Enhanced Light Extraction from OLEDs Fabricated on Flexible Patterned Substrates

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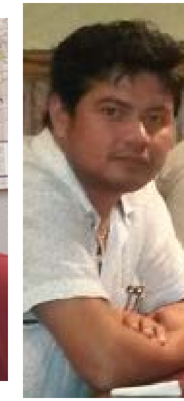


Collaborators:

MicroContinuum Inc. (MCI); Dennis Slafer; Cambridge, MA

Trovato Mfg. Inc. (TMI); Tom Trovato: Victor, NY

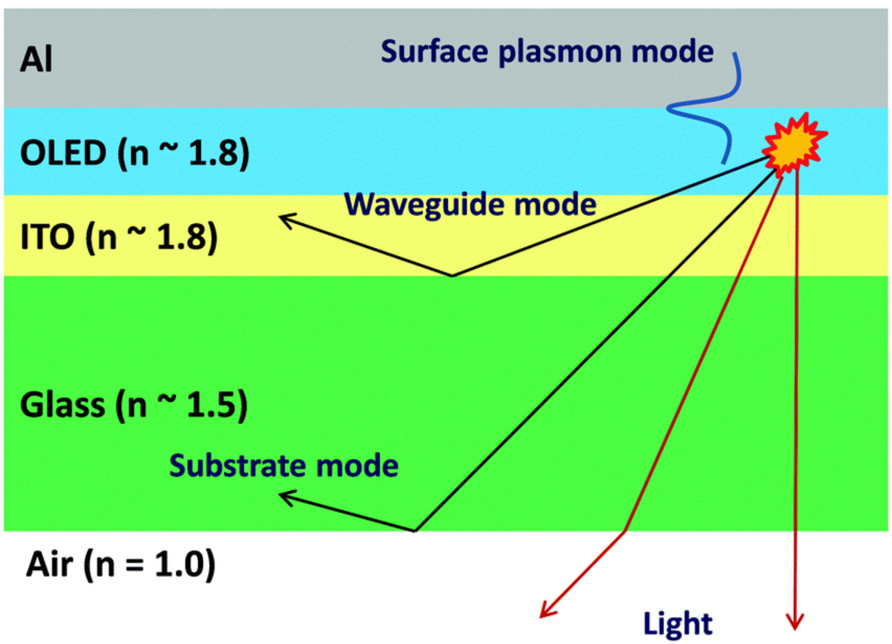
TMI's facility: computer-controlled

12- and 16-source thermal evaporators

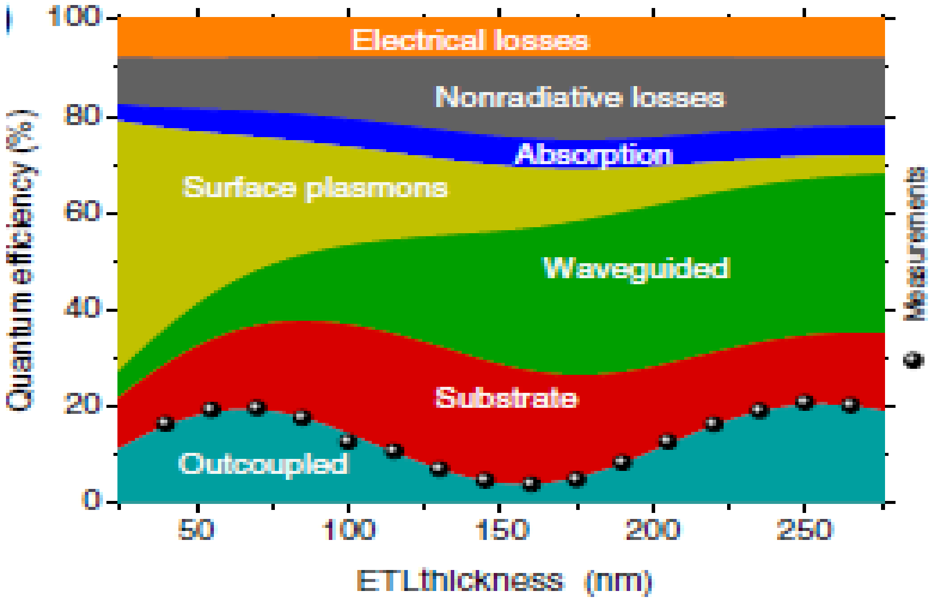
A Major Lighting Challenge:

Limited outcoupling efficiency $\quad$ $EQE = IQE \times \eta_{out} \sim 20\%$

1. Photons trapped in the substrate due to total internal reflection at the glass/air
2. Photons waveguided in the high index organic+anode layers
3. Photons dissipated at the organic/metal by surface plasmons excitation



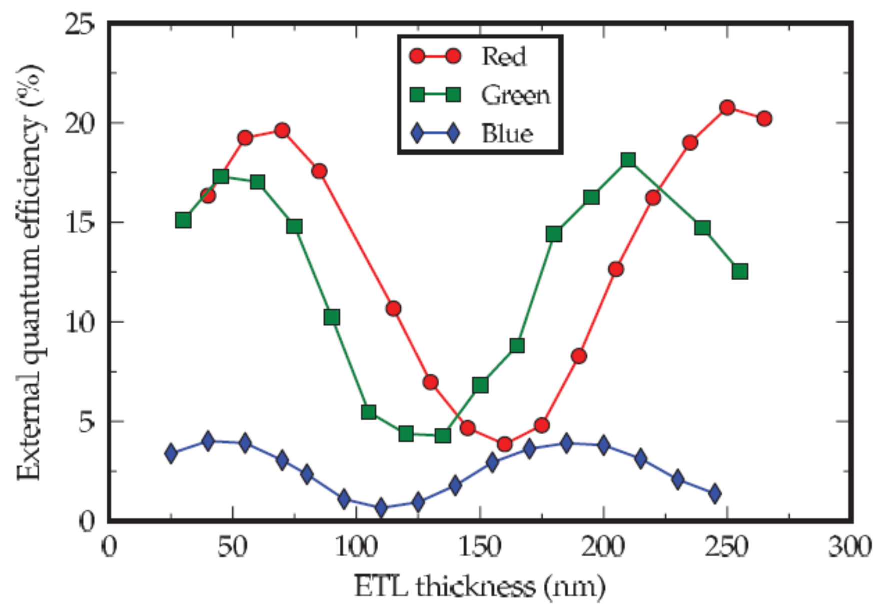
F. Zhao et al.
Mater. Chem. Frontiers, 2017



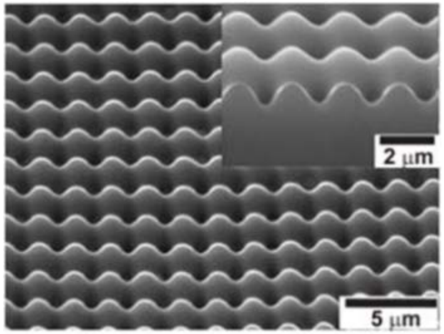
Outcoupling loss channels in a red bottom-emitting OLED vs ETL thickness – optical modeling.

R. Meerheim et al. Appl. Phys. Lett. 97, 253305 (2010)

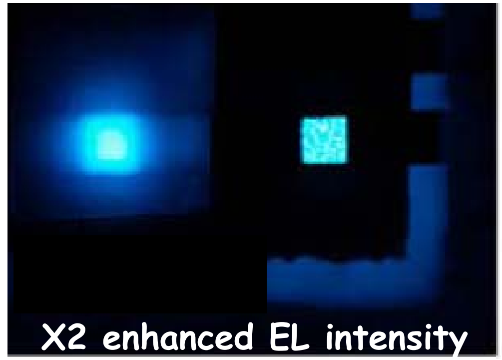
M. Furno et al. PRB 85, 115205 (2012)



