Week 2-4

Light emitters 4

Stacked WOLEDs

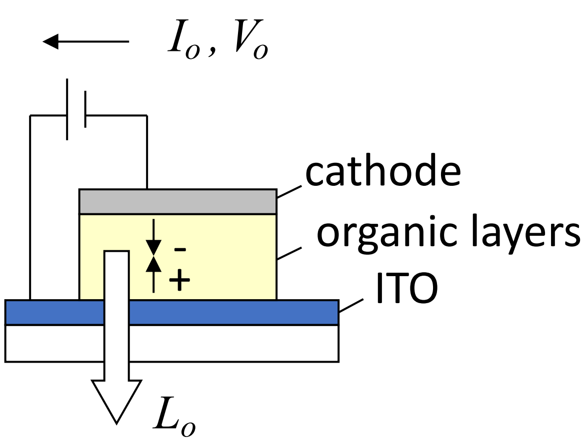
Outcoupling

Chapter 6.5.4-6.6

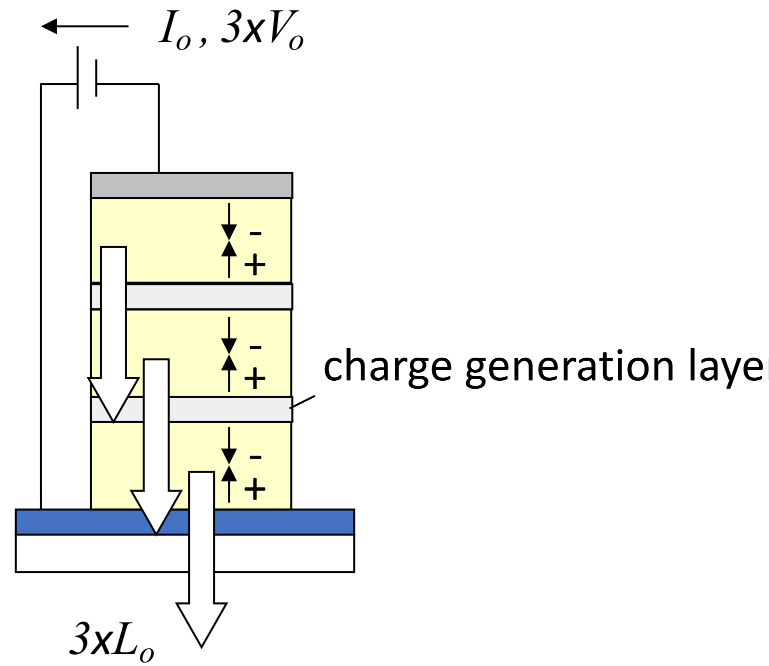
White Phosphorescent SOLEDs

Requires less current for same luminance as a single unit device

- Longer lifetime at same luminance
- Less current for a given luminance = reduced resistive power losses and heating



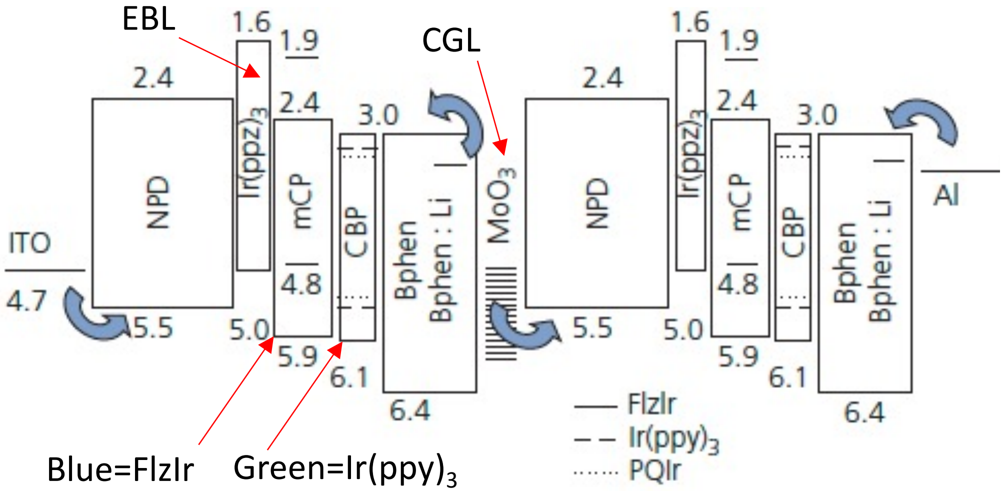
Conventional OLED



Stacked OLED (SOLED)

Lifetime and efficiency of OLEDs can be increased by vertically stacking multiple OLED units in series

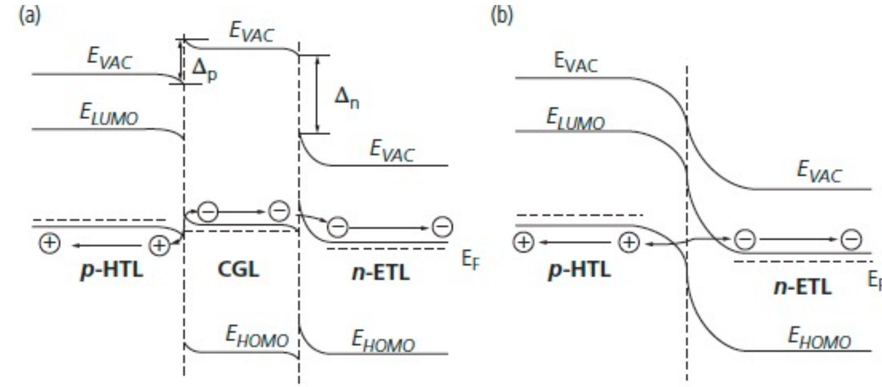
SOLED Operation Principles



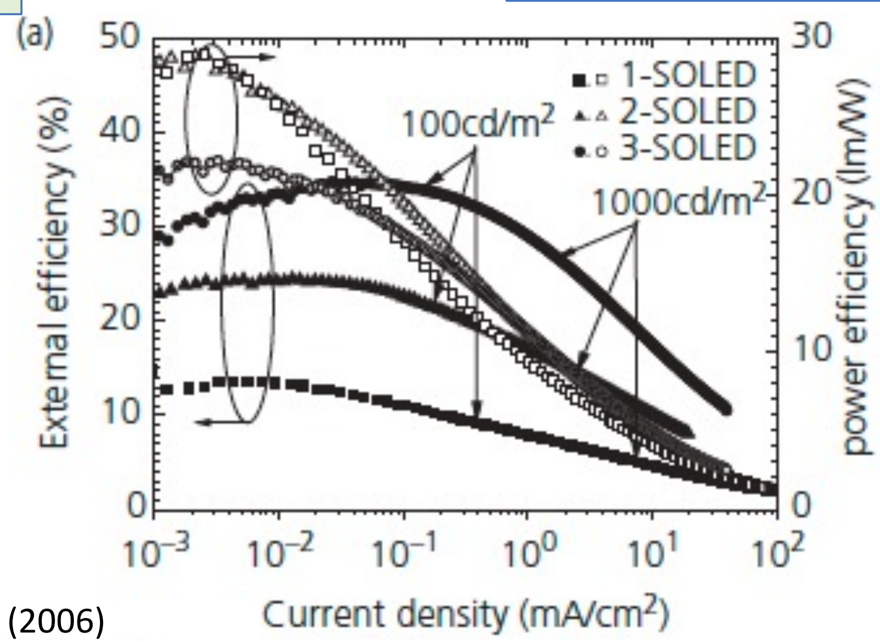
Blue=FlzIr Green=Ir(ppy)$_3$

Red=PQIr

Archetype stacked WOLED

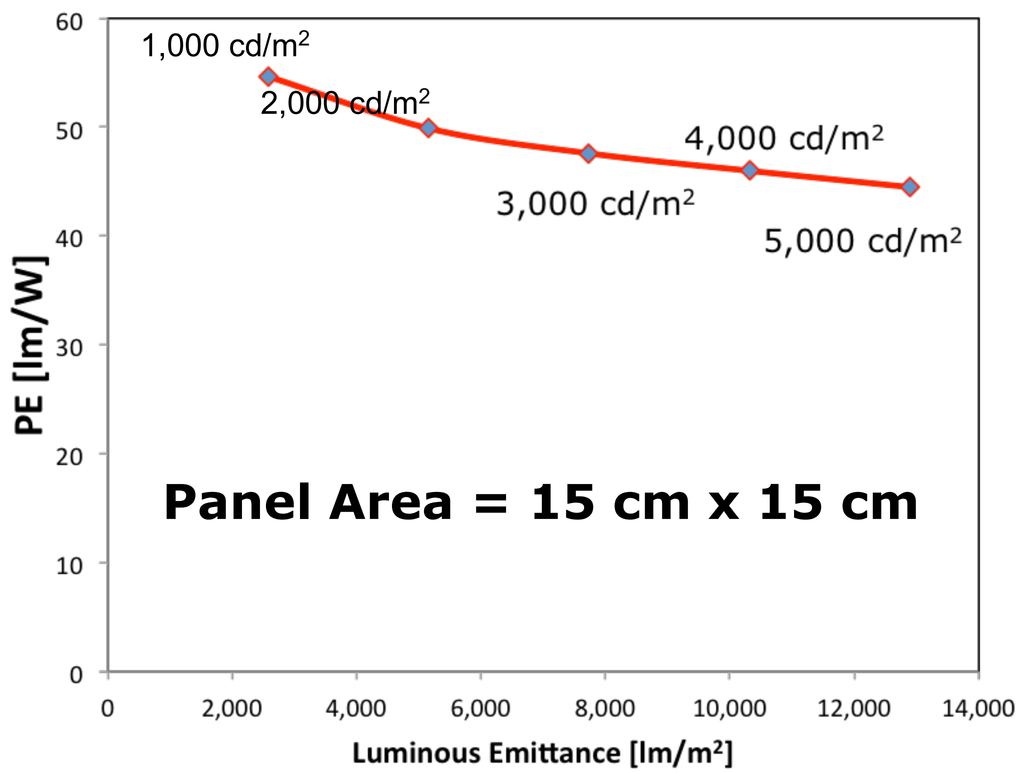


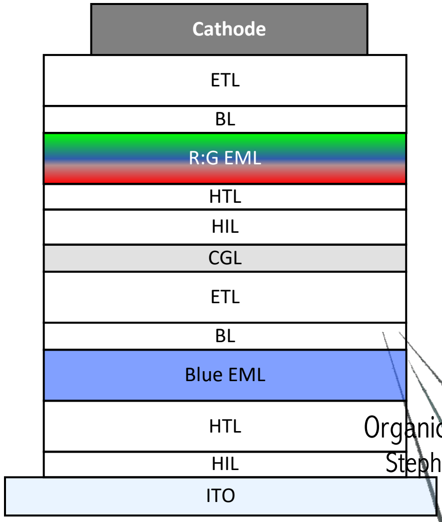
Two types of CGLS: Recombination vs. tunnel junctions



Kanno et al., Adv. Mater., 18, 339 (2006)

White SOLED Panel: Efficacy vs. Luminous Emittance

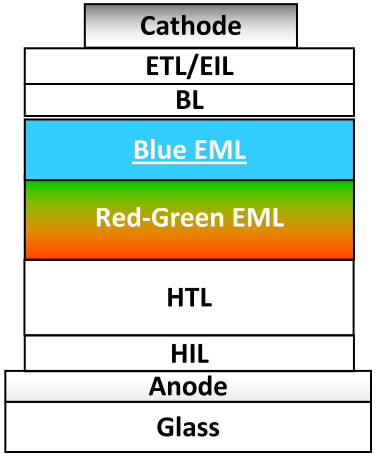




- Efficacy approaching 50 lm/W at 10,000 lm/m^2
- CRI = 83
- LT70 = 4,000 hrs

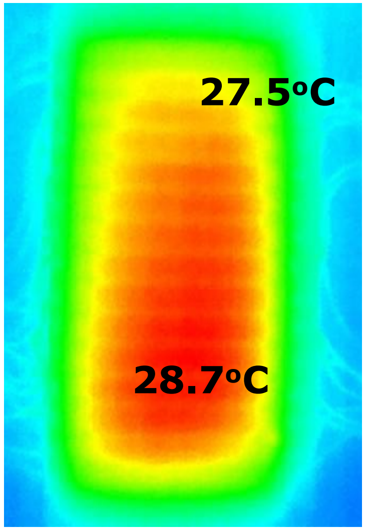
White PHOLED Panel

Panel 15 cm x 15 cm 15 mm thick	At 1,000 cd/m^2	At 3,000 cd/m^2
Efficacy [lm/W]	**58**	**49**
CRI	**82**	**83**
Luminous Emittance [lm/m^2]	2,580	7,740
Voltage [V]	3.8	4.3
1931 CIE	(0.466, 0.413)	(0.471, 0.413)
Duv	0.001	0.000
CCT [K]	2,640	2,580
Efficacy Enhancement	1.75x	1.75x
Temperature Rise [°C]	**0.7**	**7.2**
LT70 [hrs]	**30,000**	**4,000**

