Getting All the Light Out, or No Photon Left Behind

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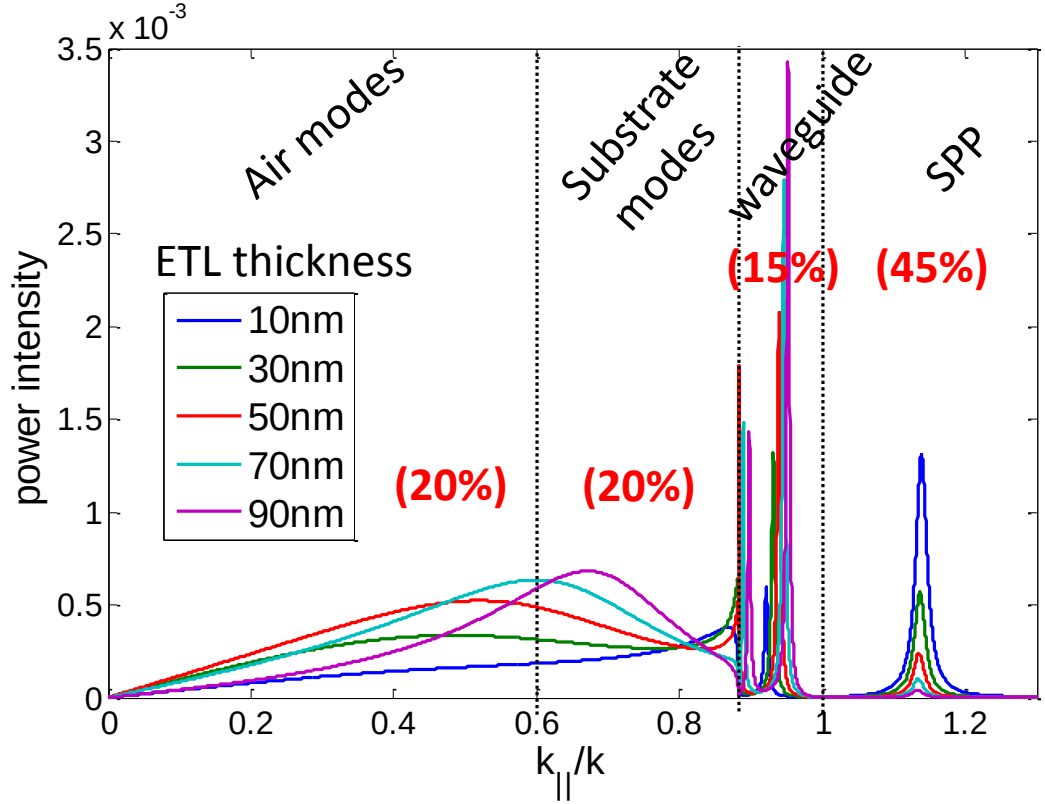
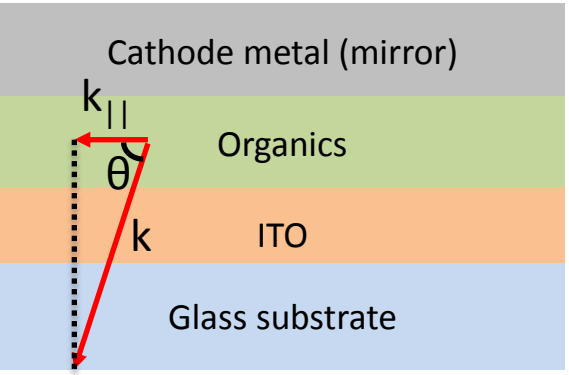
OLEDs: Major Remaining Challenges for Lighting

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

Where do all the photons go?

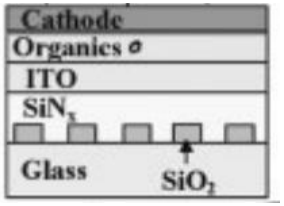


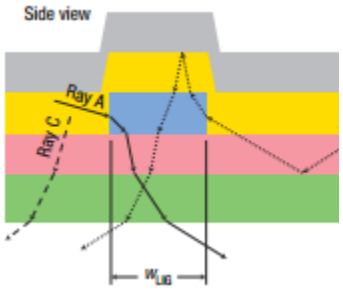


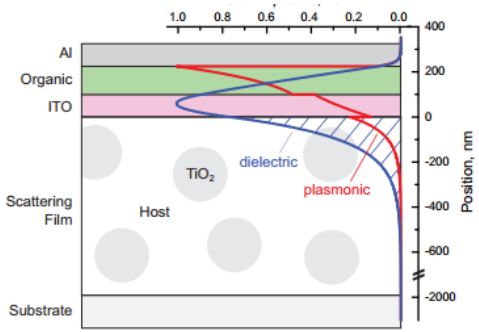
- **Air modes**: EQE first increases, then decreases with ETL thickness
- **Waveguide modes**: Only one waveguide mode TE_0 due to thin ETL (<30nm). TM_0 appears when >50nm.
- **Surface plasmon polariton modes:** Reduced with ETL thickness
- Both waveguide and SPP modes are quantized
- Total energy is the integral of Power Intensity X 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



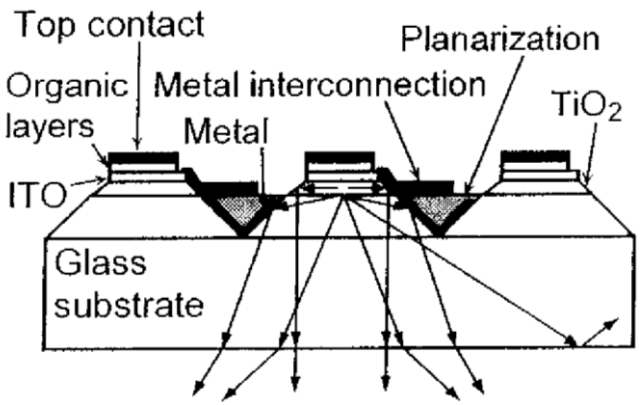




[1]Y .R. Do, et al, *Adv. Mater*. **15**, 1214 (2003).
[2]Y. Sun and S.R. Forrest, *Nat Phot*. **2**, 483 (2008).
[3]Chang, H.-W. *et al*. *J. Appl. Phys.* **113,** - (2013).

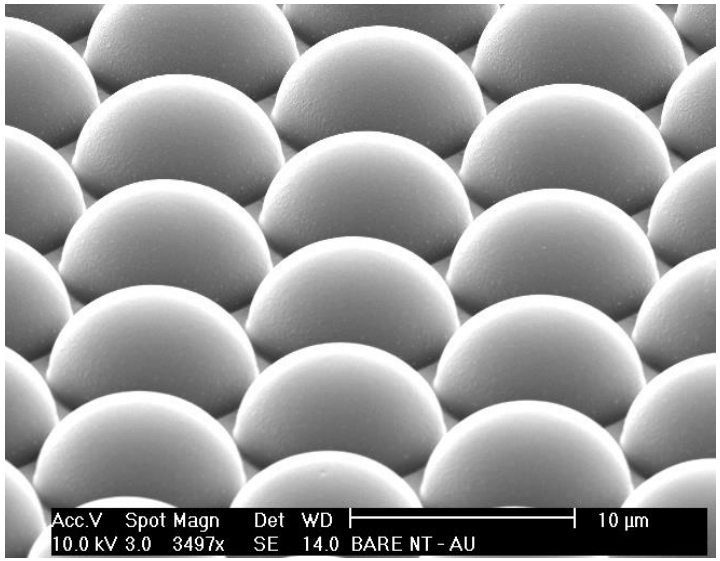
Substrate Modes: ~2X Improvement

η_{ext}~40%



Pyrimidal structures on substrate

Gu, et al., Opt. Lett., **22**, 396 (1997)



