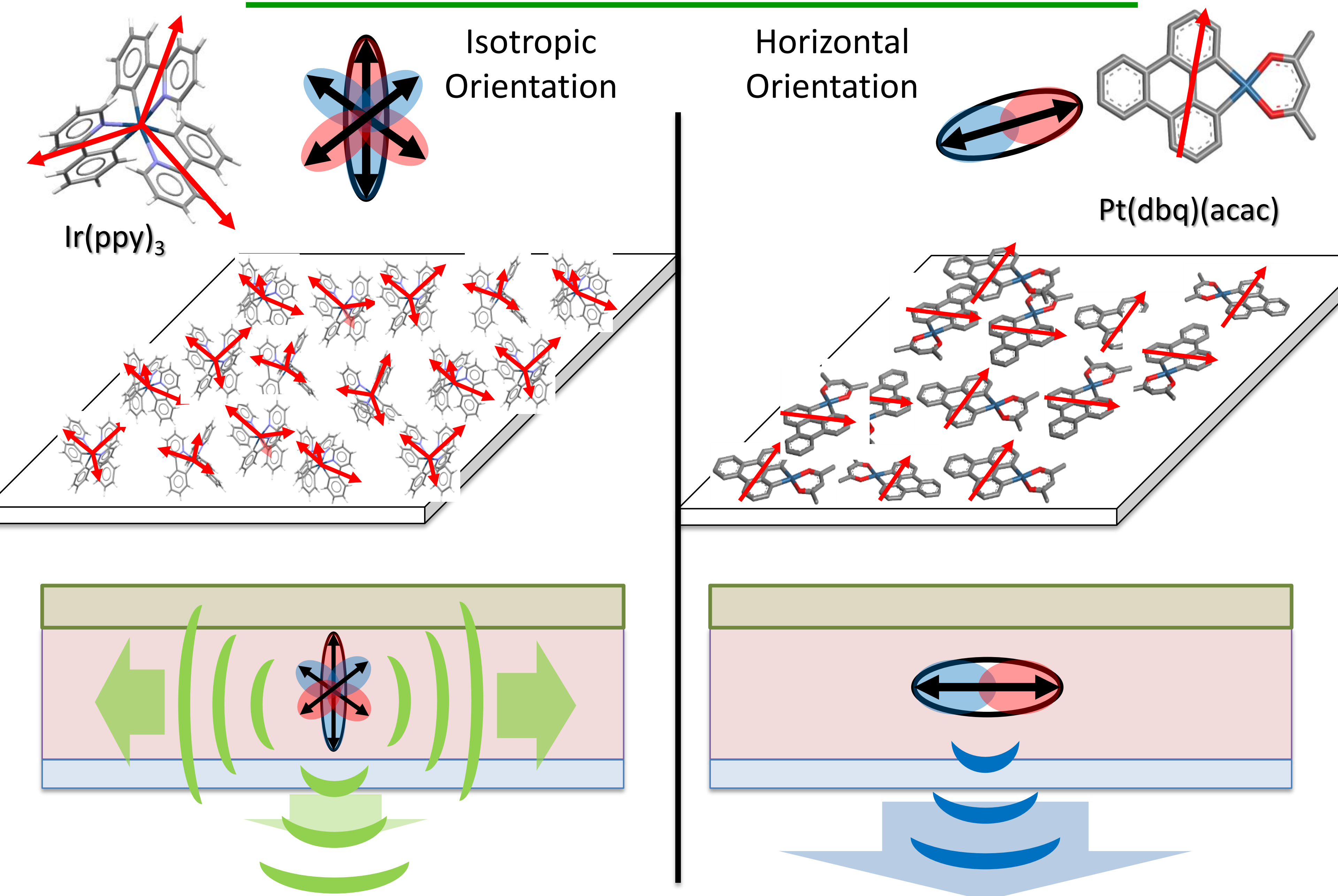
No AR Coating + Grid



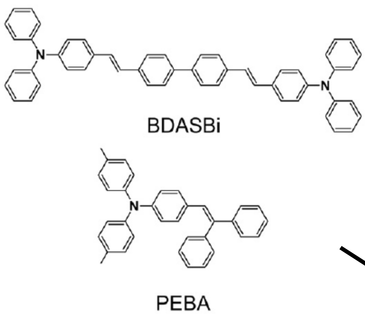
MgF$_2$ AR Coating + Grid



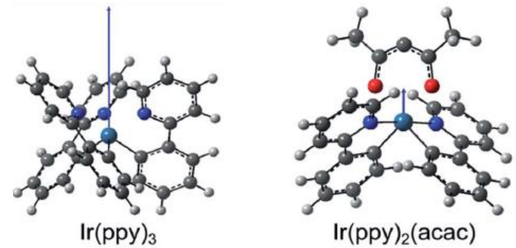
Manipulating Molecular Orientation



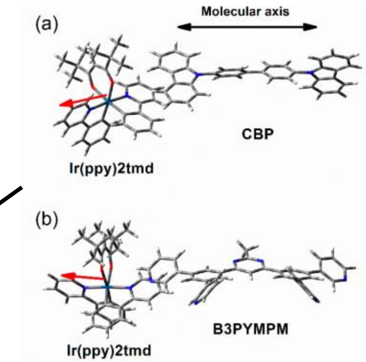
Factors Affecting Dipole Orientation



Molecular Shape
J. Frischeisen et al., Org. Electronics (2011)