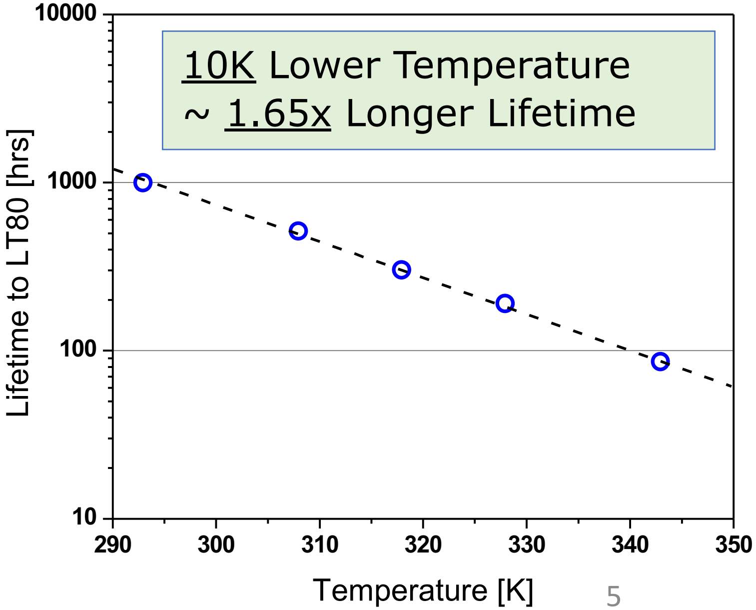


LT70 ~ 30K hrs at 1000 cd/m^2
Warm White with CCT 2640K

Lower current at constant *L*
⇒lower temperature
⇒longer lifetime

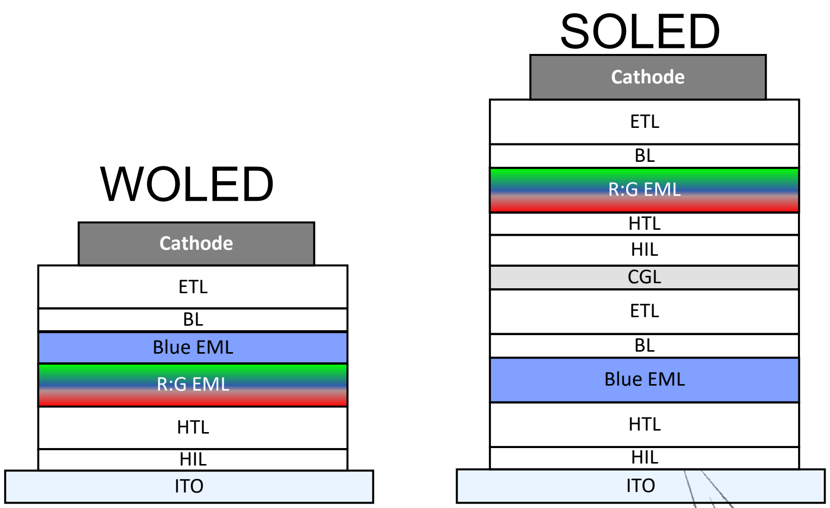


t = 60 min
3000 cd/m^2



WOLED vs. SOLED Panel Comparison

Panel 15 cm x 15 cm 82% fill factor	Single Unit WOLED*	2 Unit WSOLED
Luminance [cd/m^2]	**3,000**	**3,000**
Efficacy [lm/W]	**49**	**48**
CRI	**83**	**86**
Luminous Emittance [lm/m^2]	7,740	7,740
Voltage [V]	4.3	7.4
1931 CIE	(0.471, 0.413)	(0.454, 0.426)
Duv	0.000	0.006
CCT [K]	2,580	2,908
Temperature [°C]	**27.2**	**26.2**
LT_{70} [hrs]	**4,000**	**13,000**

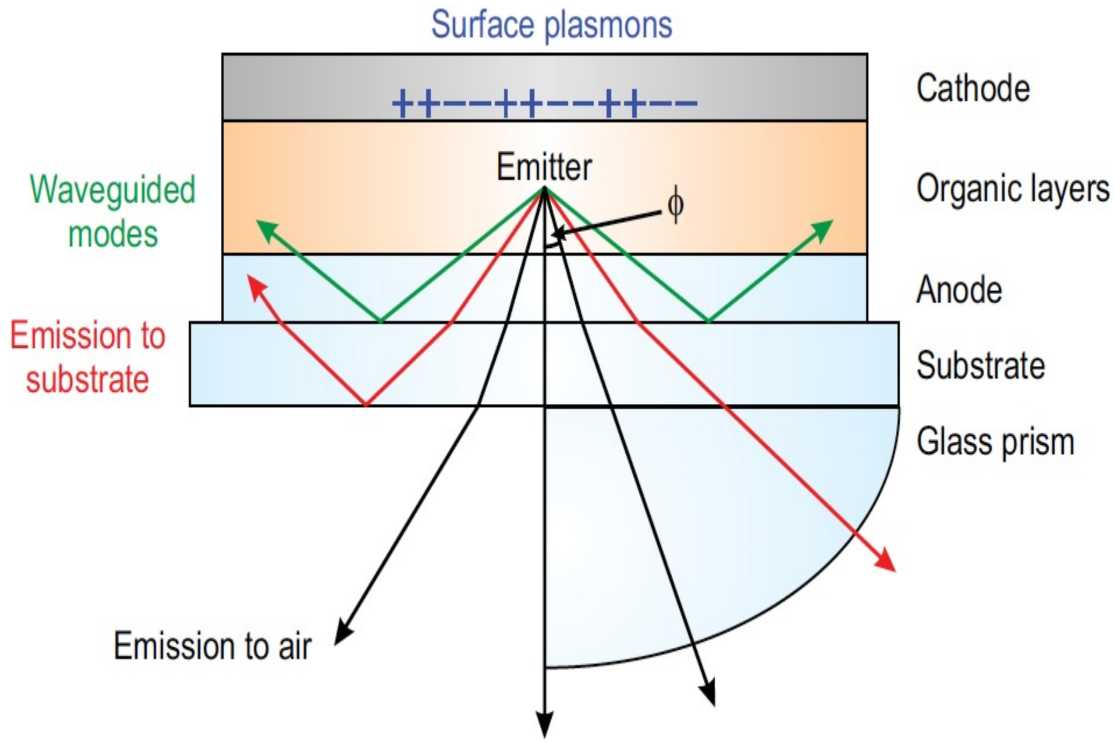


SOLED architecture: ~ 3x LT_{70} improvement vs. single unit WOLED with similar color and power efficacy

P.Levermore et al, SID Digest, 72.2, p.1060, 2011.

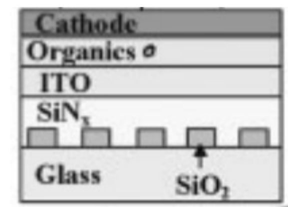
OLEDs: Not All Light Goes to the Viewer

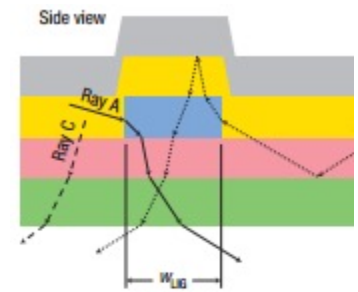
- Optical paths outcoupled with hemispherical lens

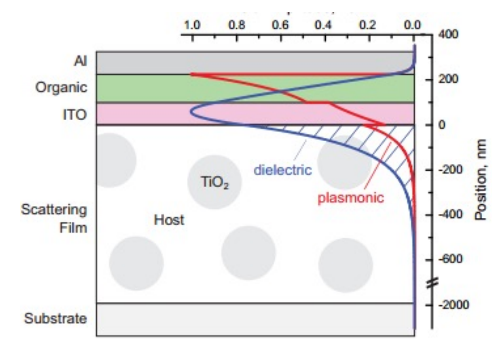


Getting all the photons out

- **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

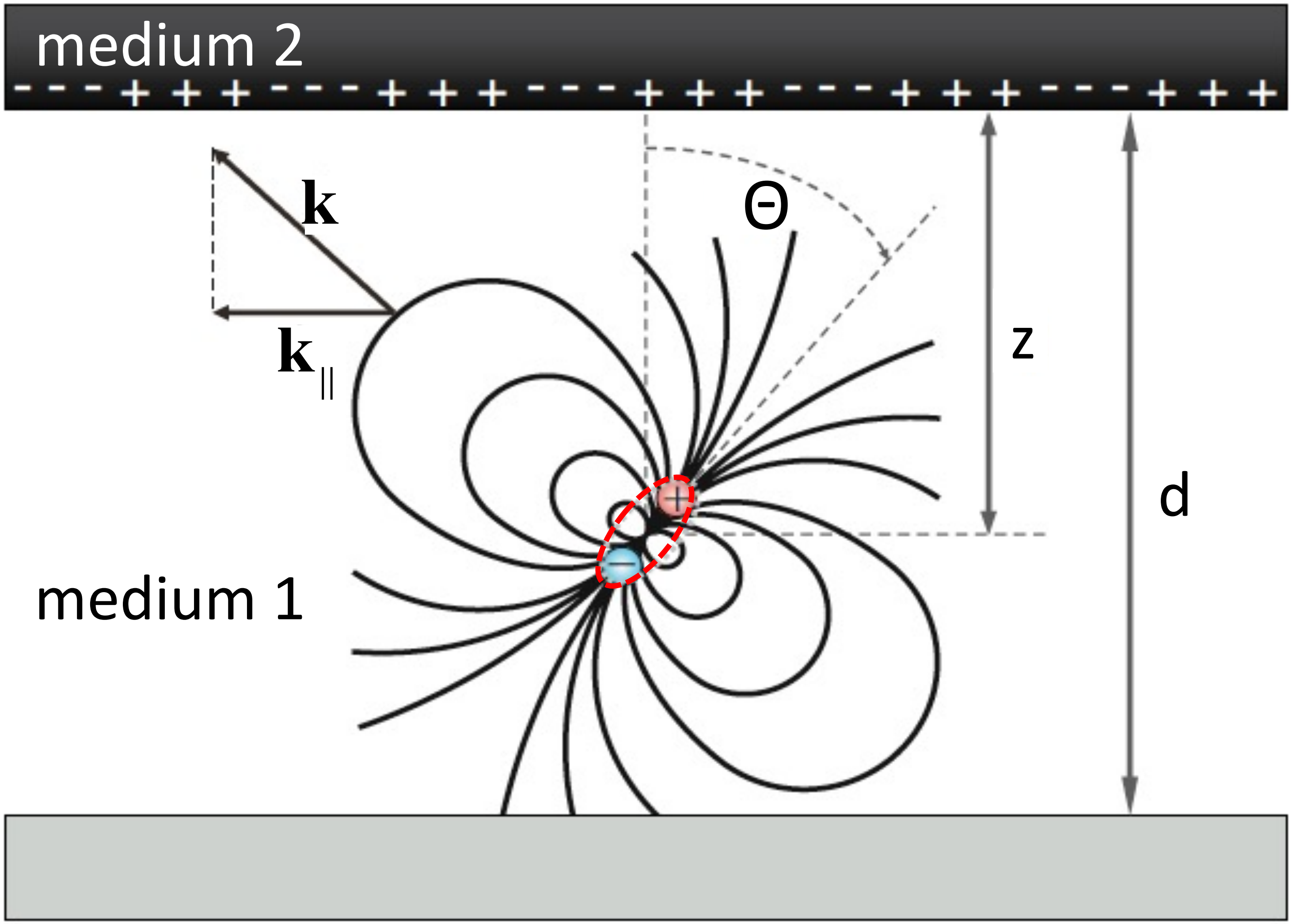




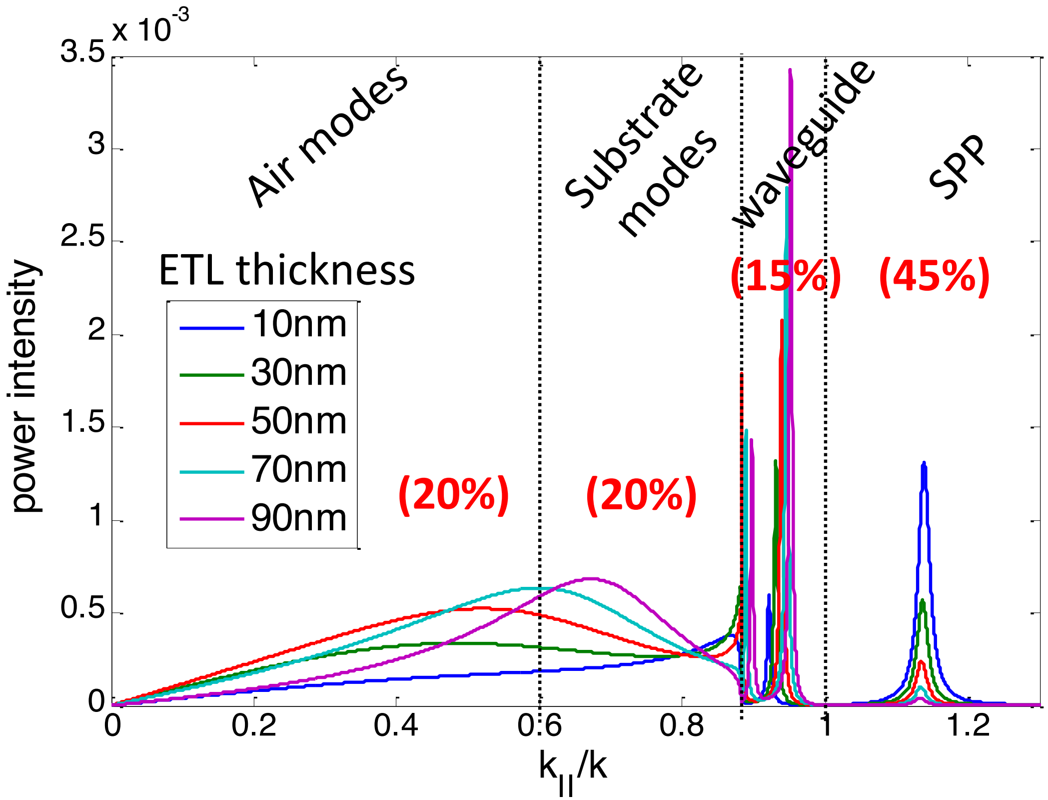


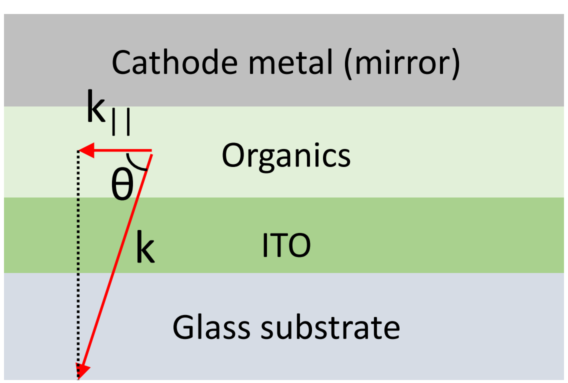
[1]Y .R. Do, et al, *Adv. Mater*. **15**, 1214 (2003).
[2]Y. Sun and S.R. Forrest, *Nat Phot*. **2**, 483 (2008).
[3]Chang, H.-W. *et al*. *J. Appl. Phys.* **113,** - (2013).