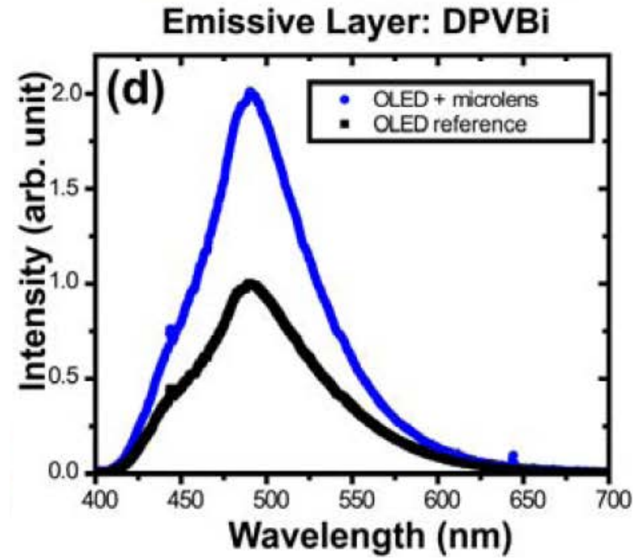
Extraction of substrate trapped light: microlens arrays



pitch



1.2 μm height; 1.6 μm dia.



Consistent ×2 enhancement with microlens array area (16×16 mm^2) >> OLED pixel area (3.3×3 mm^2)

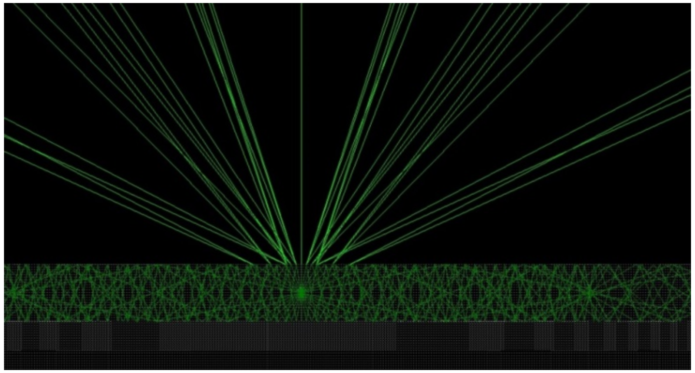
J-M. Park et al.
Opt. Express, 19, A786 (2011)

Various reports: x1.5-x1.7 enhancements with different microlens/prisms designs, some complex. Bulky hemispherical macro-structures outcoupling enhancement: x2.
Random structure scattering film or back-surface roughening also enhance outcoupling.

M. Gather, J Photon. Energy 5, 057607 (2015)

Recovering the ~50% waveguide & surface plasmon loss modes remains challenging

Innovation and advances in materials, device designs, and manufacturing are still needed to realize DOE's SSL 70% outcoupling.



Ray tracing simulations for green OLED's waveguided mode

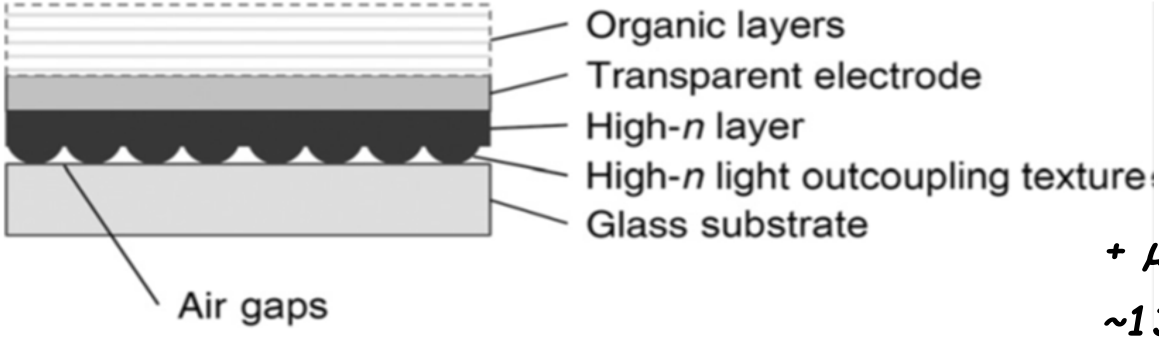
Extraction of Waveguided Light

- ❑ High index matching substrates + μLAs enhances white OLED - EQE x2.4 (34%; 81 lm/W)