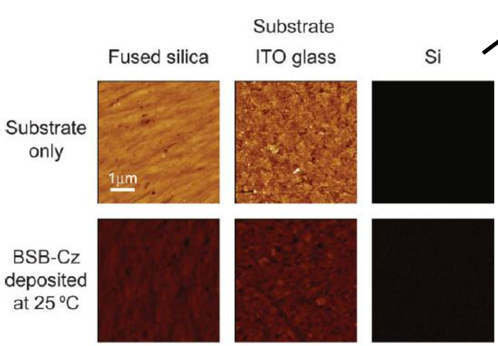
Static Dipole
A.Graf et al., J.Mat.Chem.C (2014)

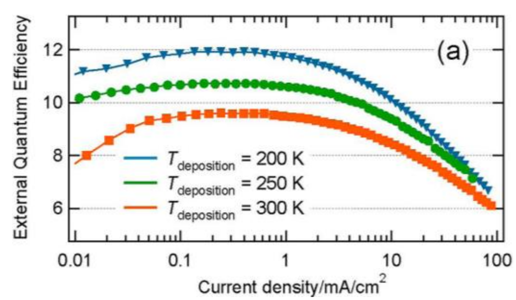


Host-Guest interaction
C.Moon et al., *Chem. Mater. (2015)*

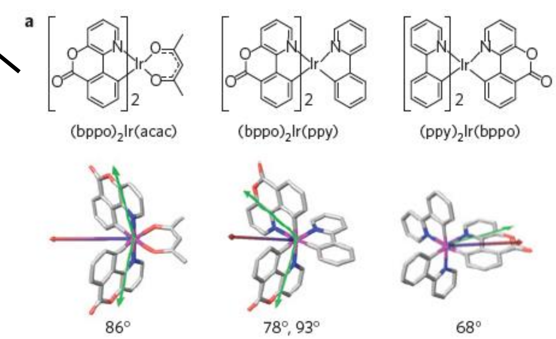
Dipole Orientation

Substrate & Substrate temp.
D.Yokoyama et al., *Adv.Func.Mat. (2010)*
T. Komino et al., *Chem.Mater. (2014)*