Molecules are radiating dipoles in inhomogeneous media



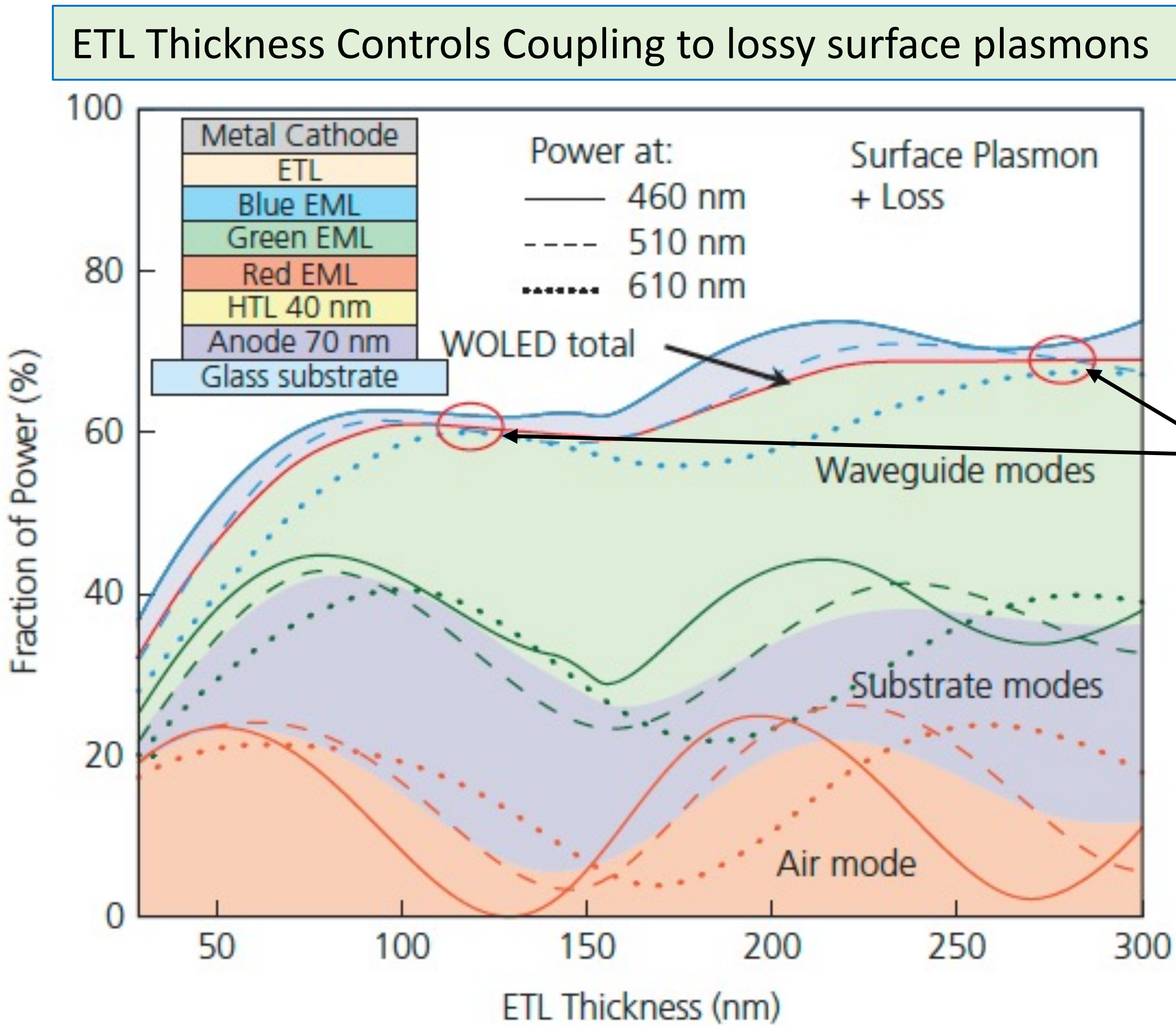
Where do all the photons go?





- **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

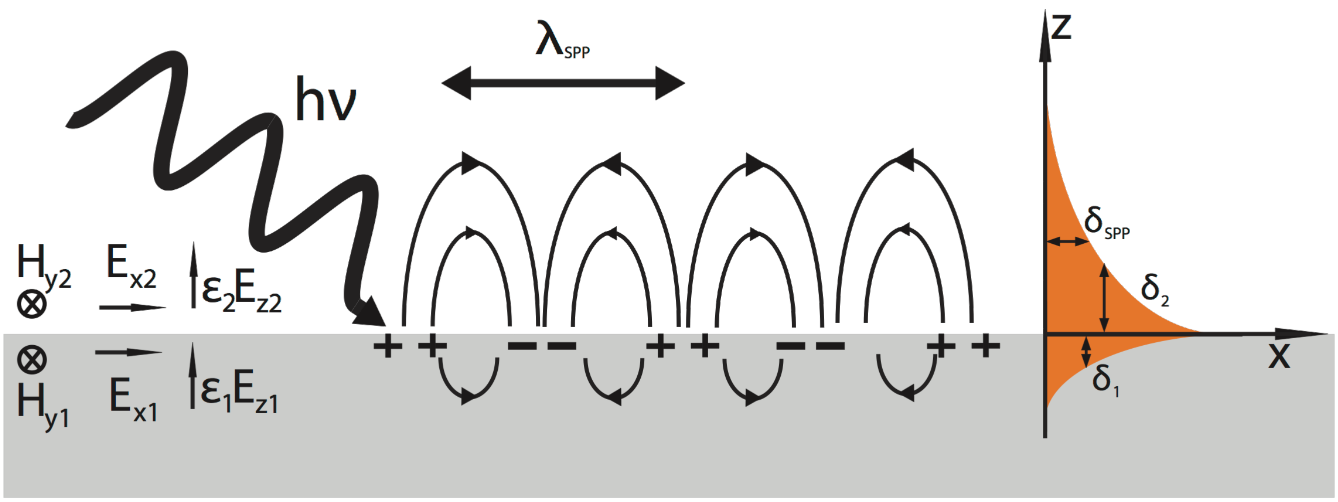
WOLED Outcoupling Can Yield True Color



Color balance achieved at two ETL thicknesses

Surface Plasmon Polariton (SPP) Modes: Major Loss Channel

$\eta_{ext} > 80\%$ (incl. substrate + waveguide modes)

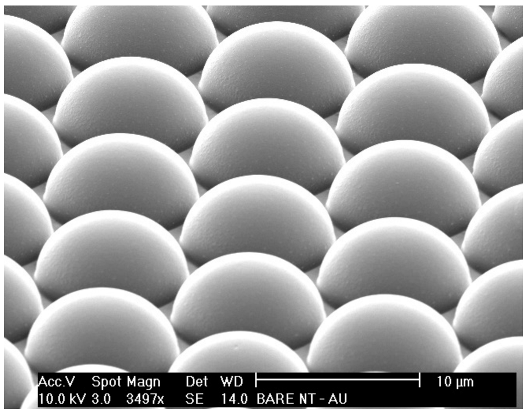


- Waveguided light excites lossy SPPs in metal cathode
- Major loss channel partially eliminated by rapid outcoupling of waveguide modes
- Most difficult to eliminate cost-effectively without impacting device structure

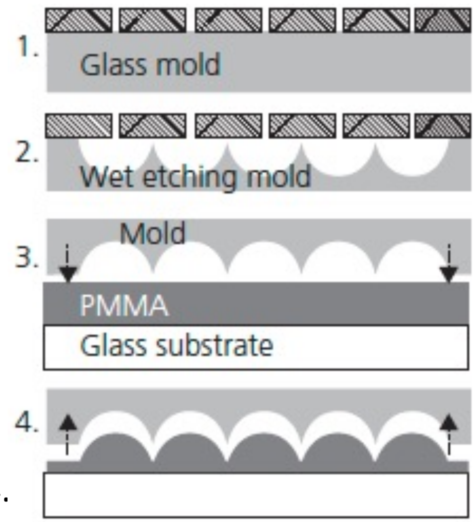
Substrate Mode Outcoupling: ~2X Improvement

η_{ext}~40%

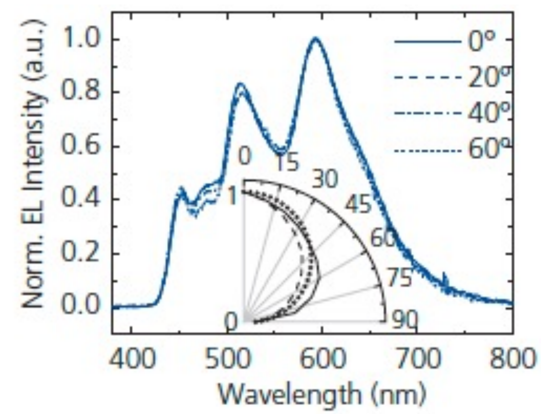
Microlens arrays: Polymer hemispheres much smaller than pixel



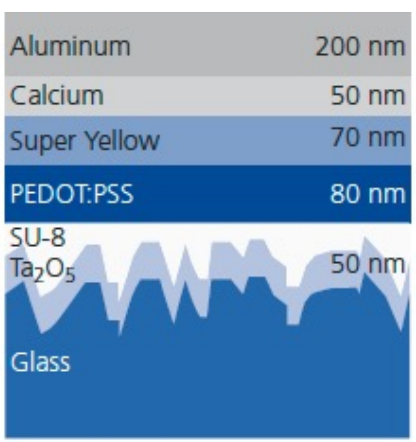
Möller, S. & Forrest, S. R. 2001. *J. Appl. Phys.,* 91**,** 3324.



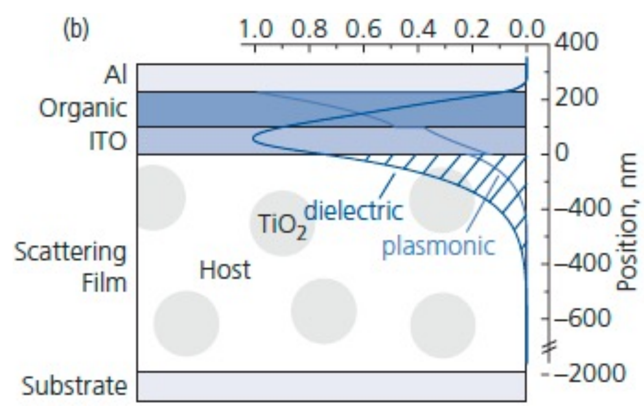
Fabrication sequence



Spectrum angle independent



Reidel, et al., Opt. Express 18 A631 (2010)

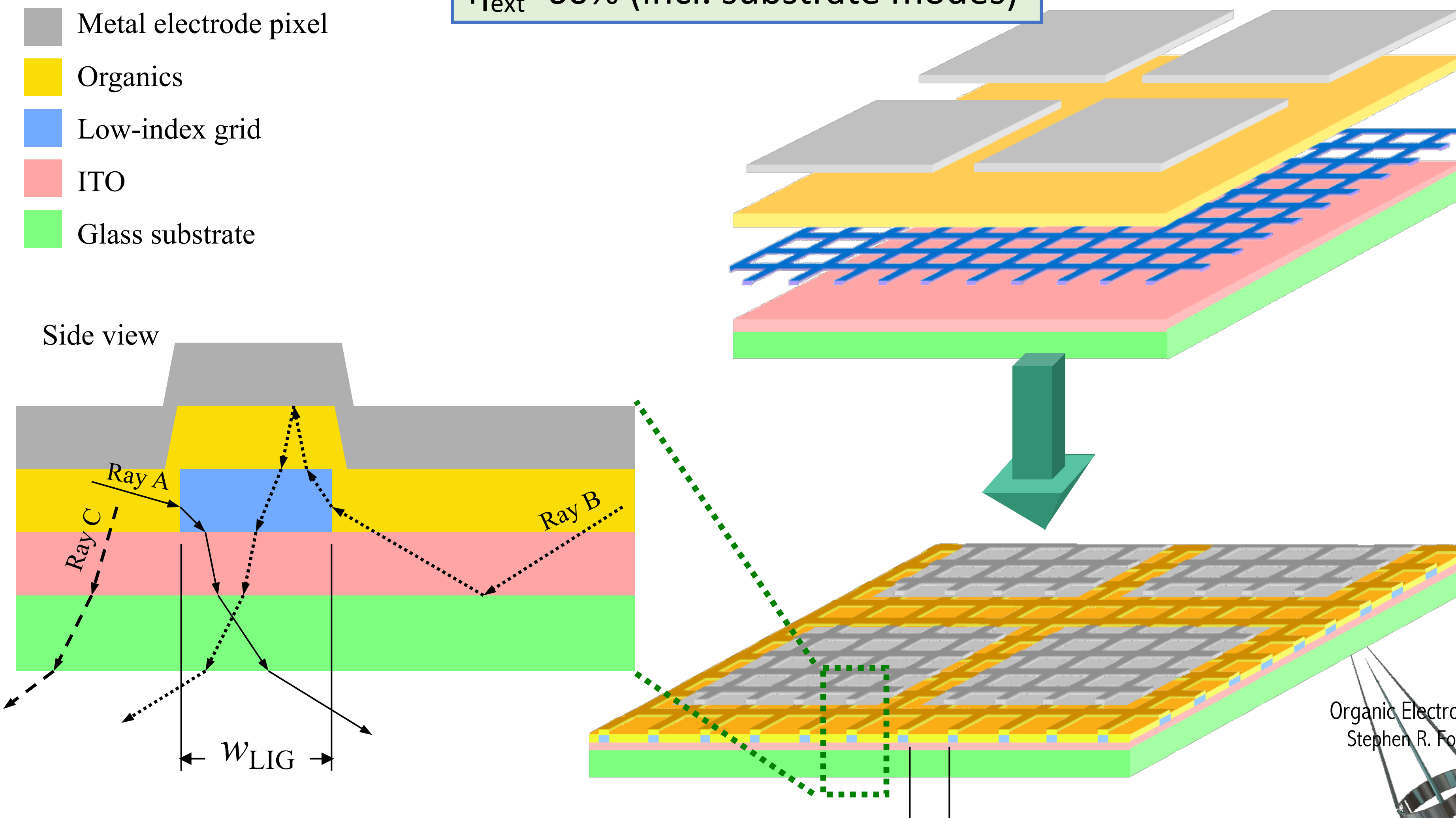


Chang, et al., J. Appl. Phys., 113 204502 (2013)