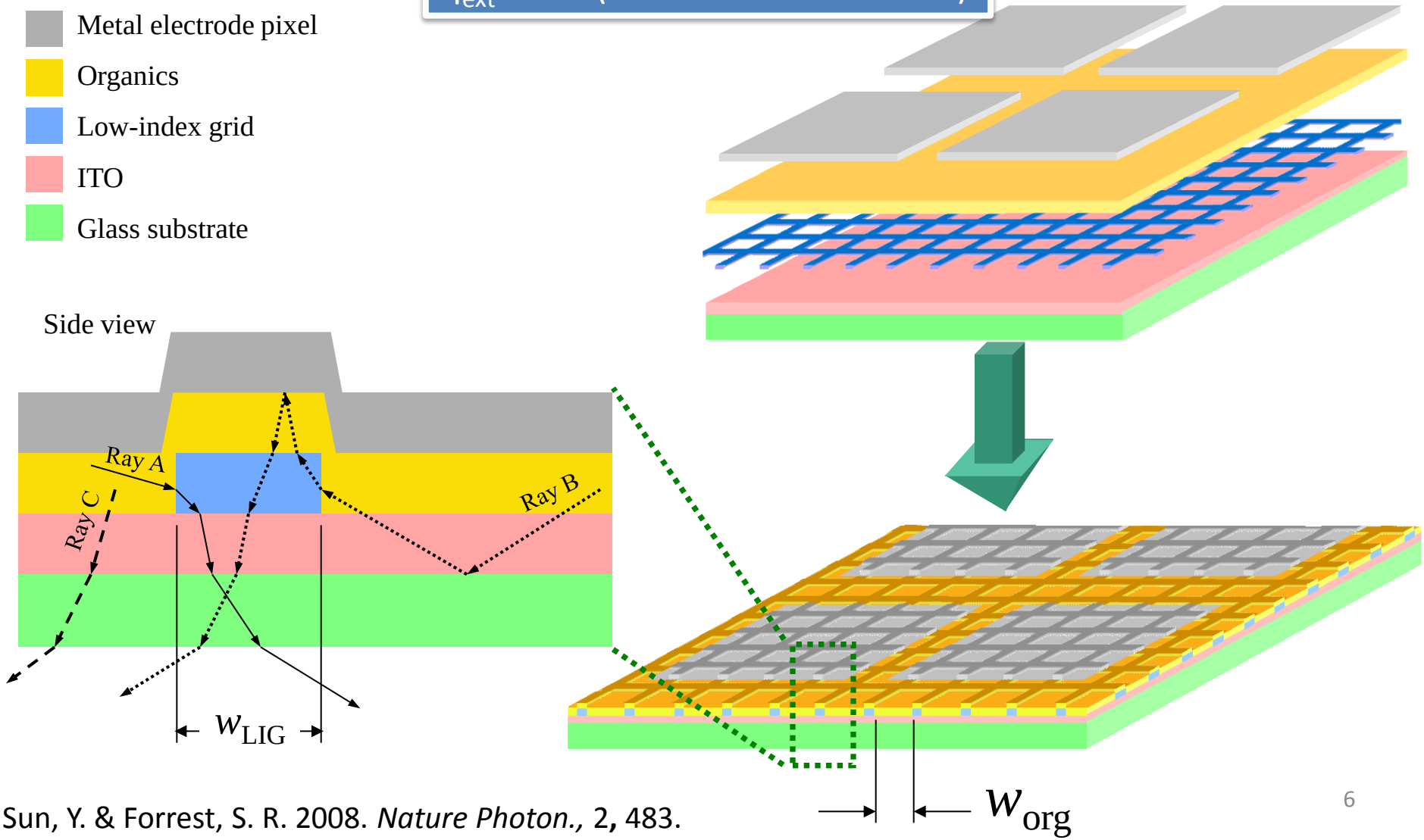
Microlens arrays

- Polymer hemispheres
- Much smaller than pixel

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

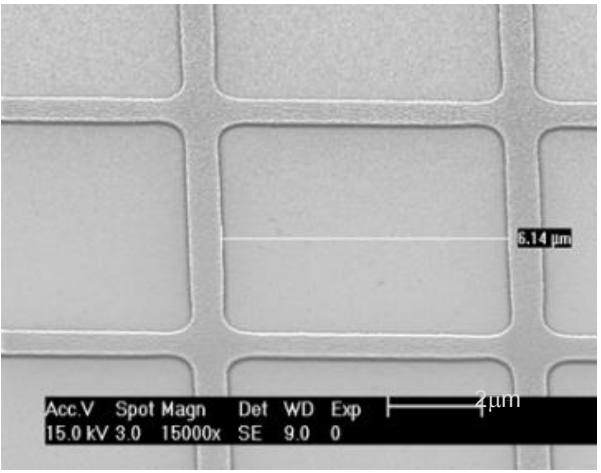
Waveguide Modes
Embedded Low Index Grid

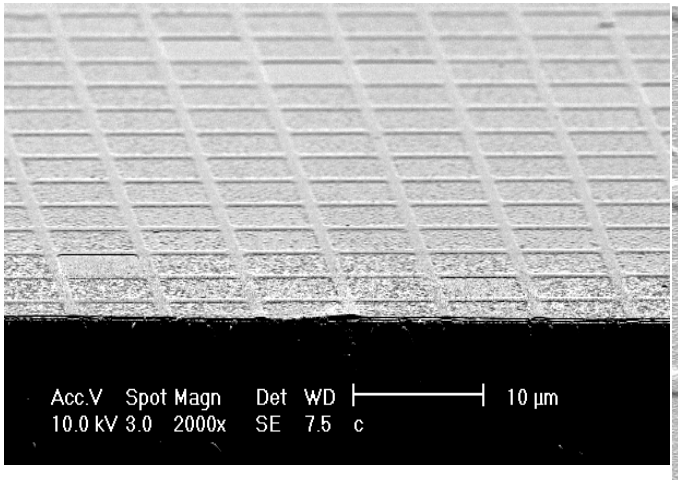
η_{ext}~60% (incl. substrate modes)

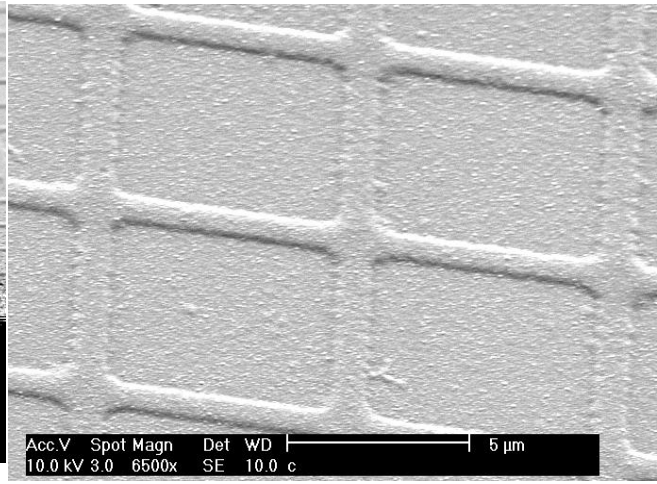


Sun, Y. & Forrest, S. R. 2008. *Nature Photon.*, 2, 483.