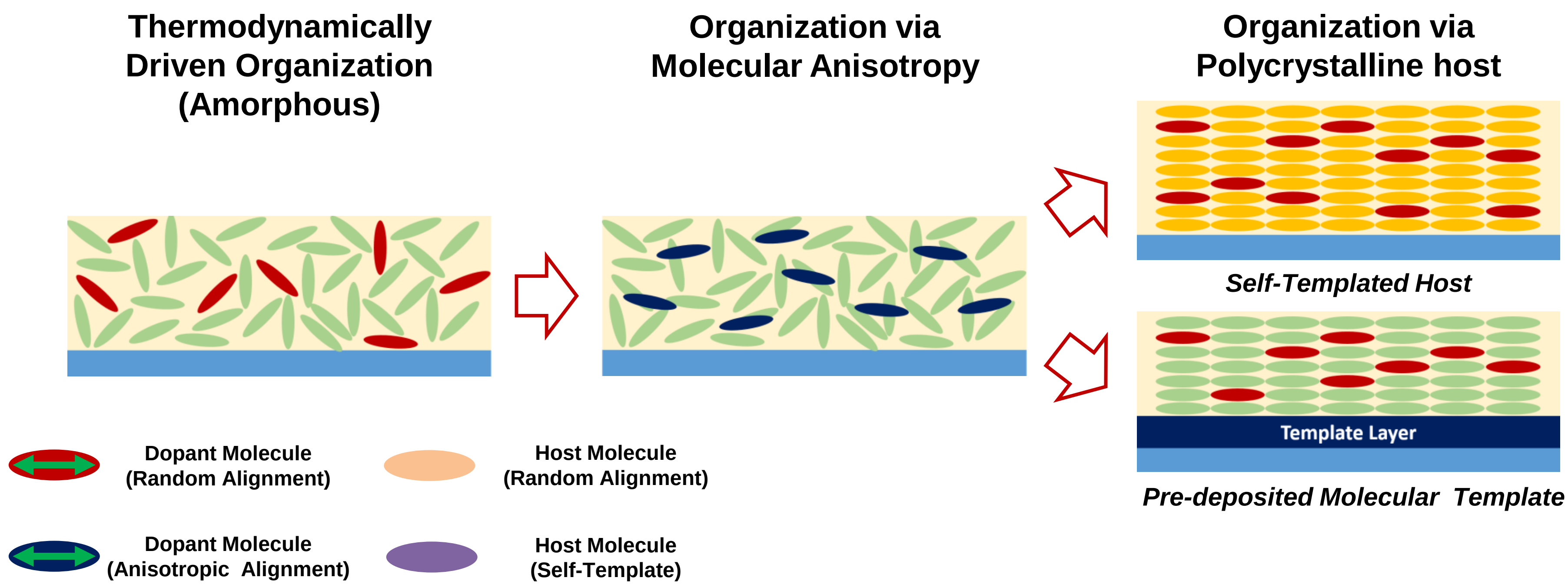




Ligand Effect
M.Jurow et al., *Nat. Mater. (2016)*

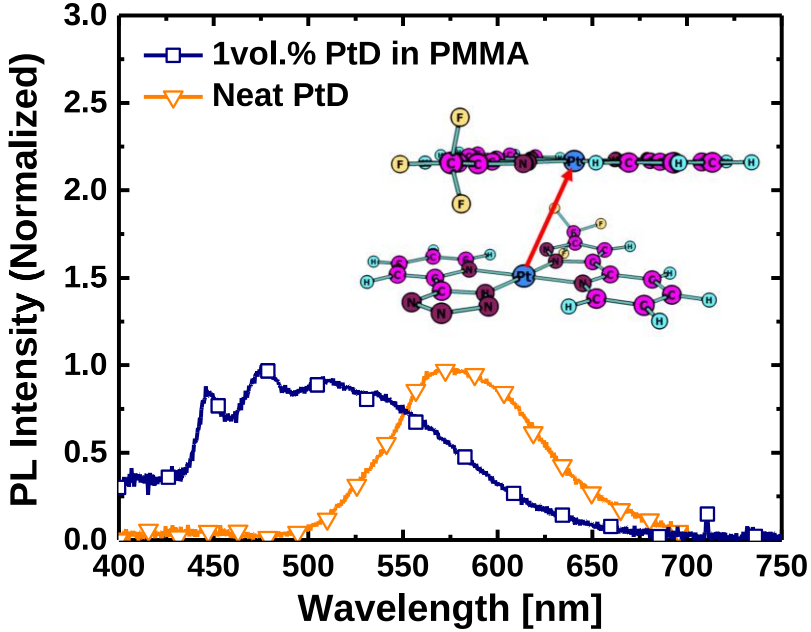


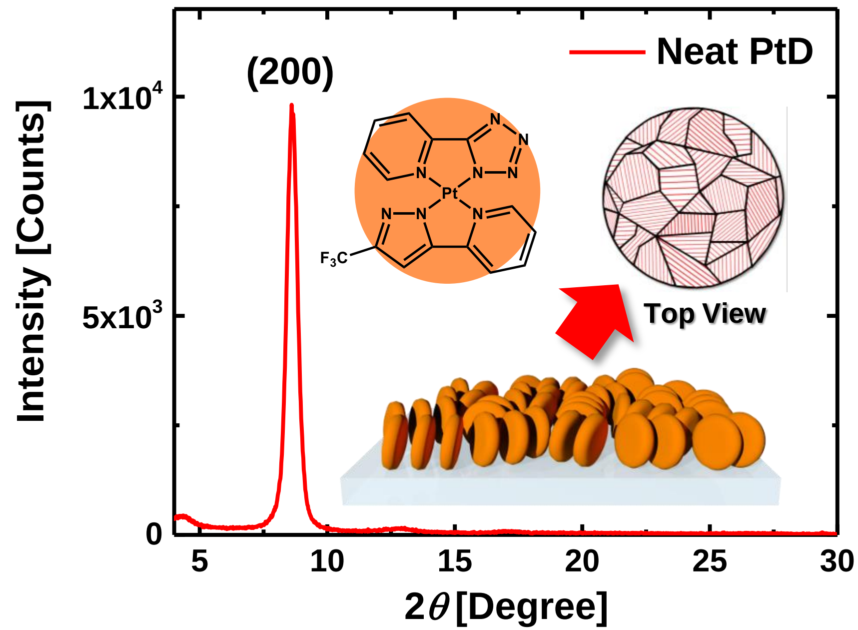
Use **Templating** to Force TDM Orientation