⇐ Scattering and surface roughness also can reduce substrate modes

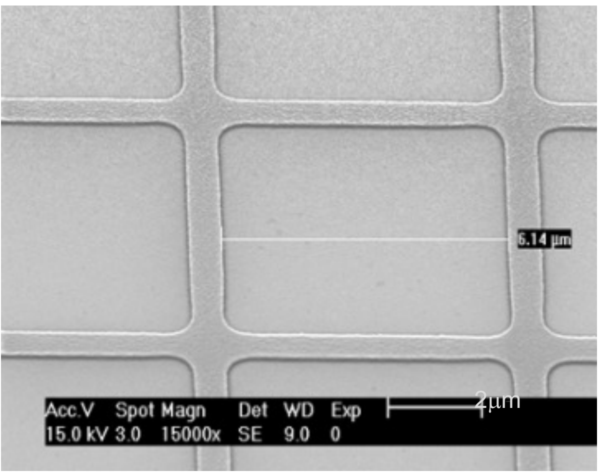
Waveguide Mode Outcoupling: Embedded Low Index Grid

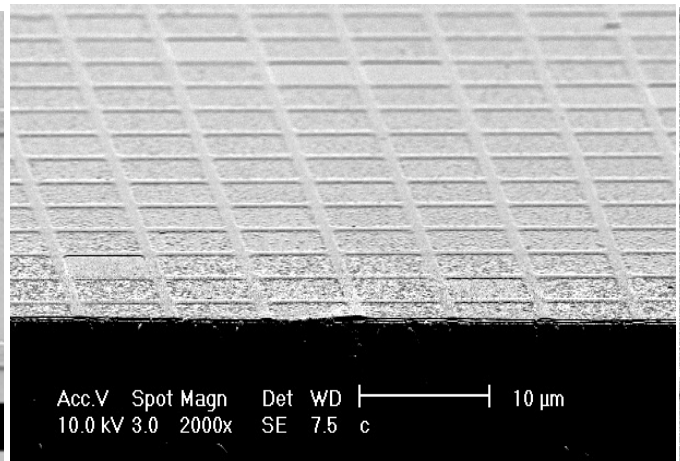
η_{ext}~60% (incl. substrate modes)

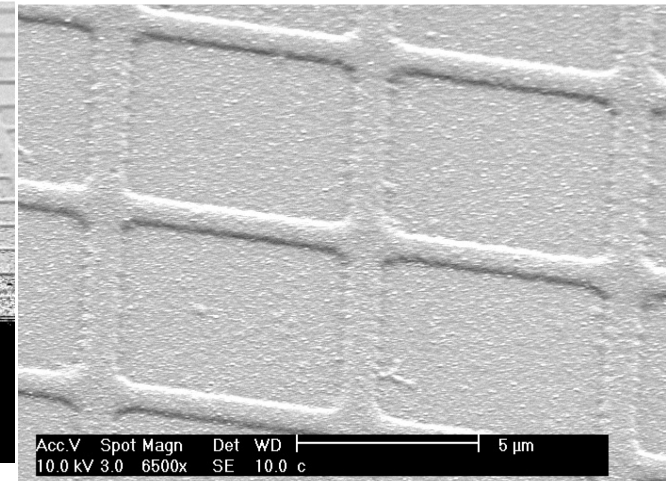


Sun, Y. & Forrest, S. R. 2008. *Nature Photon.*, **2**, 483.

Low Index Grid Images

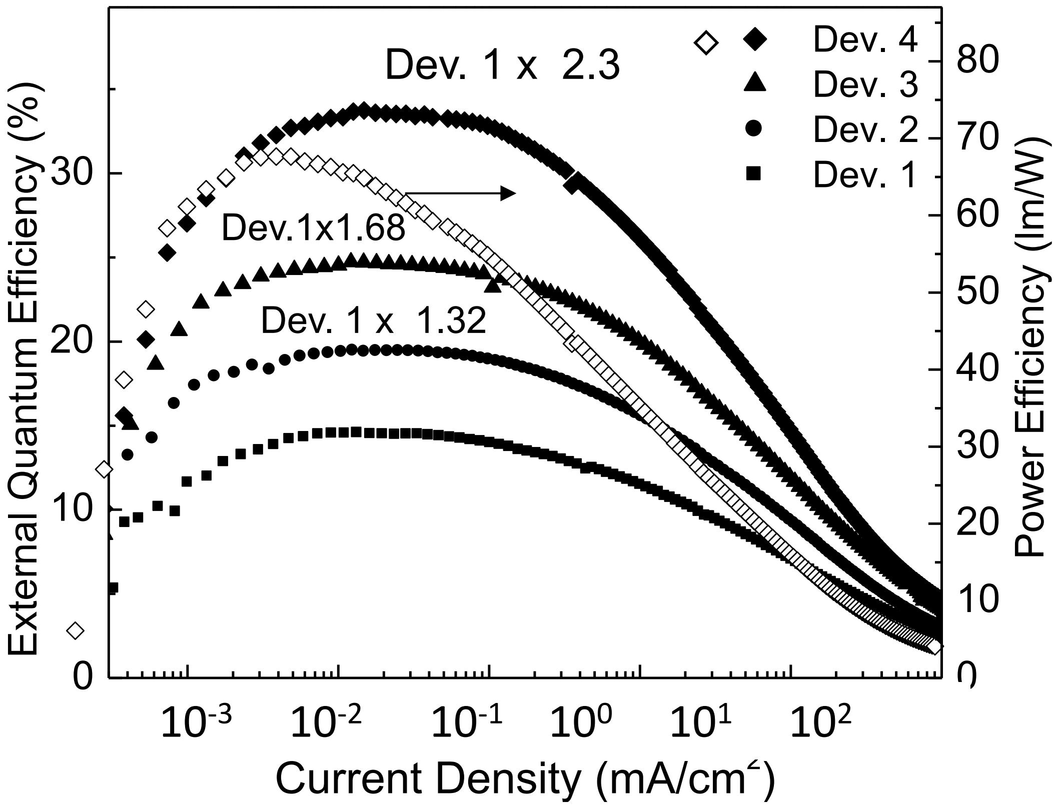


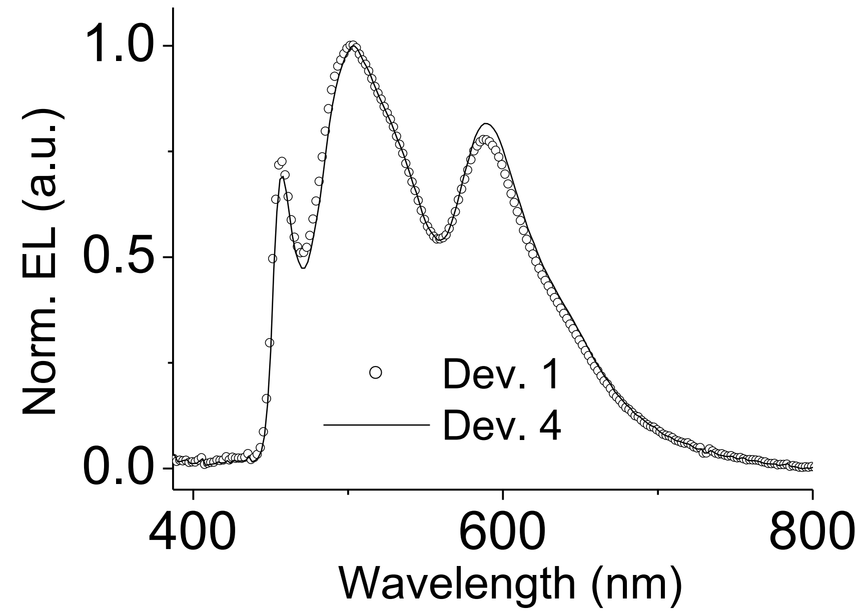




- OLED >> Grid size >> Wavelength
- Embedded into OLED structure
- May partially decouple waveguide mode from SPPs

Hybrid WOLED Performance
Using Embedded Grids + Microlens Arrays





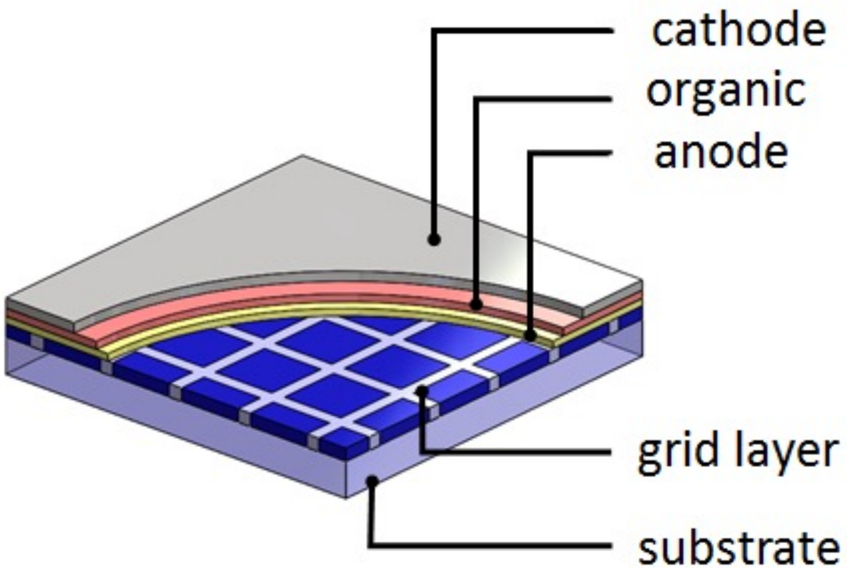
Method is Wavelength Independent

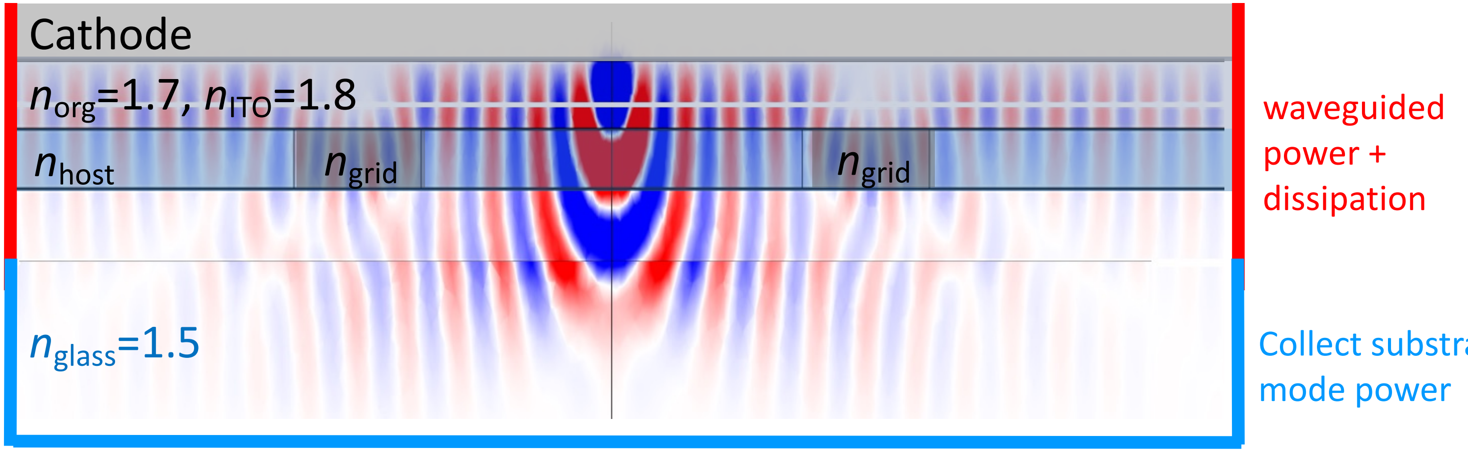
Device 1: Conventional
Device 2: LIG only
Device 3: Microlenses only
Device 4: LIG + Microlenses

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)
- The grid is removed from the OLED active region
- Waveguided light is scattered into substrate and air modes





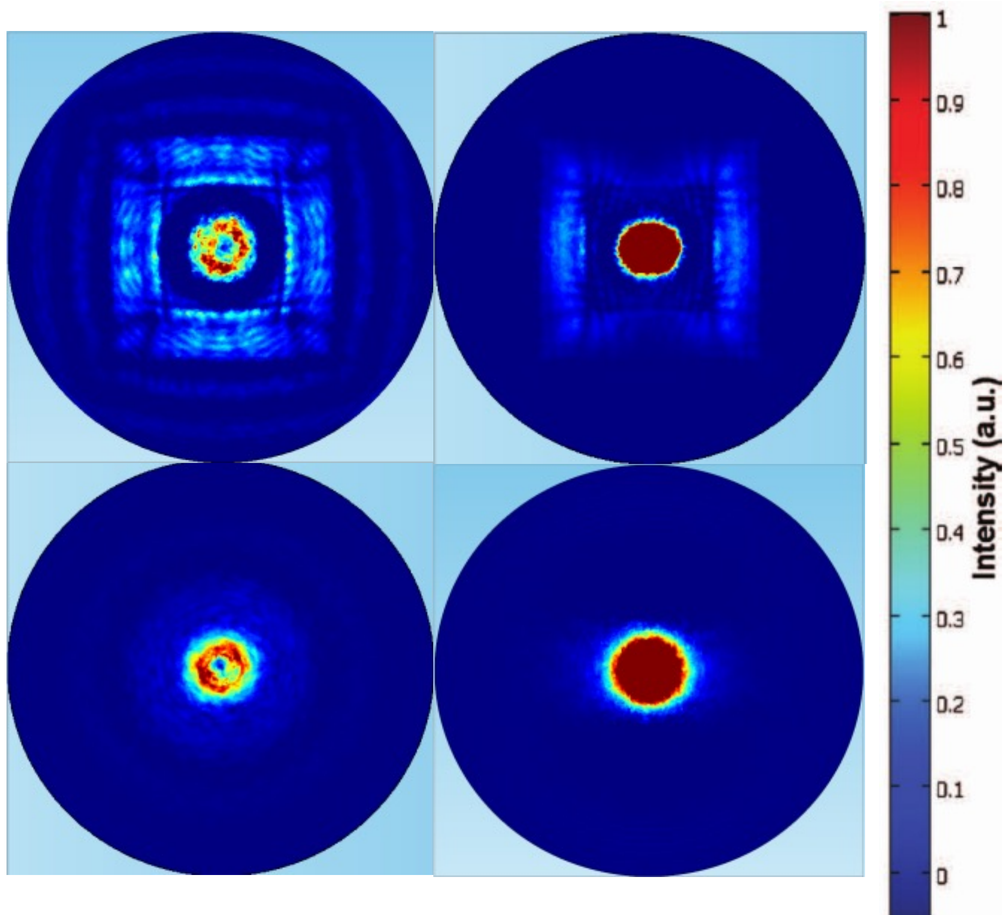
Qu,et al., *Nature Photonics* (2015), **9**, 758