The Real Things

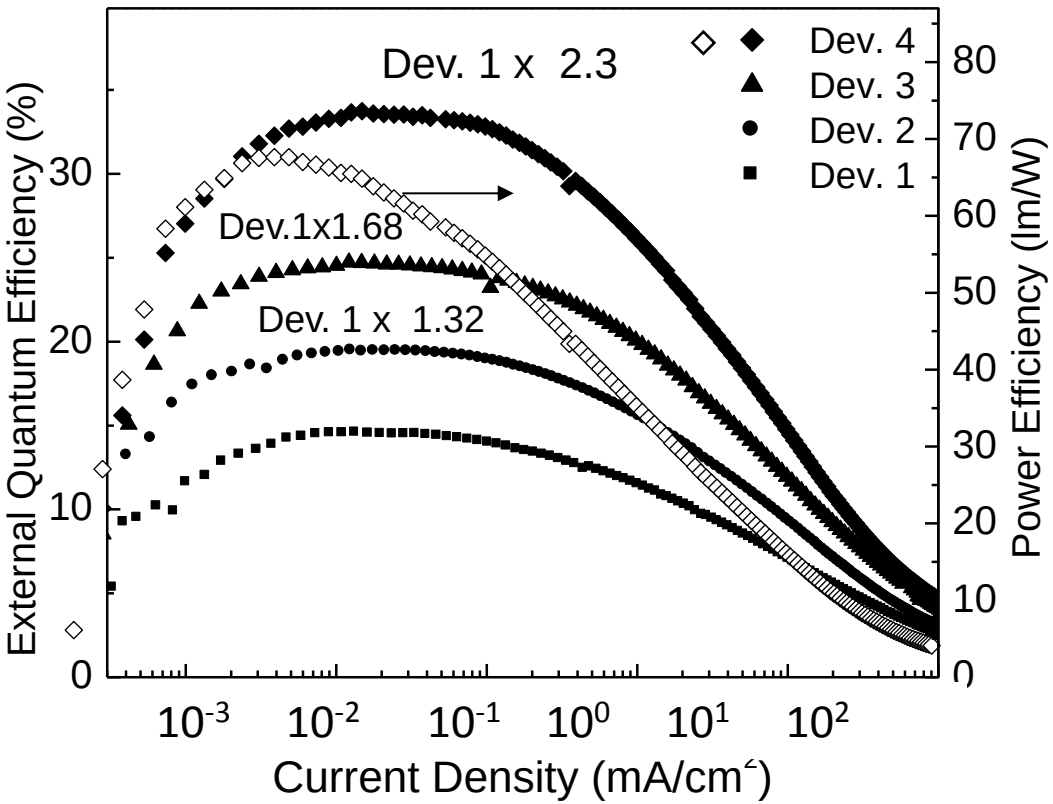


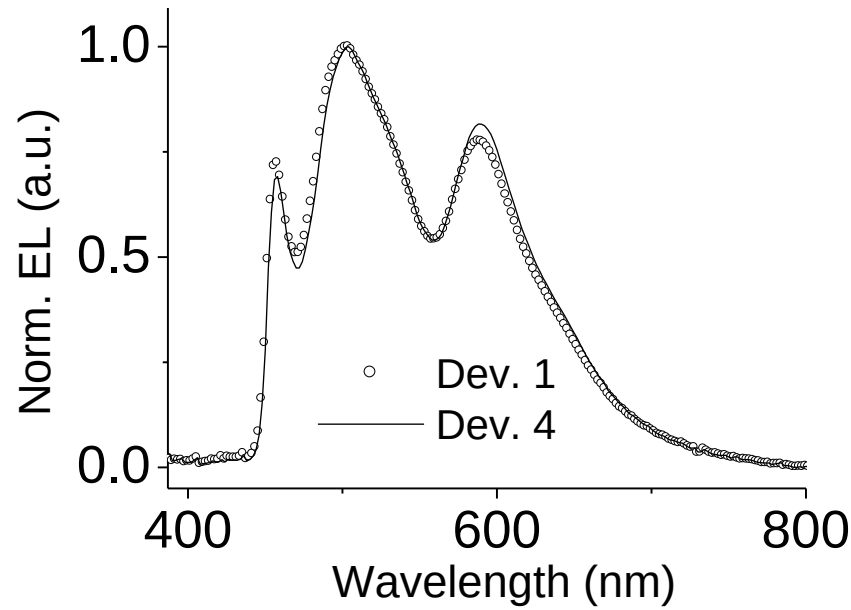




- OLED >> Grid size >> Wavelength
- Embedded into OLED structure
- May partially decouple waveguide mode from SPPs