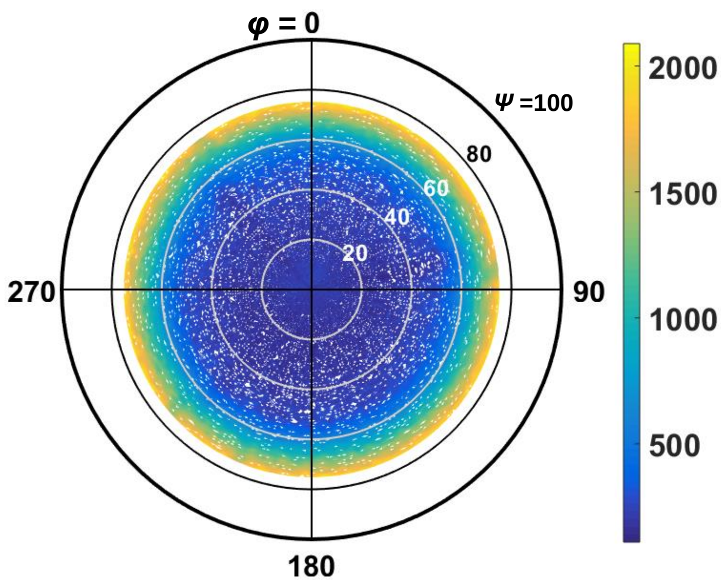


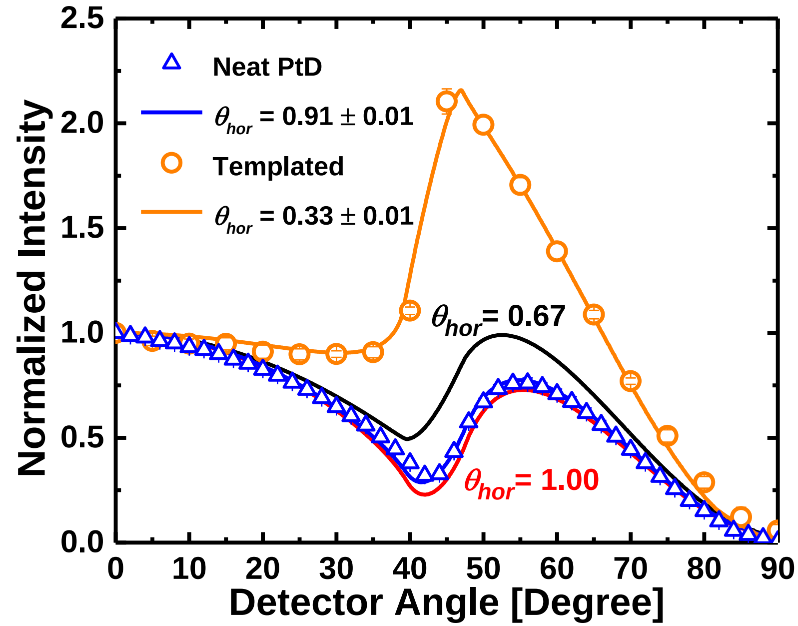
Advantage: Structure driven by growth process, not molecular design
Disadvantage: Finding appropriate growth conditions to obtain structure