Emission field calculations

VERTICAL DIPOLE | HORIZONTAL DIPOLE

WITH GRID

WITHOUT GRID

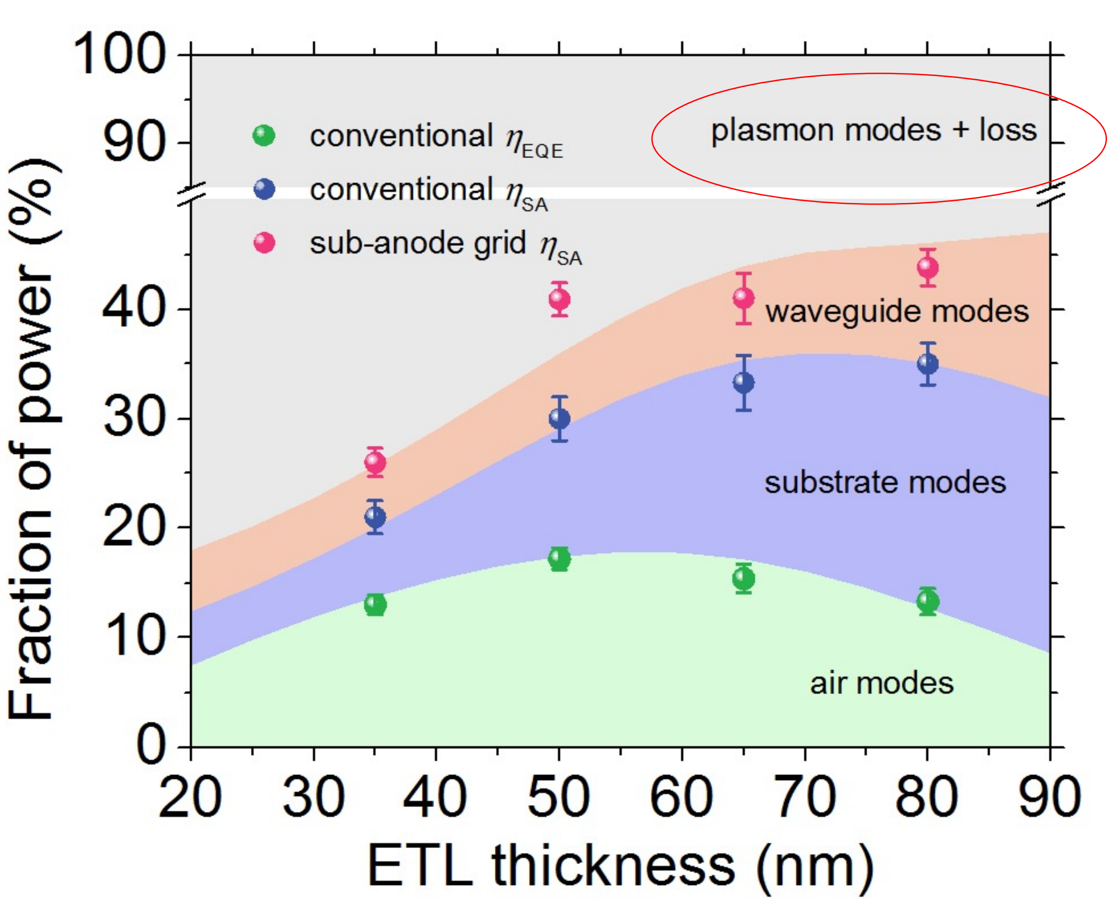


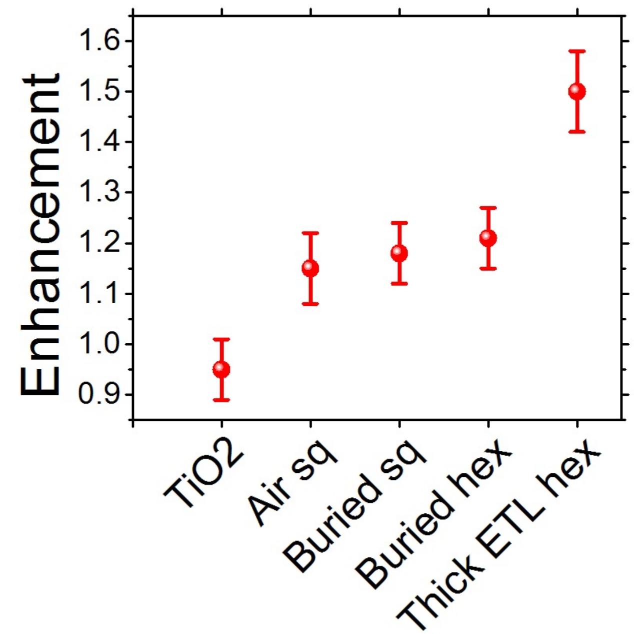
Mostly in-plane (Waveguided)

Mostly out-of-plane (Glass + air)

Qu,et al., *Nature Photonics* (2015), **9**, 758

Optical Power Distribution





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

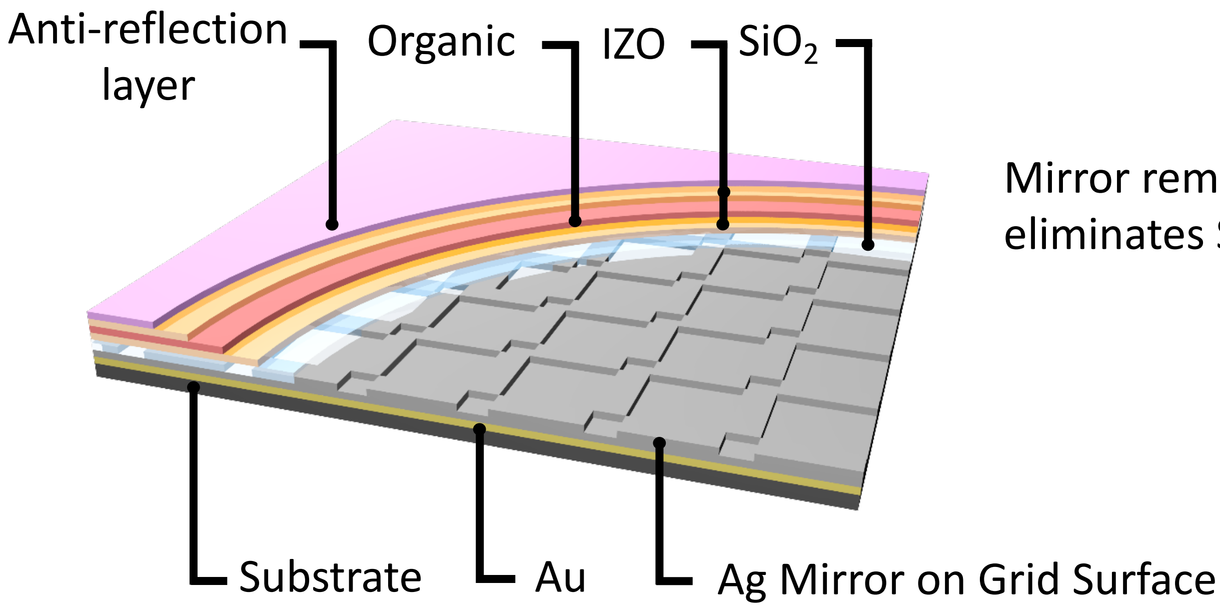
Thick-ETL organic structure:

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

Qu,et al., *Nature Photonics* (2015), **9**, 758

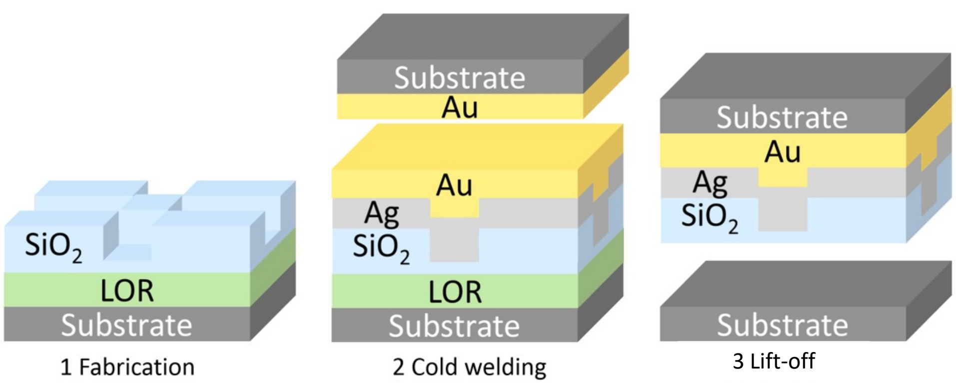
Eliminating SPPs Using Sub-Anode Grid + Mirror