Device Performance Using Embedded Grids + Microlens





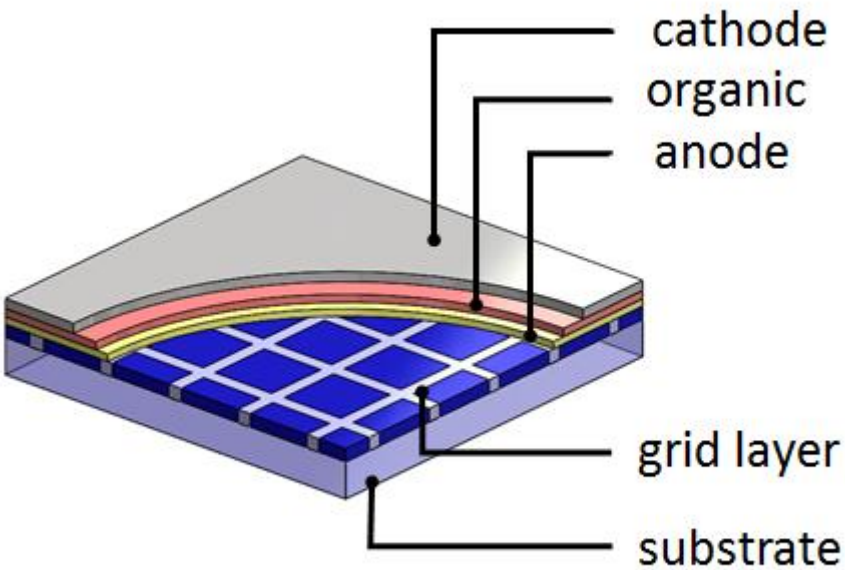
Method is Wavelength Independent

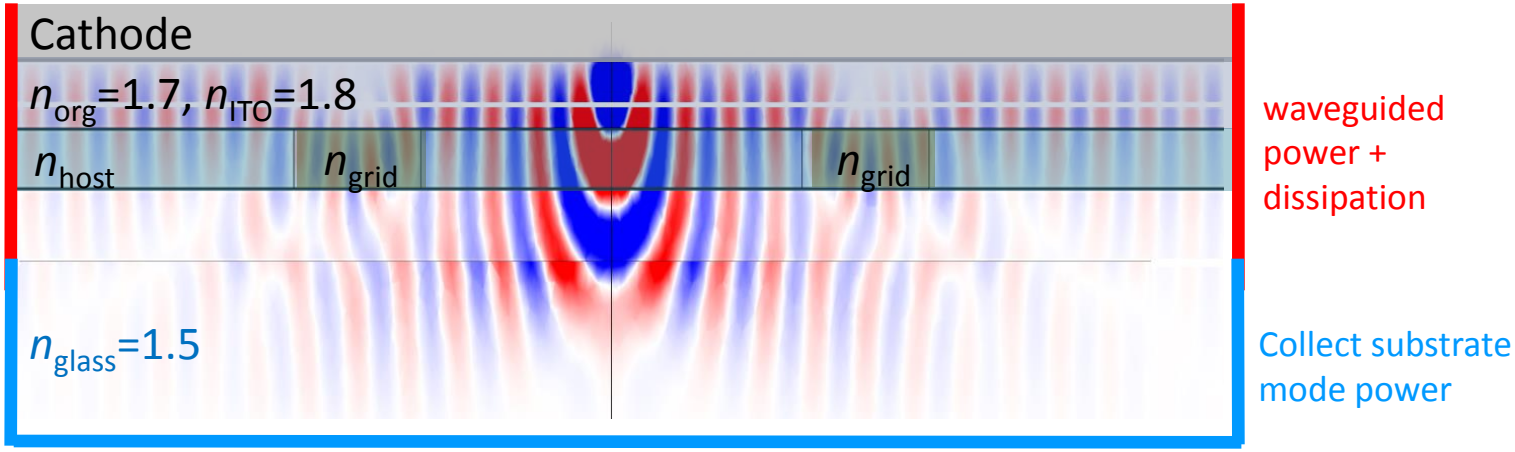
Device 1: Conventional
Device 2: LIG only
Device 3: Microlenses only
Device 4: LIG + Microlenses