Examples of Alignment via Templating



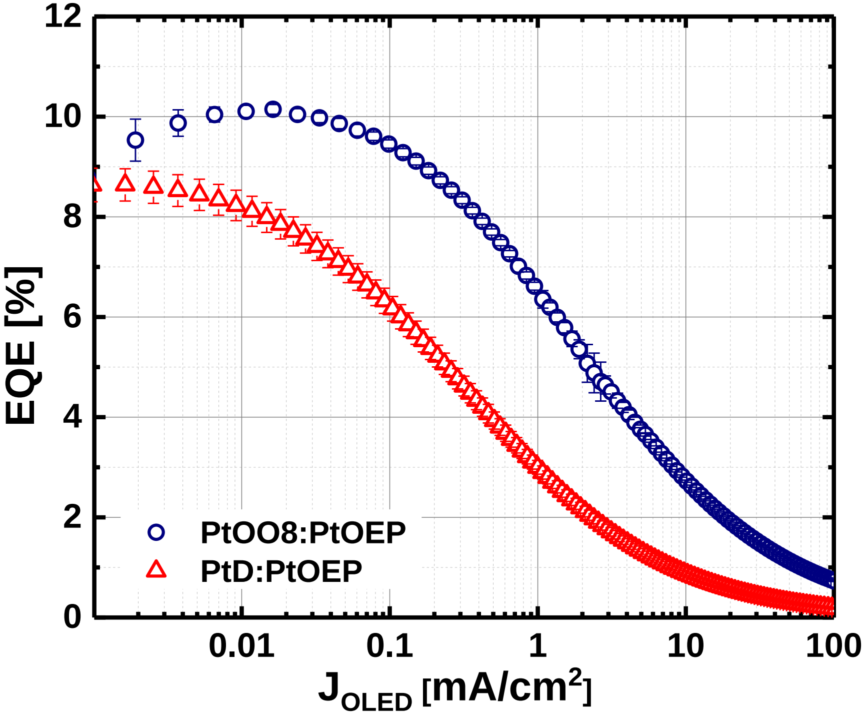


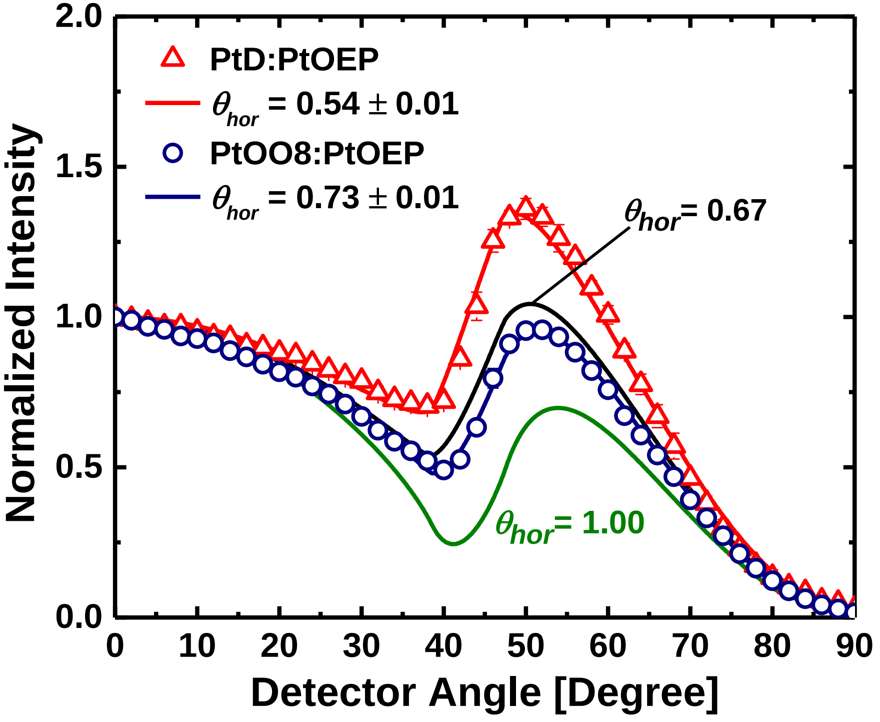




Collaborators: M. Thompson, M. Omari, J. Li

High Efficiency Devices via Self Templating





Conclusions

- Outcoupling solutions should have these properties
  - Low cost
  - Angle and wavelength independent
  - Minimal impact on established OLED and materials designs
- Sub-anode grid outcouples *all* waveguide modes
- With top emission, SPP and waveguide modes not excited
  - No impact on electrical characteristics
  - No significant optical effect

Thanks!

- OCM Group
  - Yue Qu
  - Jonchang Kim
  - Michael Slootsky
- Mark Thompson
- Mohammed Omari
- Jian Li