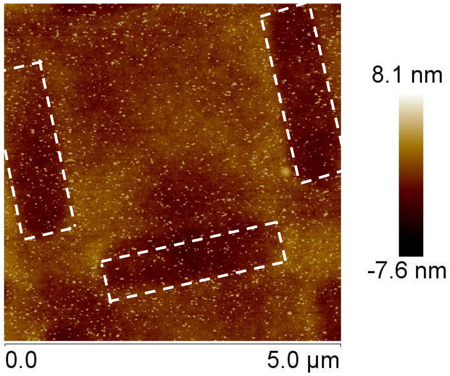
Top Emitting OLED



Mirror remote from EML eliminates SPP excitation

Substrate Fabrication



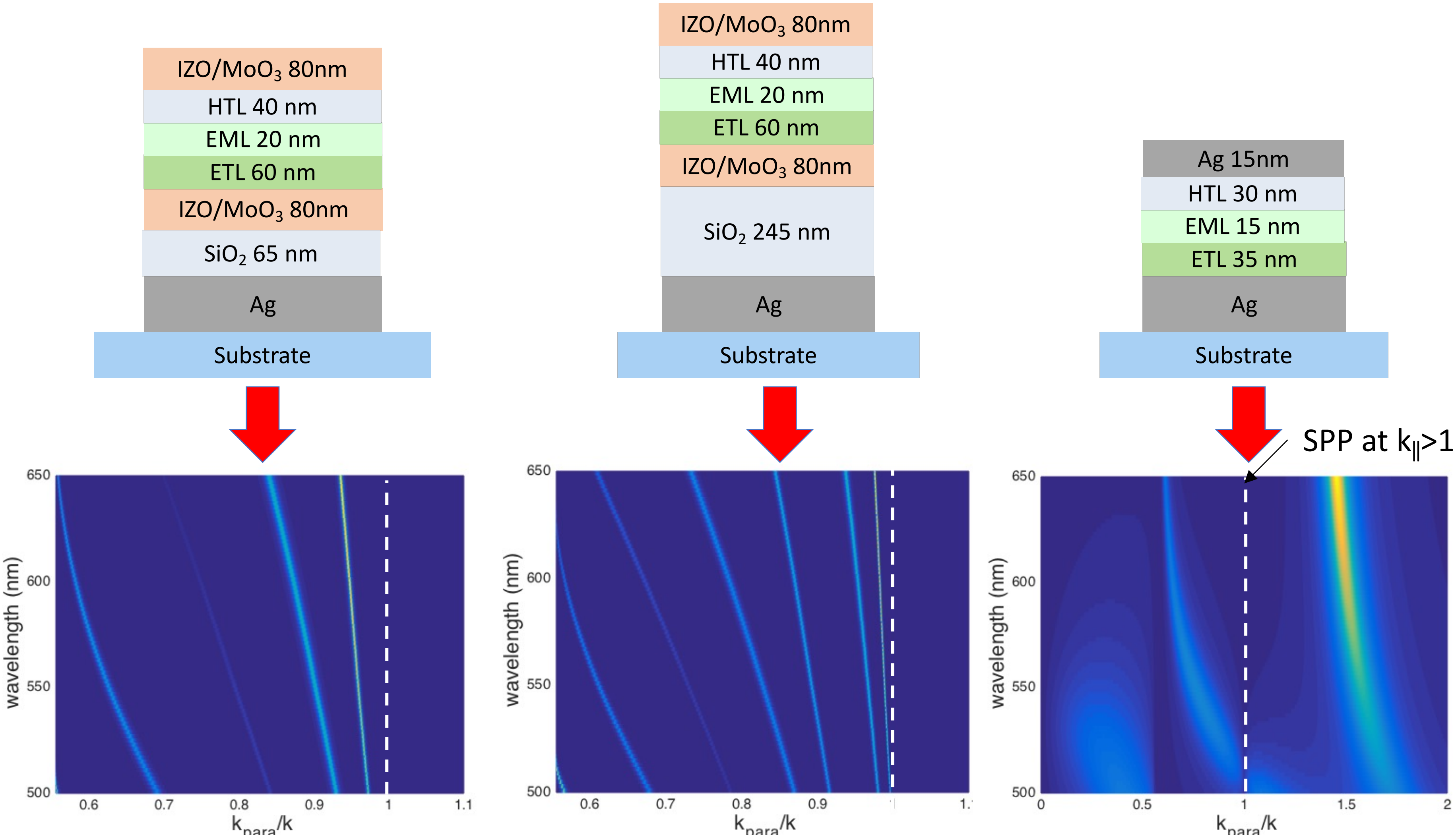


Qu, et al. ACS Photonics, 4, 363 2017

Sub-electrode grid modeling

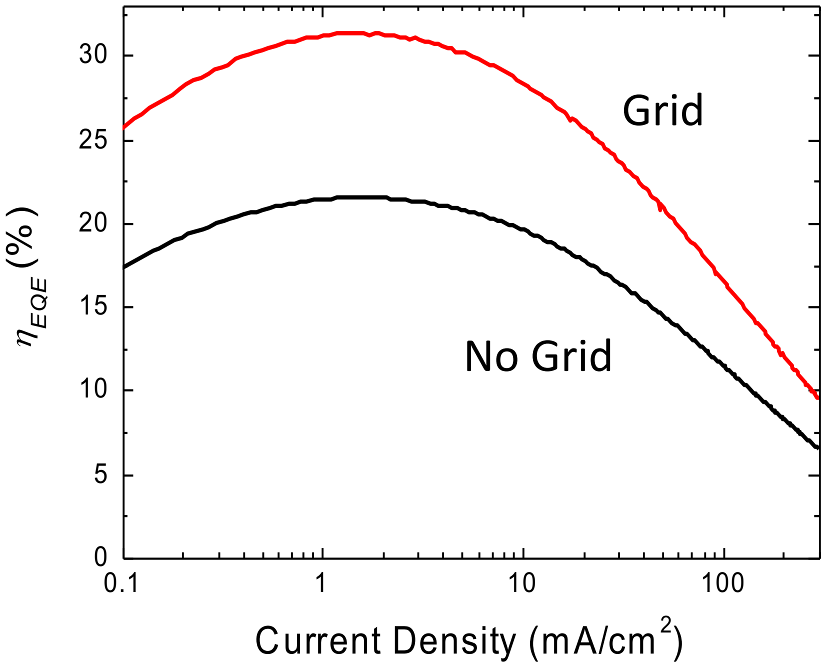
Variable Waveguide Widths Above Mirror Prevent Mode Propagation via Scattering

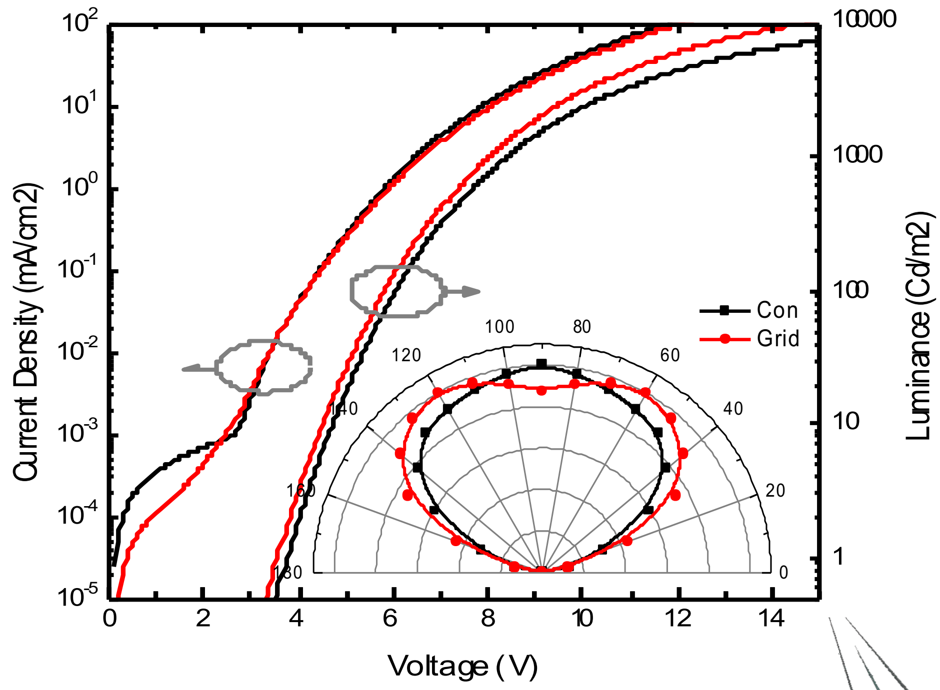
raised mirror section | depressed mirror section | no waveguide



Qu, et al. ACS Photonics, 4, 363 2017

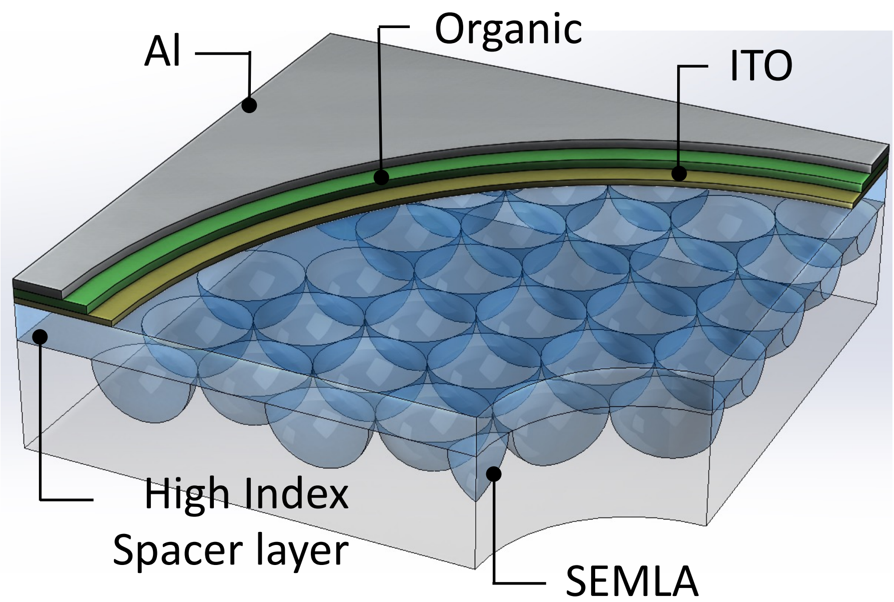
Performance with and without grid+mirror





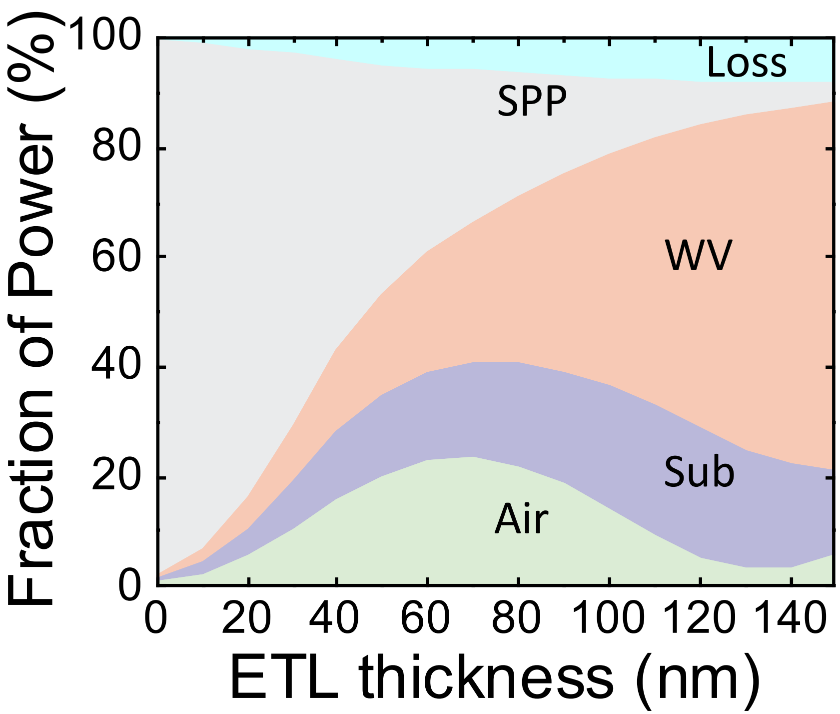
Qu, et al. ACS Photonics, 4, 363 2017

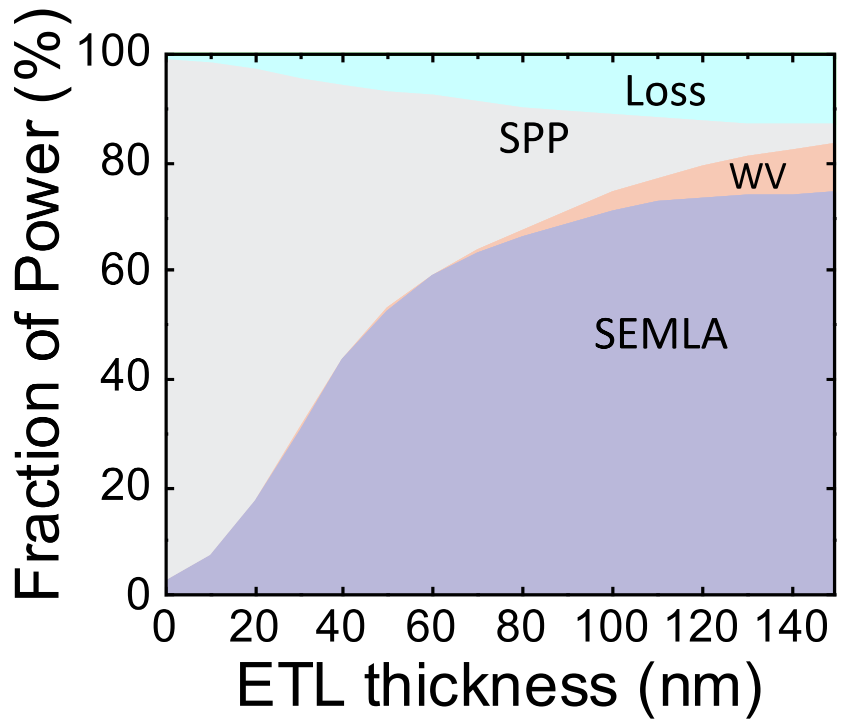
Getting All the Light Out: Sub-Electrode Microlens Array (SEMLA)



Qu, Y., et al. 2018. ACS Photonics, **5**, 2453.

SEMLAs Change the Outcoupling Landscape

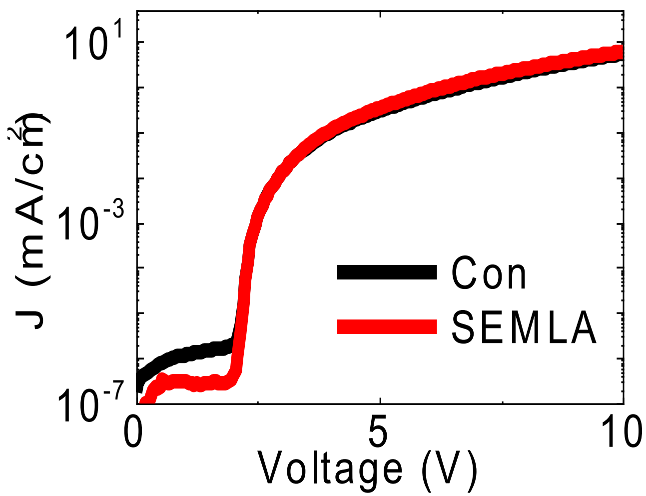


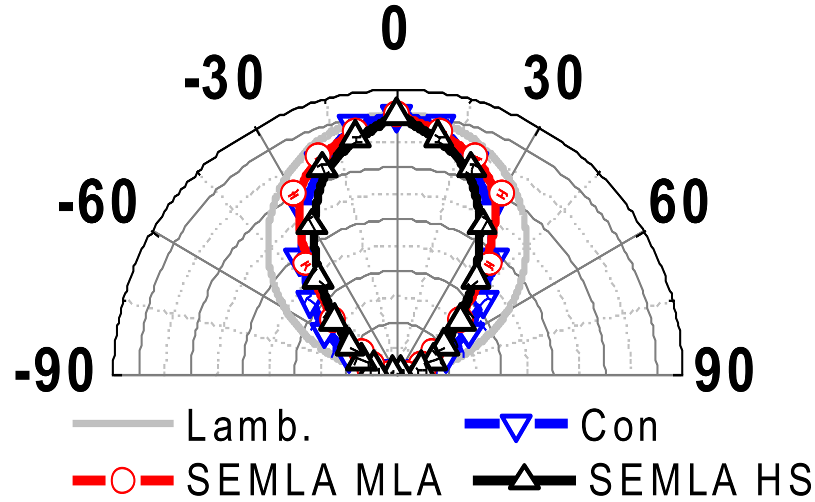


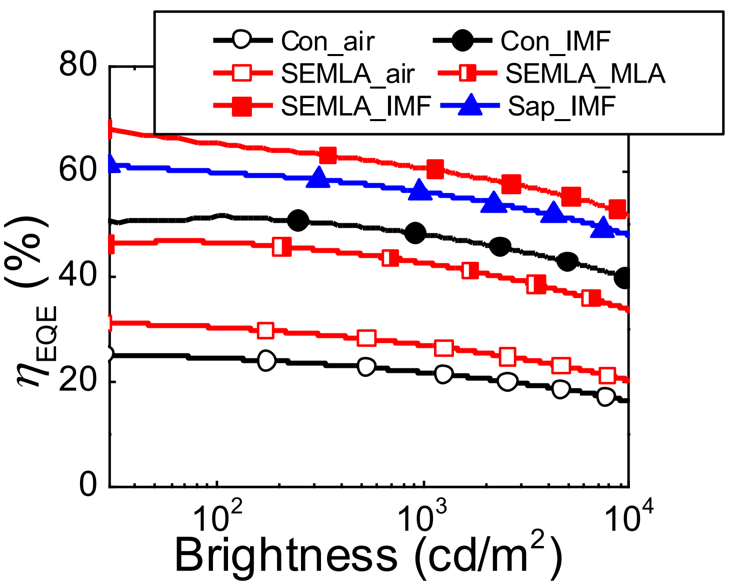
SPPs not completely eliminated

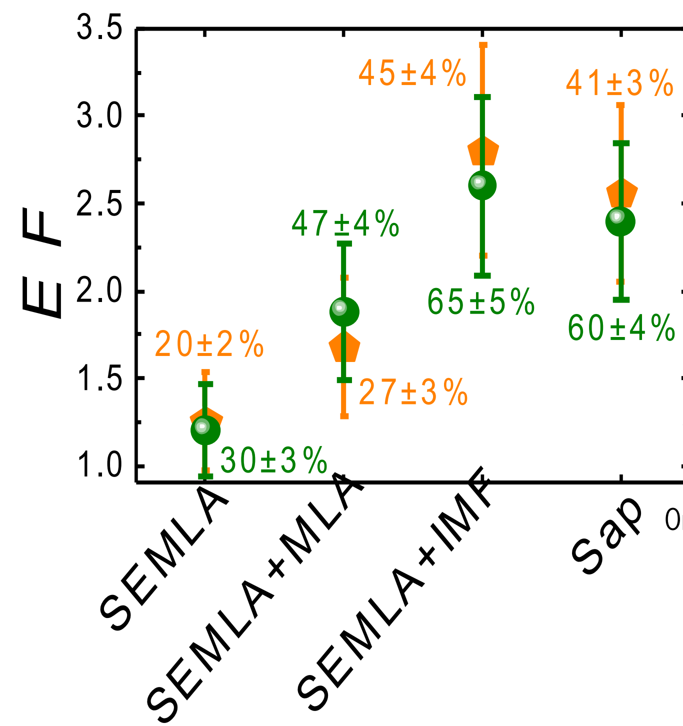
Qu, Y., et al. 2018. ACS Photonics, **5**, 2453.