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

A better approach: Sub-Anode Grid

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





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

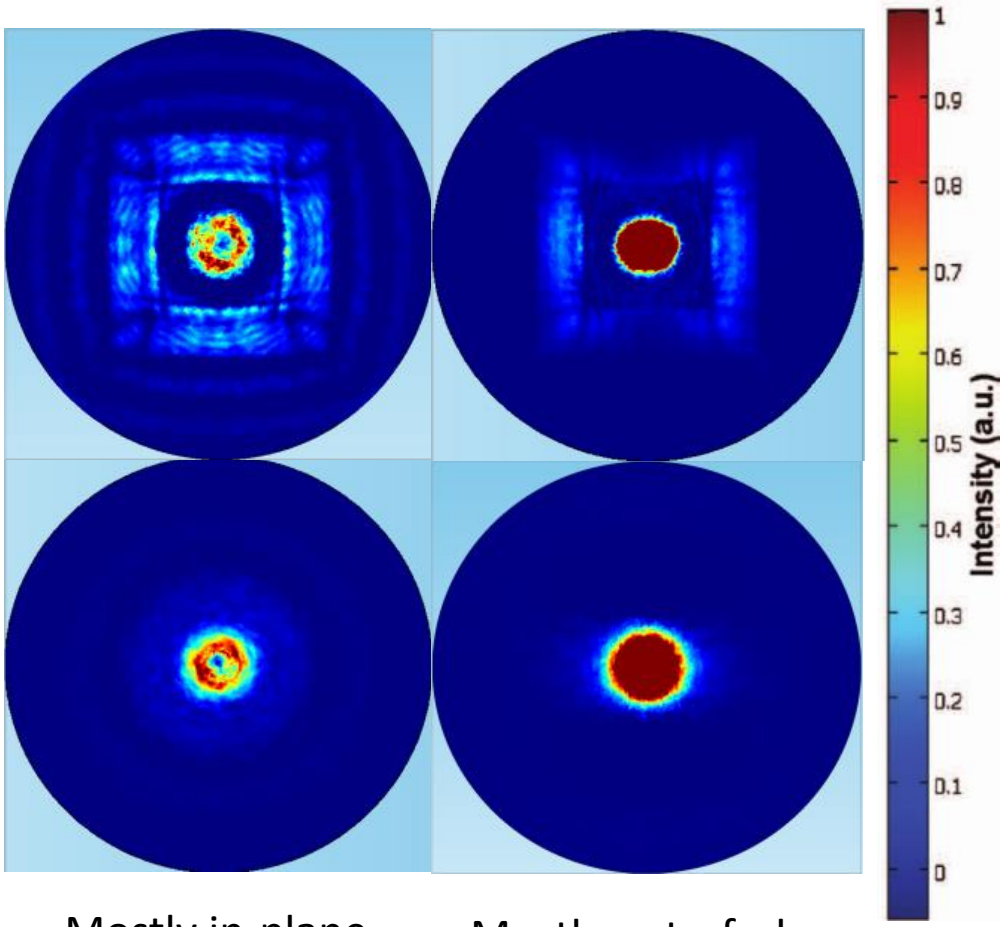
Emission fields

VERTICAL DIPOLE

HORIZONTAL DIPOLE

WITH GRID

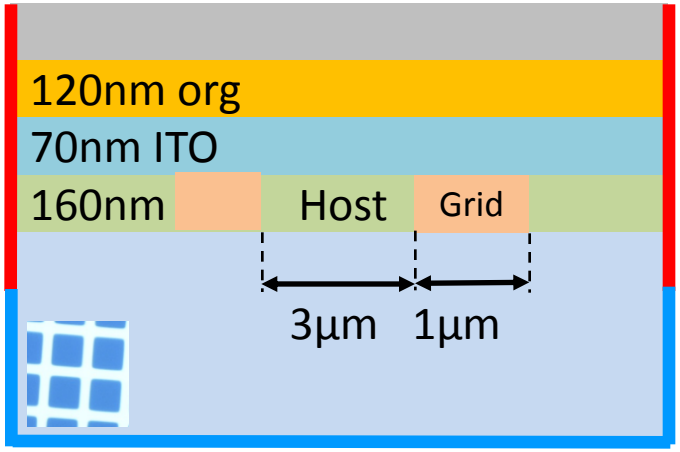
WITHOUT GRID

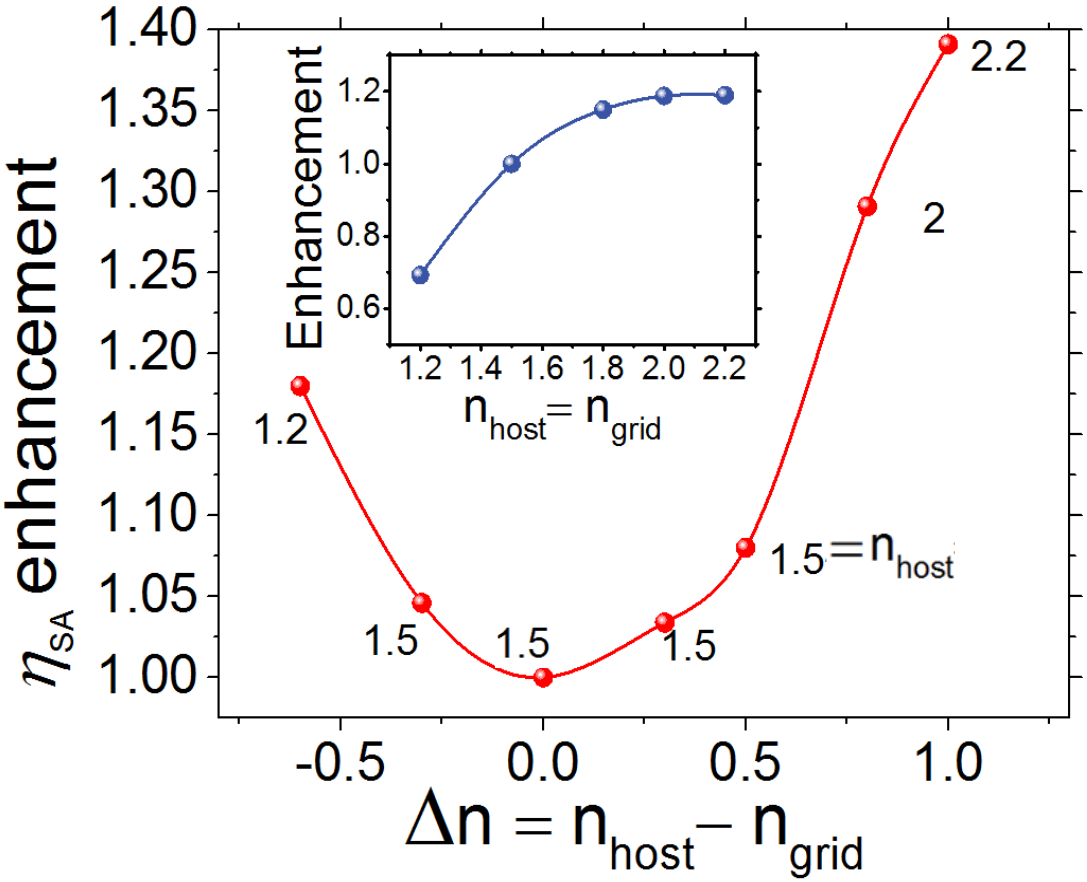


Mostly in-plane (Waveguided)

Mostly out-of-plane (Glass + air)

Effects of Refractive Index

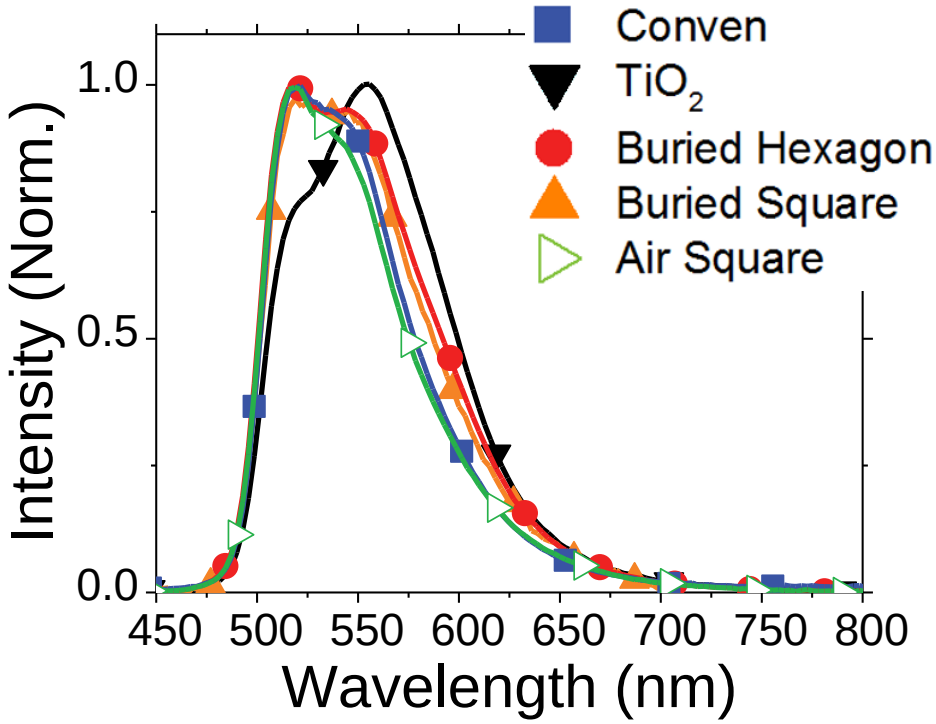


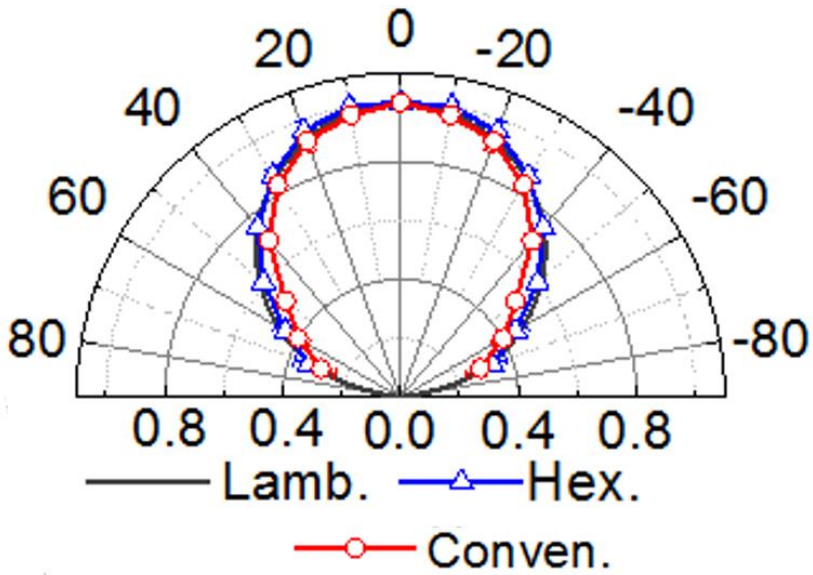


Simulation results

- Larger Refractive index difference gives higher enhancement
- <u>This is not a cavity effect</u>

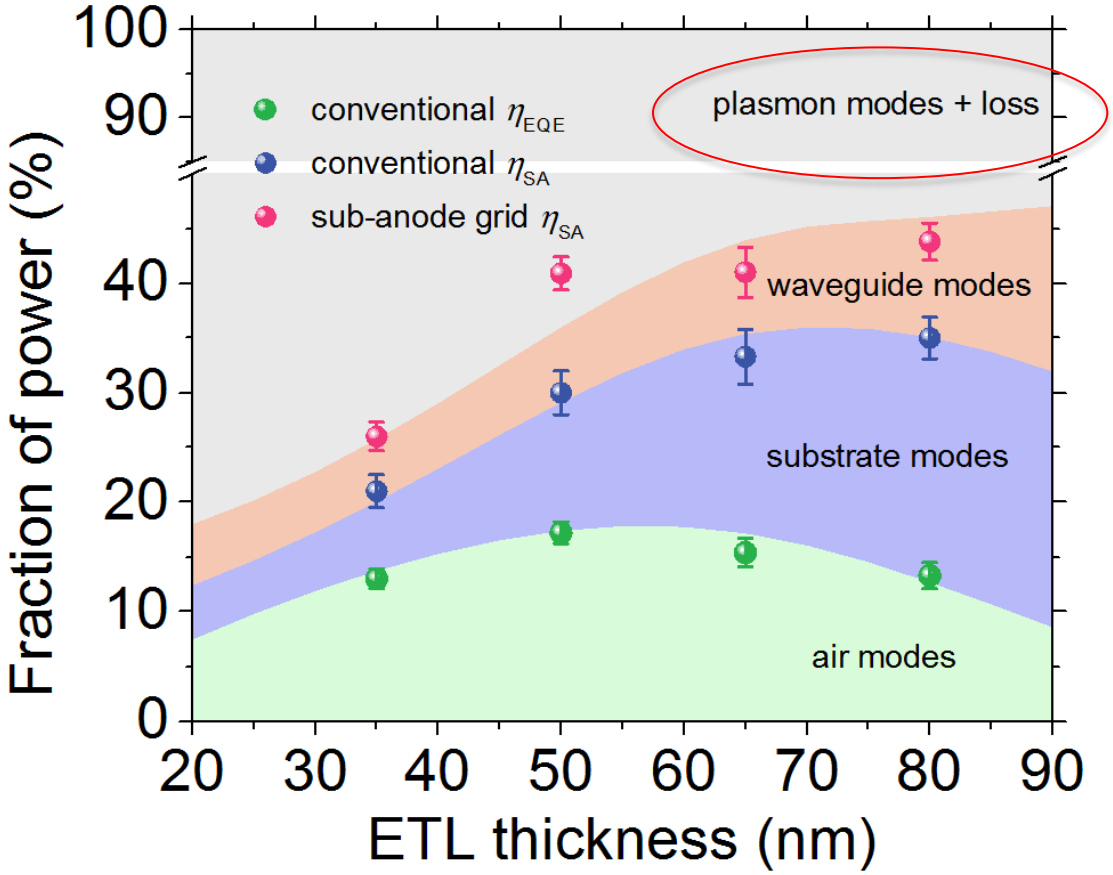
Optical Characteristics



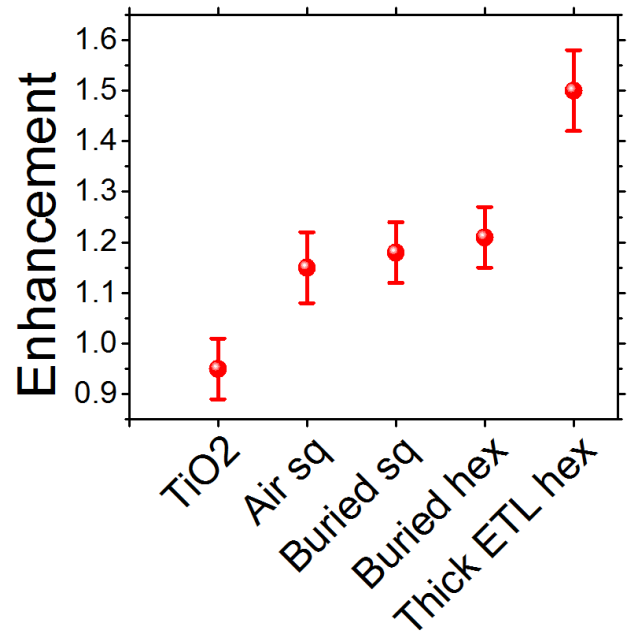


Little or no impact on emission characteristics of the OLED

Optical Power Distribution



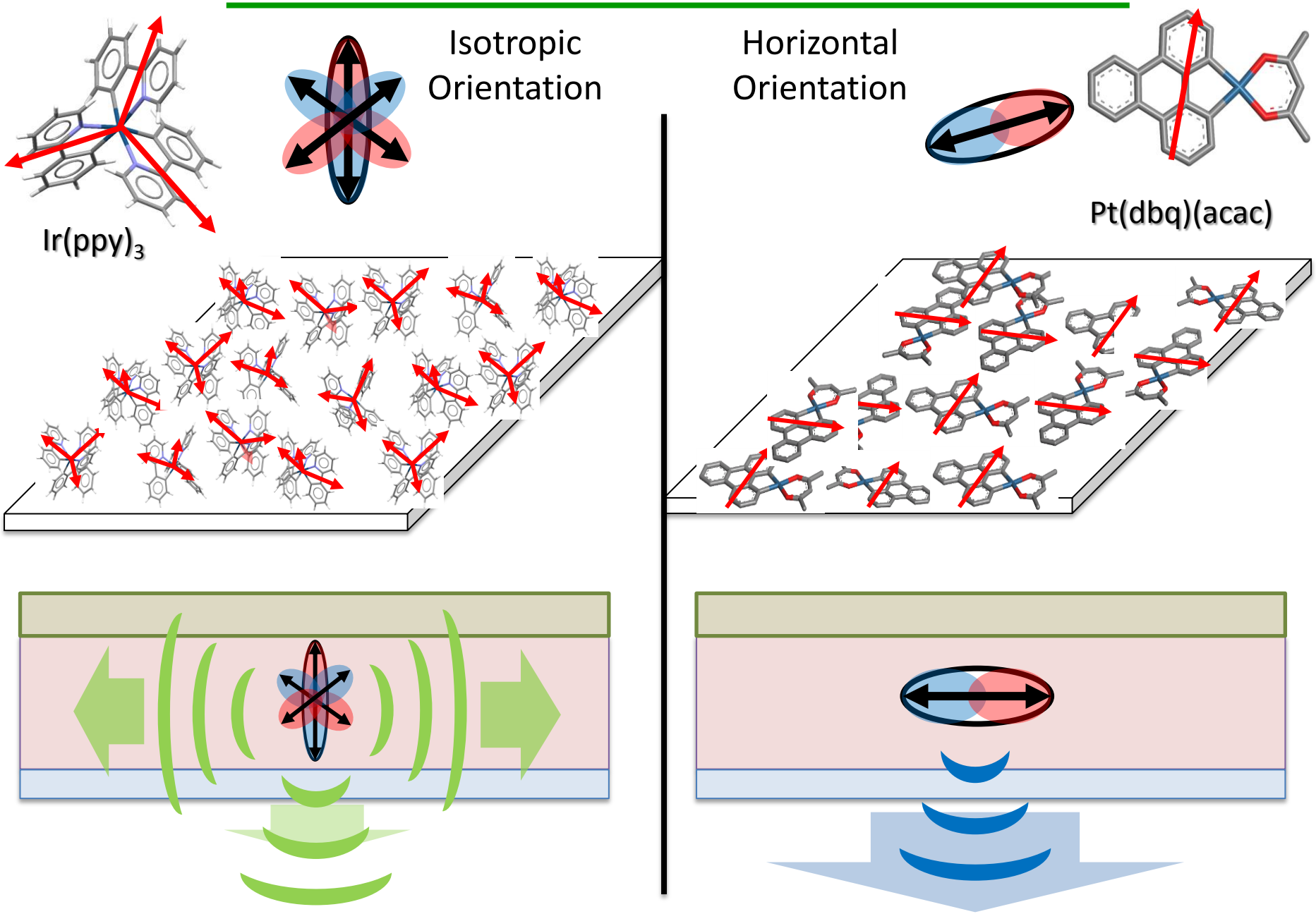
2nm MoO_3/40nm CBP/15nm CBP:Ir(ppy)$_3$/xnm TPBi/1nm LiF/Al