SEMLA Performance



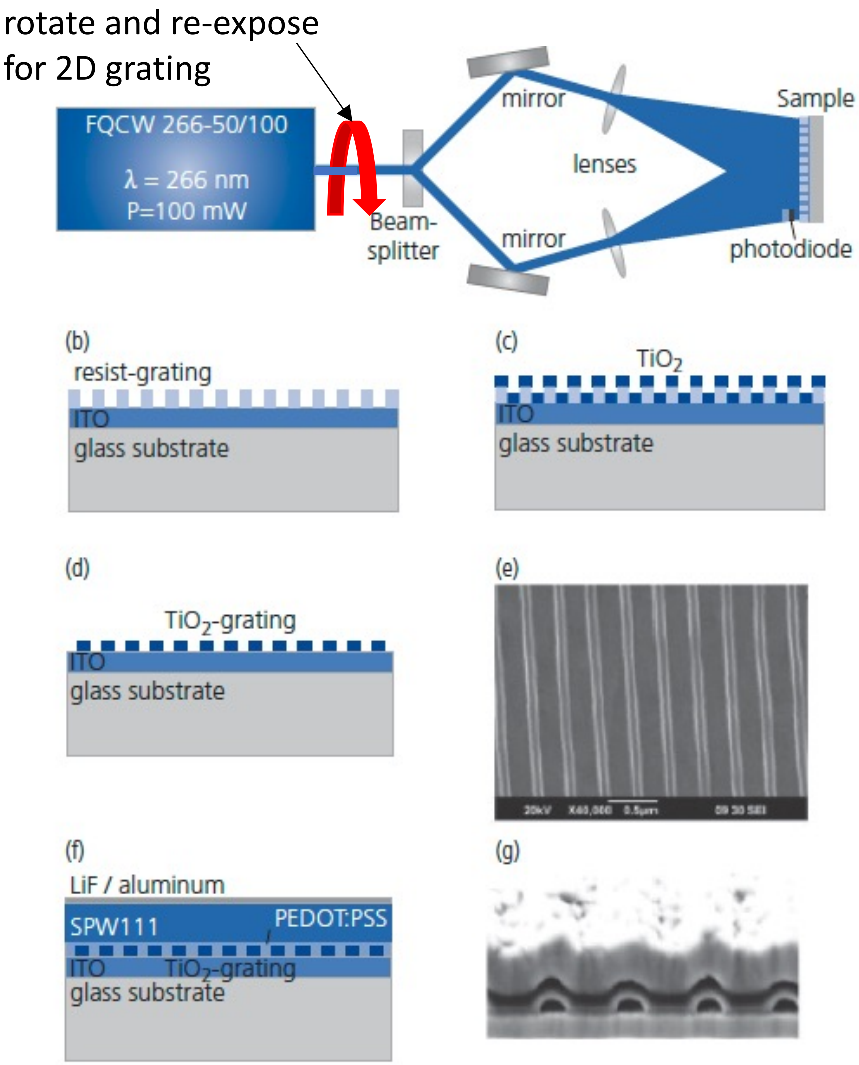






Qu, Y., et al. 2018. ACS Photonics, **5**, 2453.

Gratings Provide Efficient Waveguide Mode Outcoupling



Process for fabricating 1D and 2D gratings using optical interference resist exposure

Advantages

Can be very efficient

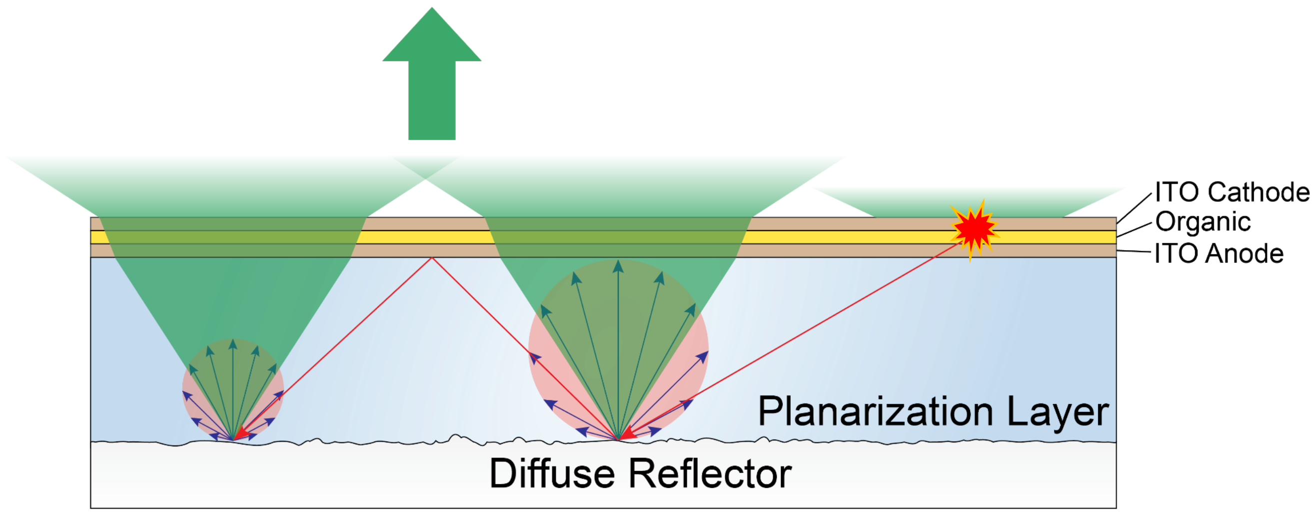
Disadvantages

Requires high resolution photolith over large areas

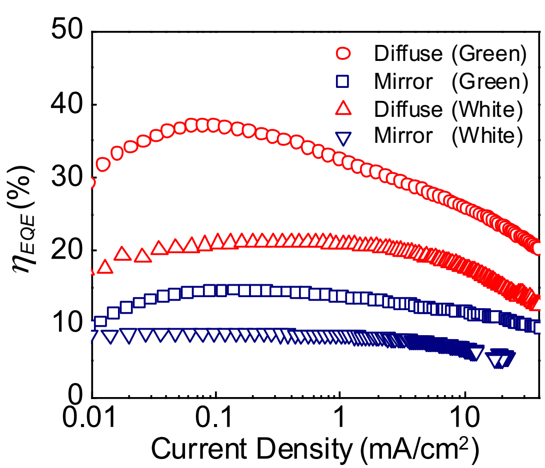
Very wavelength and angle dependent

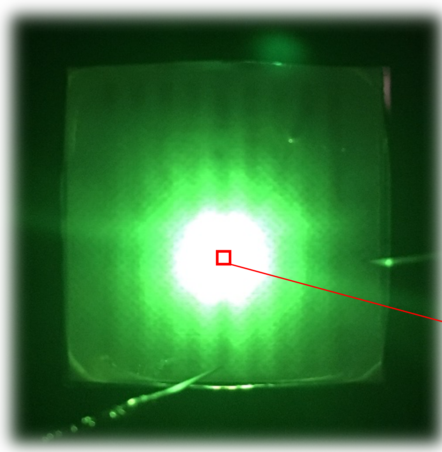
Bocksrocker et al., Opt. Express, 20, A932 (2012)

Diffuse Reflectors: Low Cost & Simple



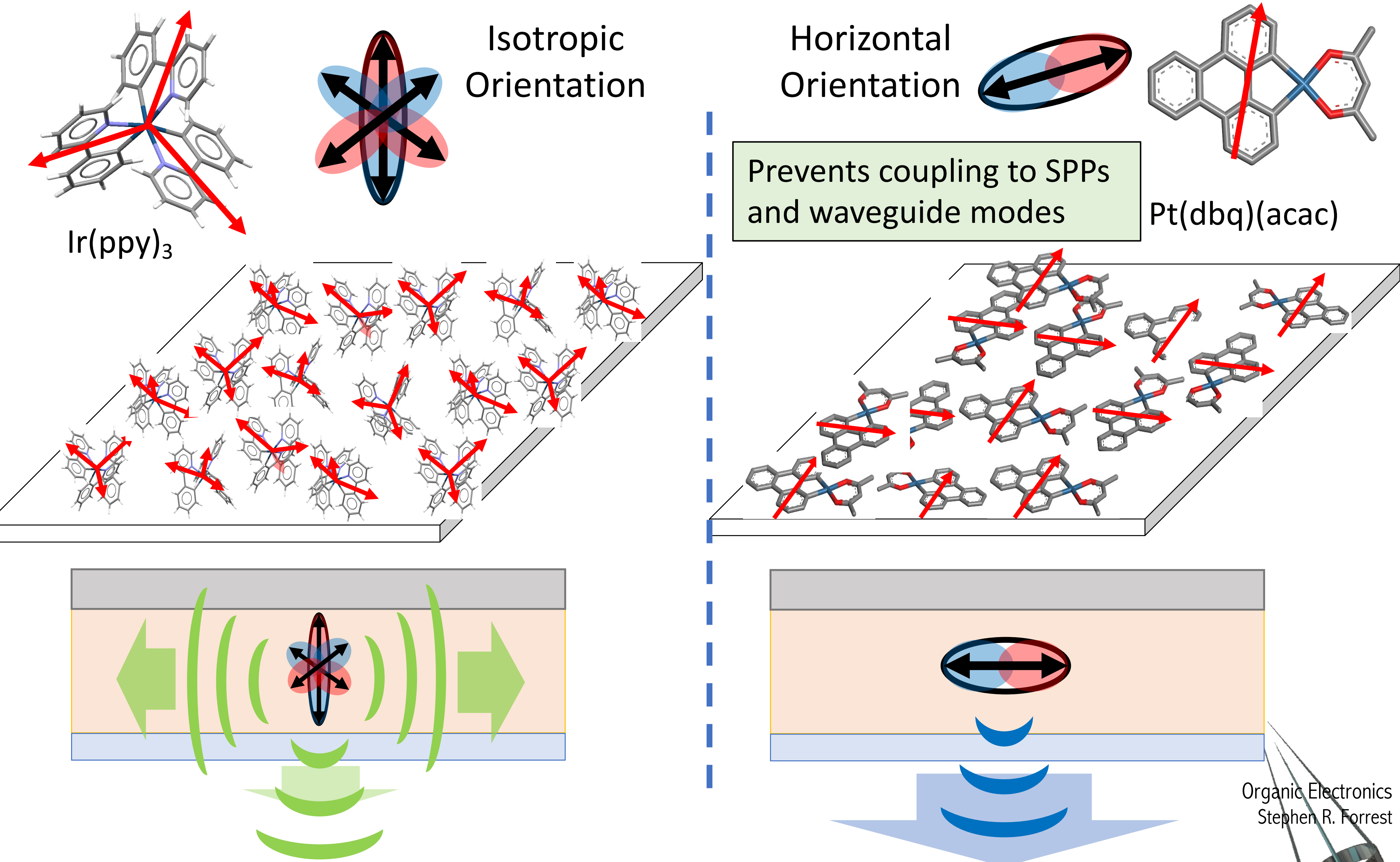
Teflon is the best diffuse dielectric reflector





Kim, J., et al. (2018), ACS Photonics, **5**, 3315.