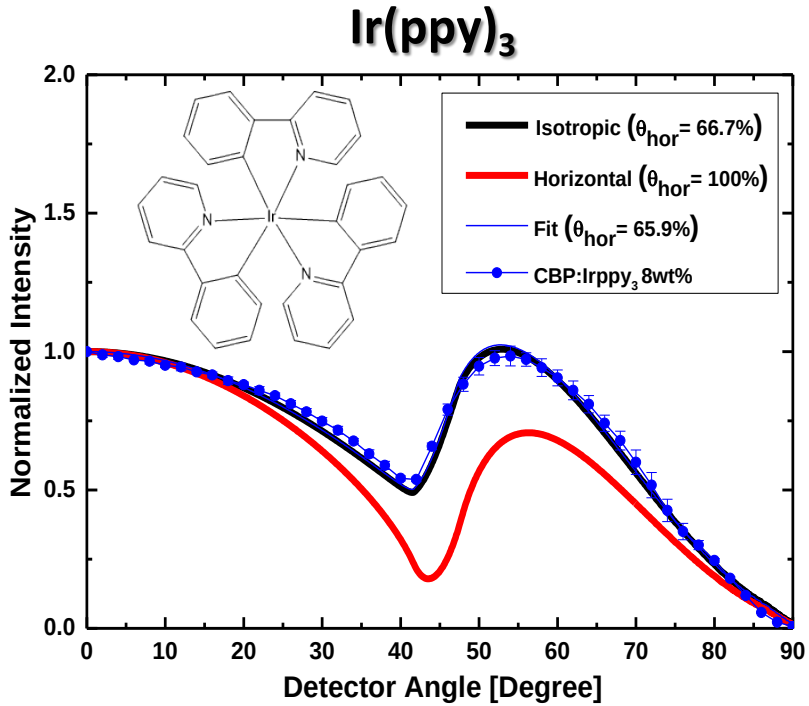
Thick-ETL organic structure:

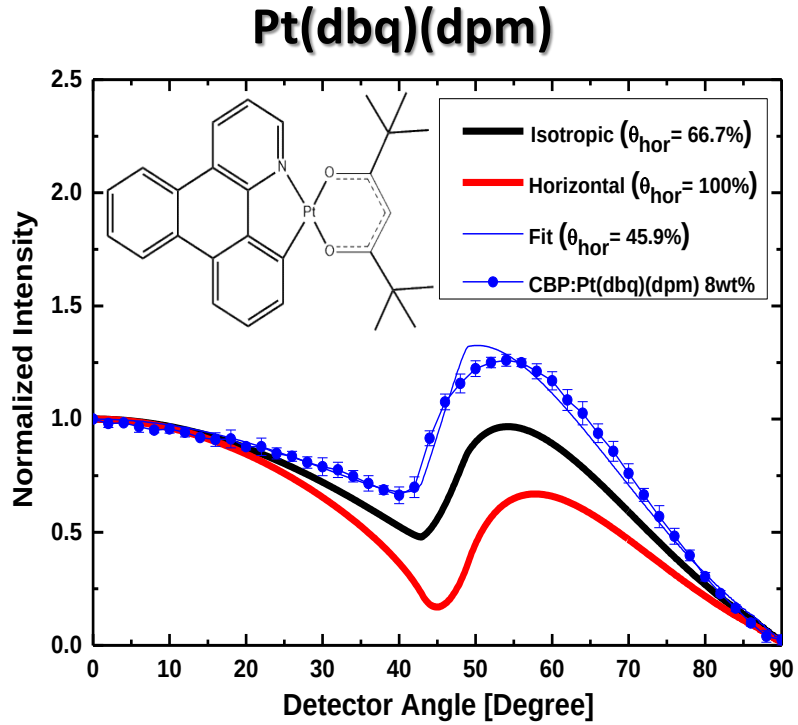
340nm grid/70nm ITO/2nm MoO_3/40nm TcTa/15nm CBP: Ir(ppy)$_3$/10nm TPBi/230nm Bphen:Li/Al

Manipulating Molecular Orientation



Example results



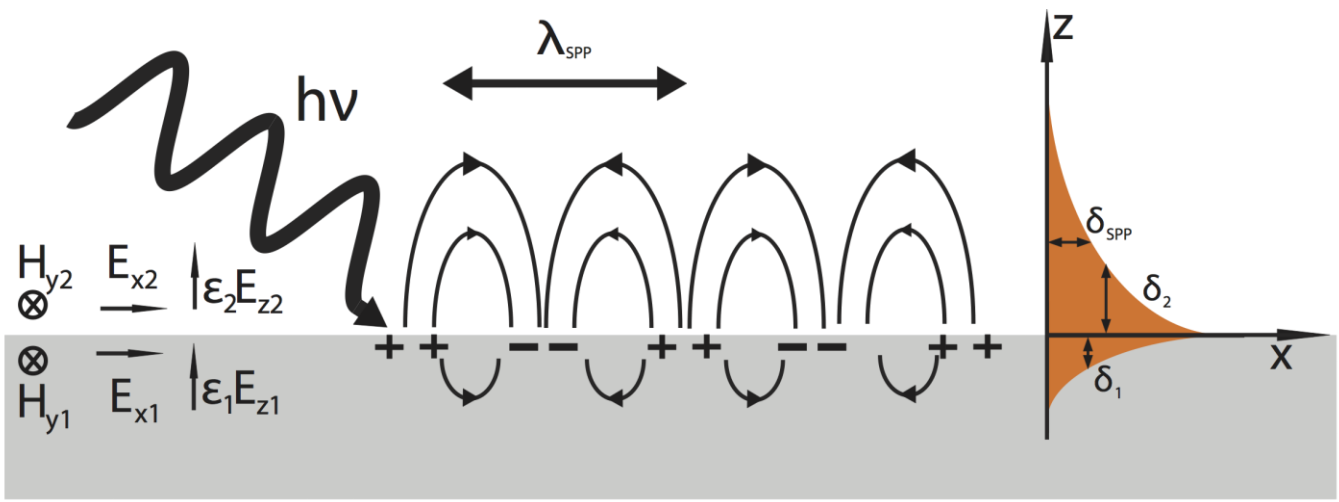


<u>Approach largely impractical</u>

- Added constraints on molecular design
- Added constraints on process (growth) conditions: may not align as expected
- Added constraints on device architecture
- Alignment is never “perfect”: only modest improvements

The Last Frontier: Surface Plasmon Polariton (SPP) Modes

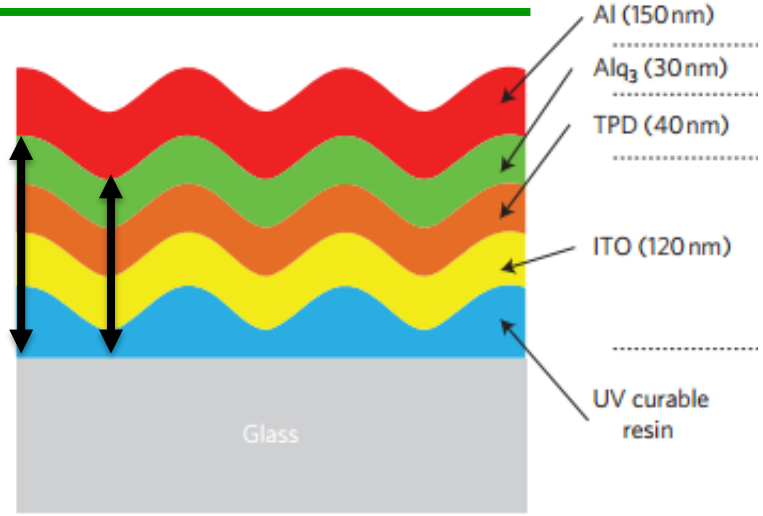
η_{ext} > 80% (incl. substrate + waveguide modes)