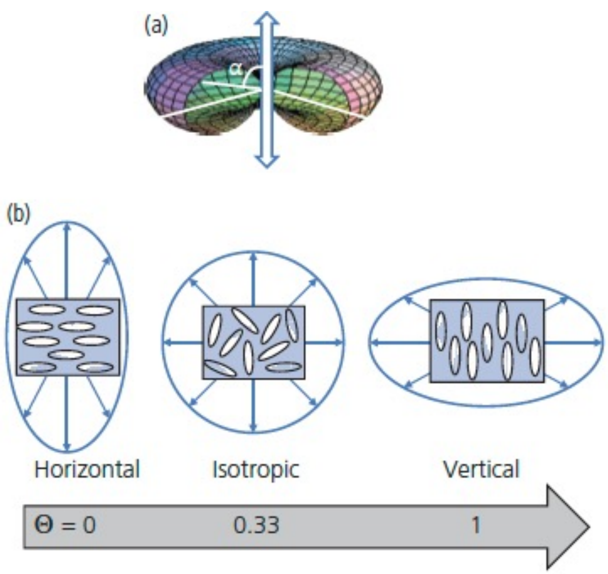
Outcoupling Enhancements by Molecular Orientation

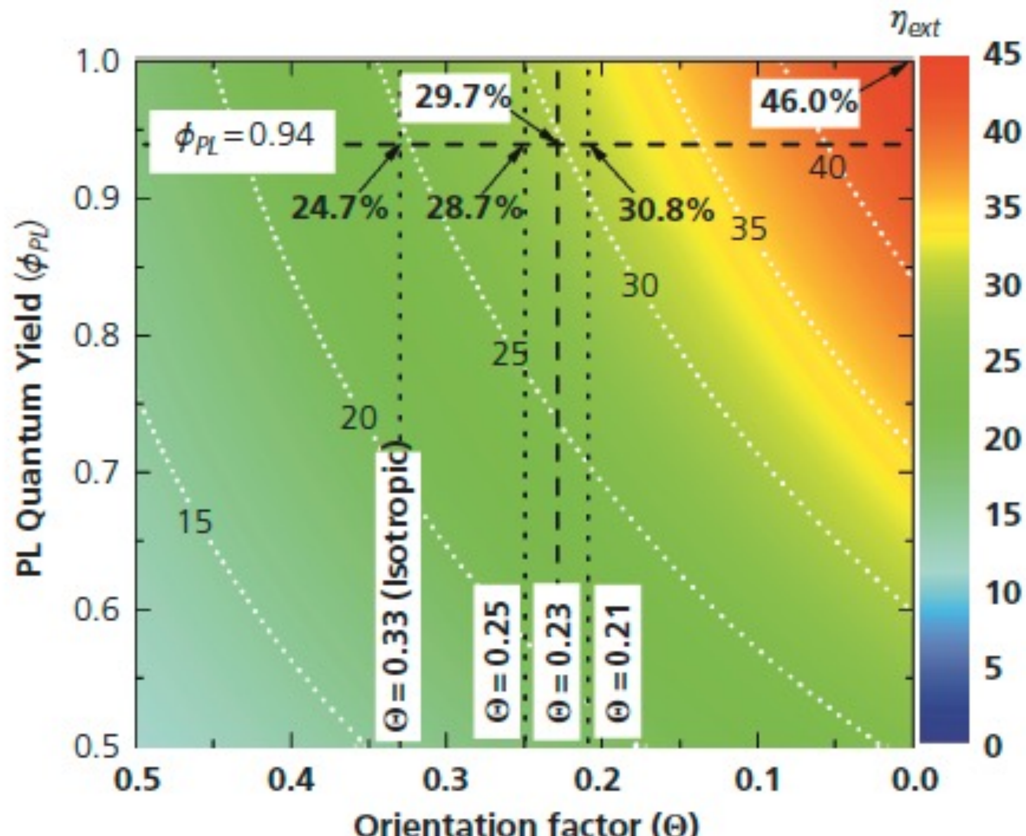


Planar molecules (e.g. Pt-complexes) more likely to align than octahedral (tris-Ir complexes)

Outcoupling Improvements via Alignment

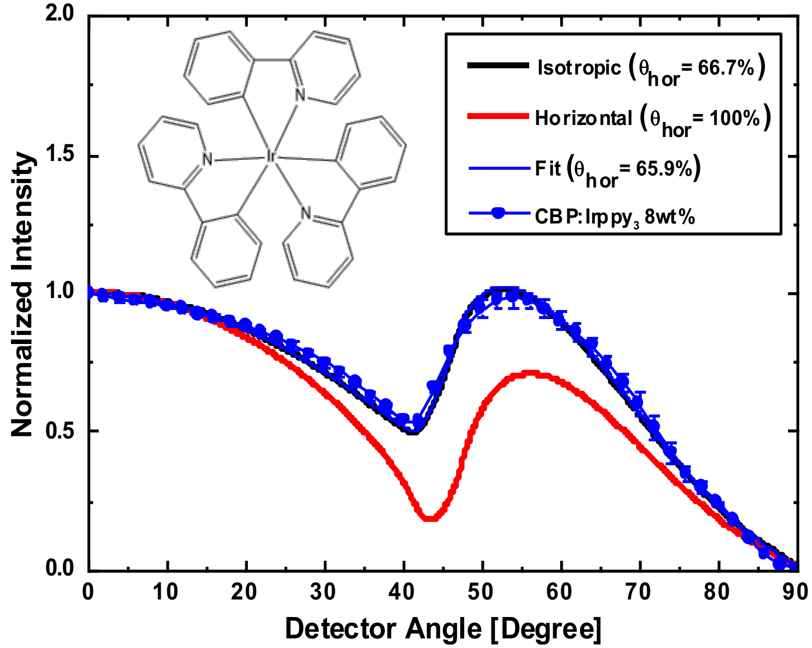
Calculated dipole field

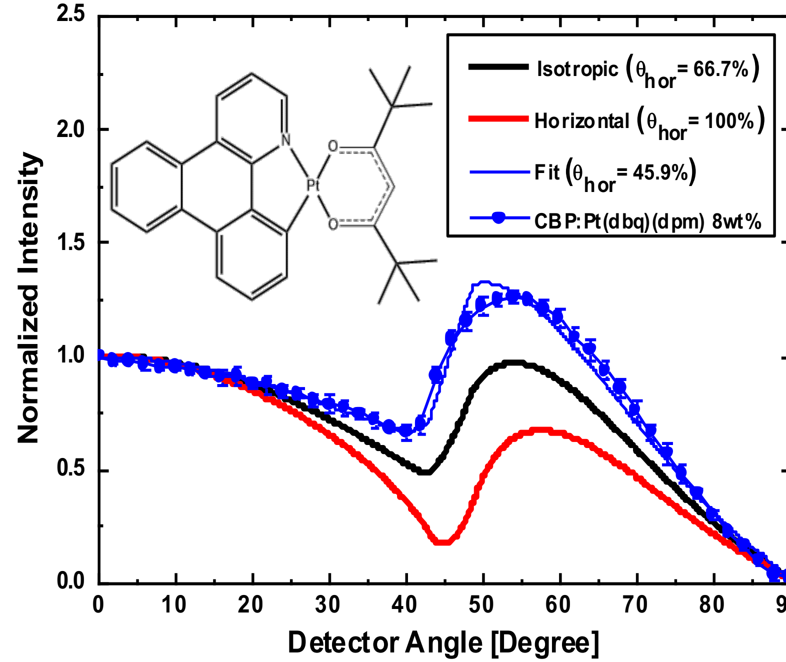




Kim et al., Adv. Funct. Mater., 23, 3896 (2013)

Example results





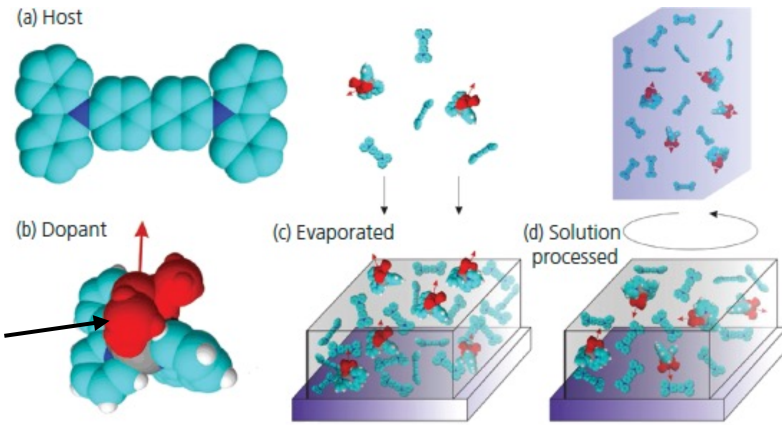
Ratio of light emitting by vertical to horizontal dipoles: $\Theta = \frac{TM_{\parallel}}{TE_{\perp} + TM_{\perp} + TM_{\parallel}}$

<u>Approach challenges</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

Alignment is Driven by Energy and Deposition Dynamics

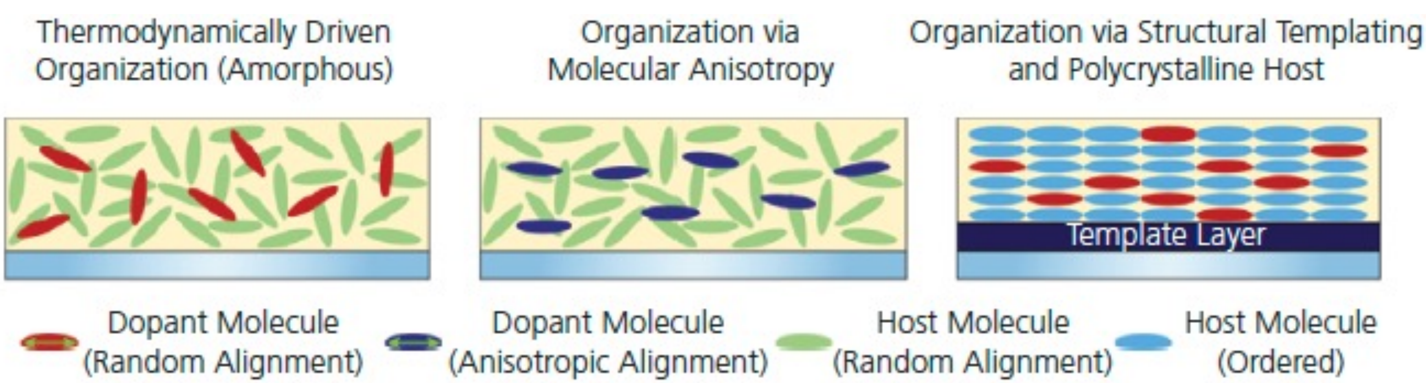
Example: Ir(ppy)$_2$acac



aliphatic acac

Lampe, et al. Chem. Mater. 28, 712 (2016)

Molecular functionalization can drive orientation: Aliphatic groups avoid substrate

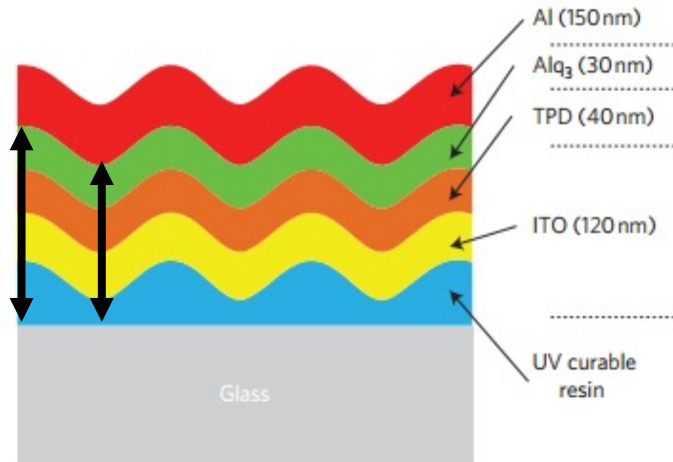


Alignment can be "forced" by seeding the substrate with a thin molecular template

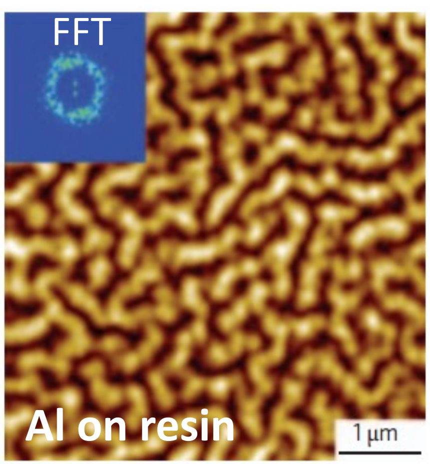
Kim, et al. Adv. Mater. 31, 1900921 (2016)

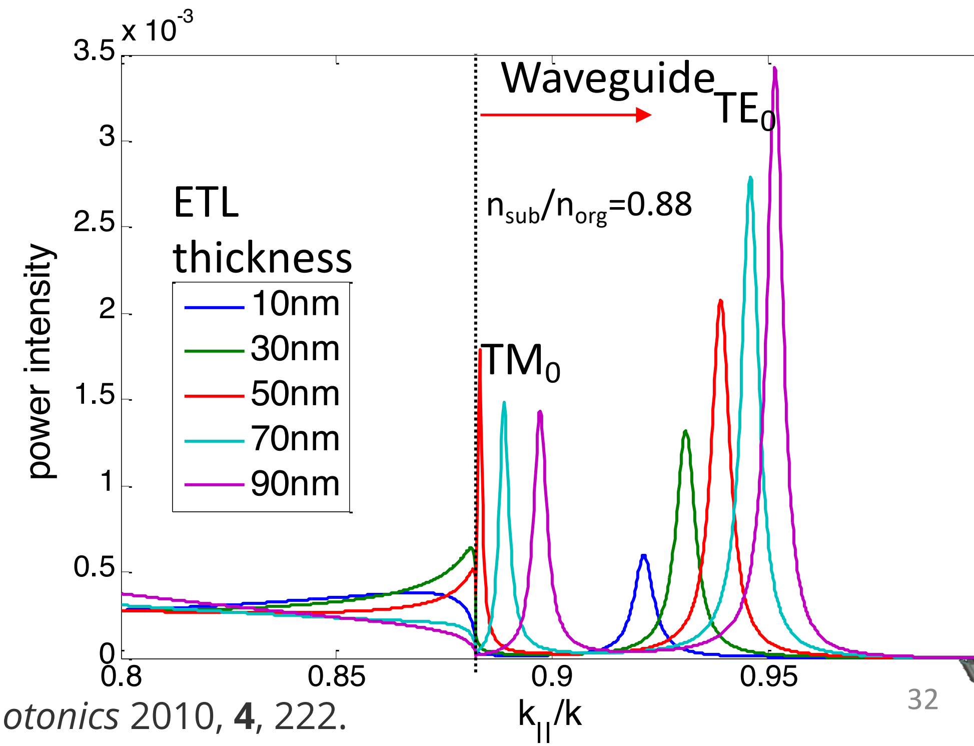
Substrate Corrugations Can Outcouple Waveguide Modes

- 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.



A possible approach: Surface buckling?





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

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R. Forrest