- 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

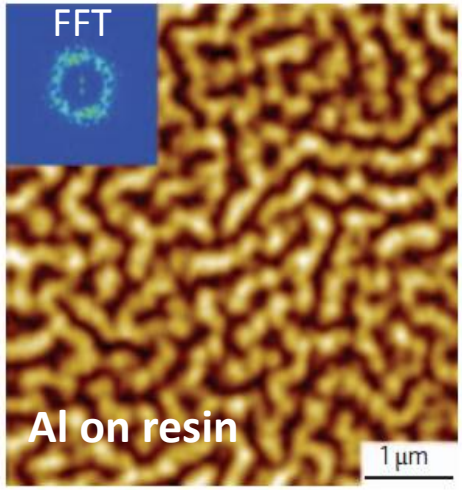
One possible solution: Surface corrugations

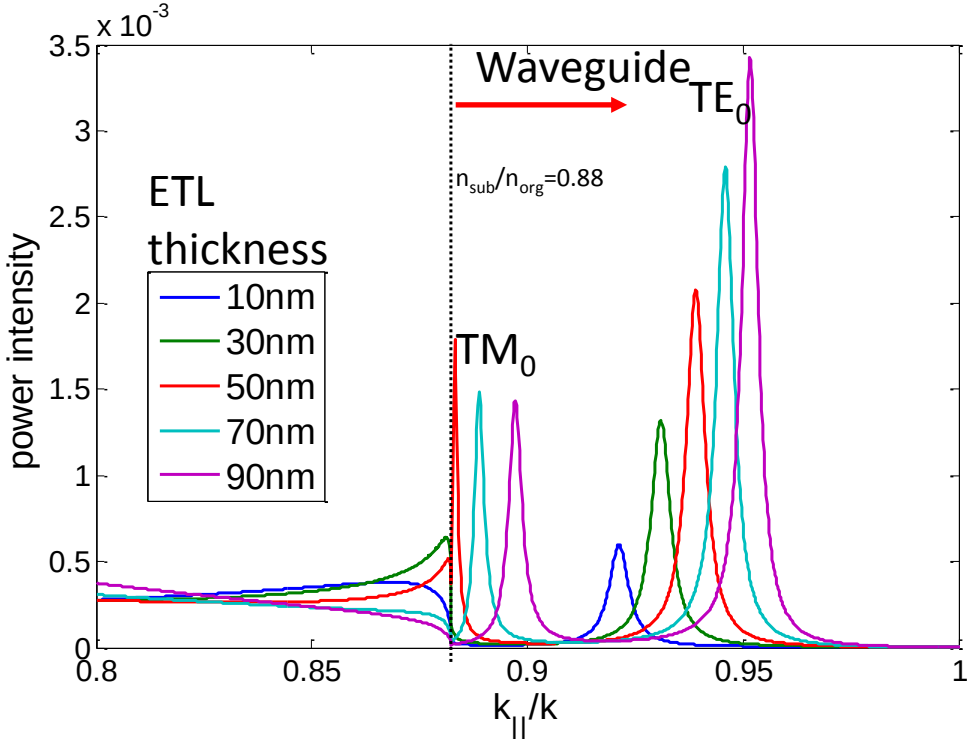
- Waveguide thickness varies due to the corrugation.
- As the thickness changes, the mode distribution changes.
- When the waveguided power travels from thin to thick areas, the k vector needs to change direction to keep "being trapped". Otherwise, the light is extracted.



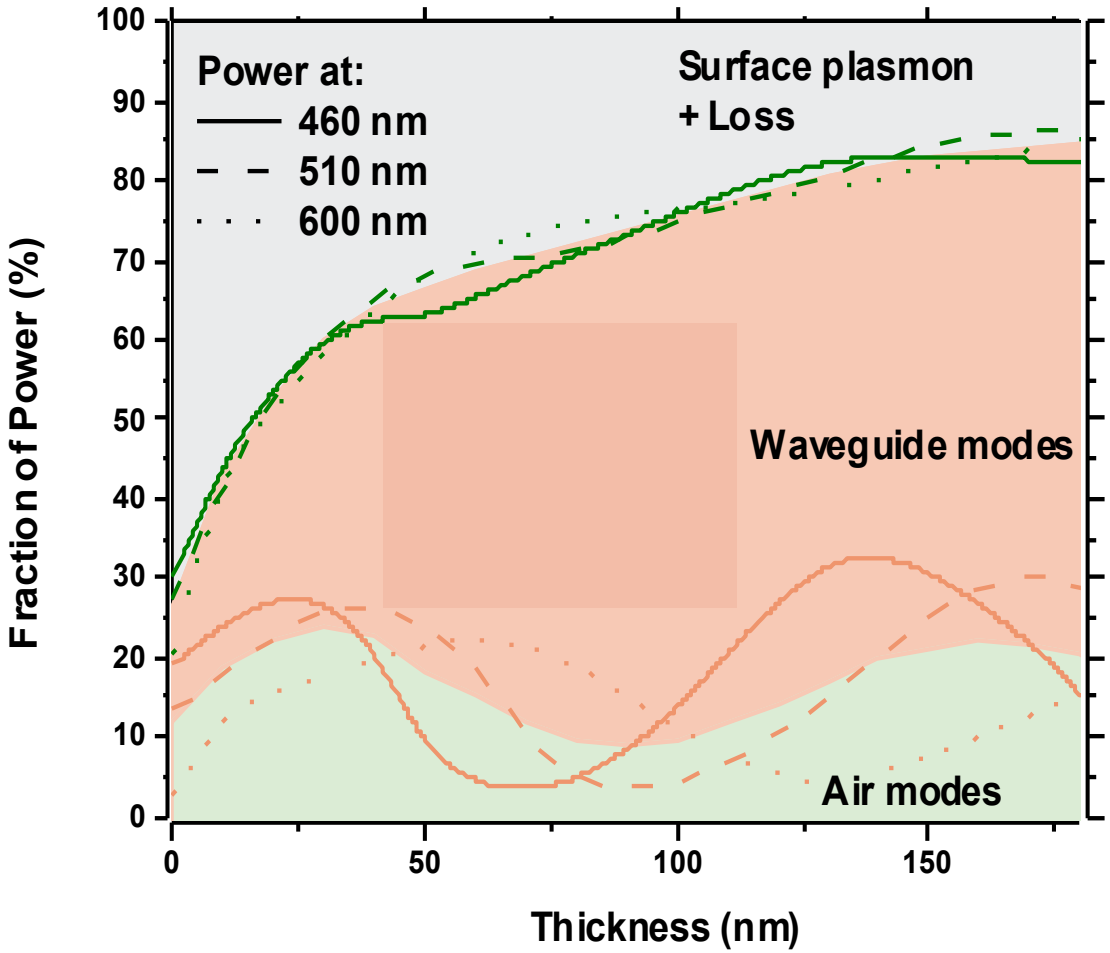
W. H. Koo, et al, *Nat. Photonics* 2010, **4**, 222.

A possible approach: Surface buckling?





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!

Conclusions

- Optimal criteria for outcoupling solutions
  - Low cost
  - Angle and wavelength independent
  - Minimal impact on established OLED and materials designs
- Sub-anode grid outcouples *all* waveguide modes
- No impact on electrical characteristics
- No significant optical effect
- No active dead zone
- SPP Modes are the final frontier
  - 80% outcoupling may be possible if appropriate techniques are employed