S. Reineke et al. Nature 459, 234 (2009)

Sub-Anode approaches

- ❑ High *n* = *1.77* textured thin film PEN; replacing high *n* glass (Panasonic)



+ μLA on standard glass:

~130 lm/W, EQE ~56%

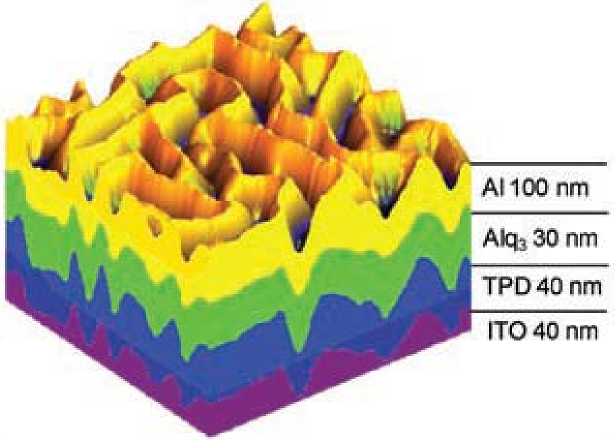
N. Ide et al. J. Photopolym. Sci. Technol. 27, 357 (2014)

- Nano-particle based scattering layers between the substrate and ITO; 240 nm TiO_2 NPs (n ~2.2)/polymer (n ~1.5) spin-coated 2 μm film:
  white OLED: EQE increased from 22.5% to 34%; to 46% +μLA (69 lm/W).
  H.-W. Chang et al. J. Appl. Phys. 113, 204502 (2013)

- A non-diffractive dielectric scattering grid layer (SiO_2 *n* ~1.5 or air grid in TiO_2 *n* ~2.2) + μLA.
  In green OLED, EQE increased from ~15% to ~18% - to 40% with the μLA.
  Power efficiency increased from 36 to 43 to 95 lm/W *Y. Qu Nat. Photon. 9, 758 (2015)*

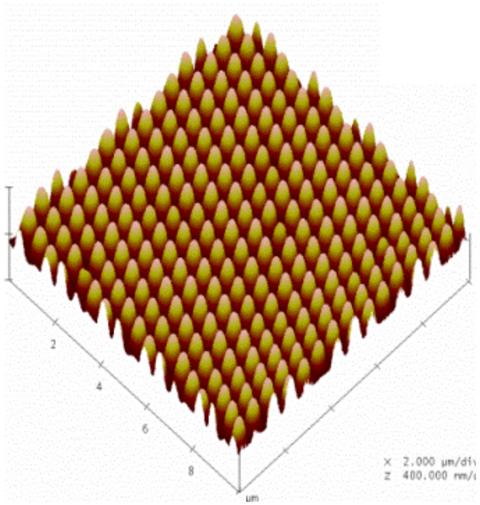
Surface Plasmon loss remains a major issue

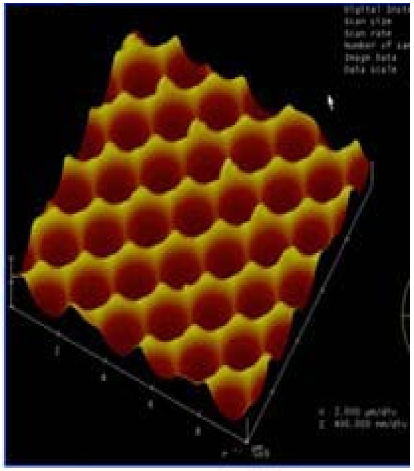
buckling structure was shown to mitigate surface plasmon excitation in a green OLED.
W.H. Koo et al. Adv. Mater. 23, 1003 (2011)



Potential Issues

- **Expensive substrates in particular for scaling; environmental issues**
- **Some scattering films show viewing angle – dependent spectra**
- **Some complex designs are prone to shorts**

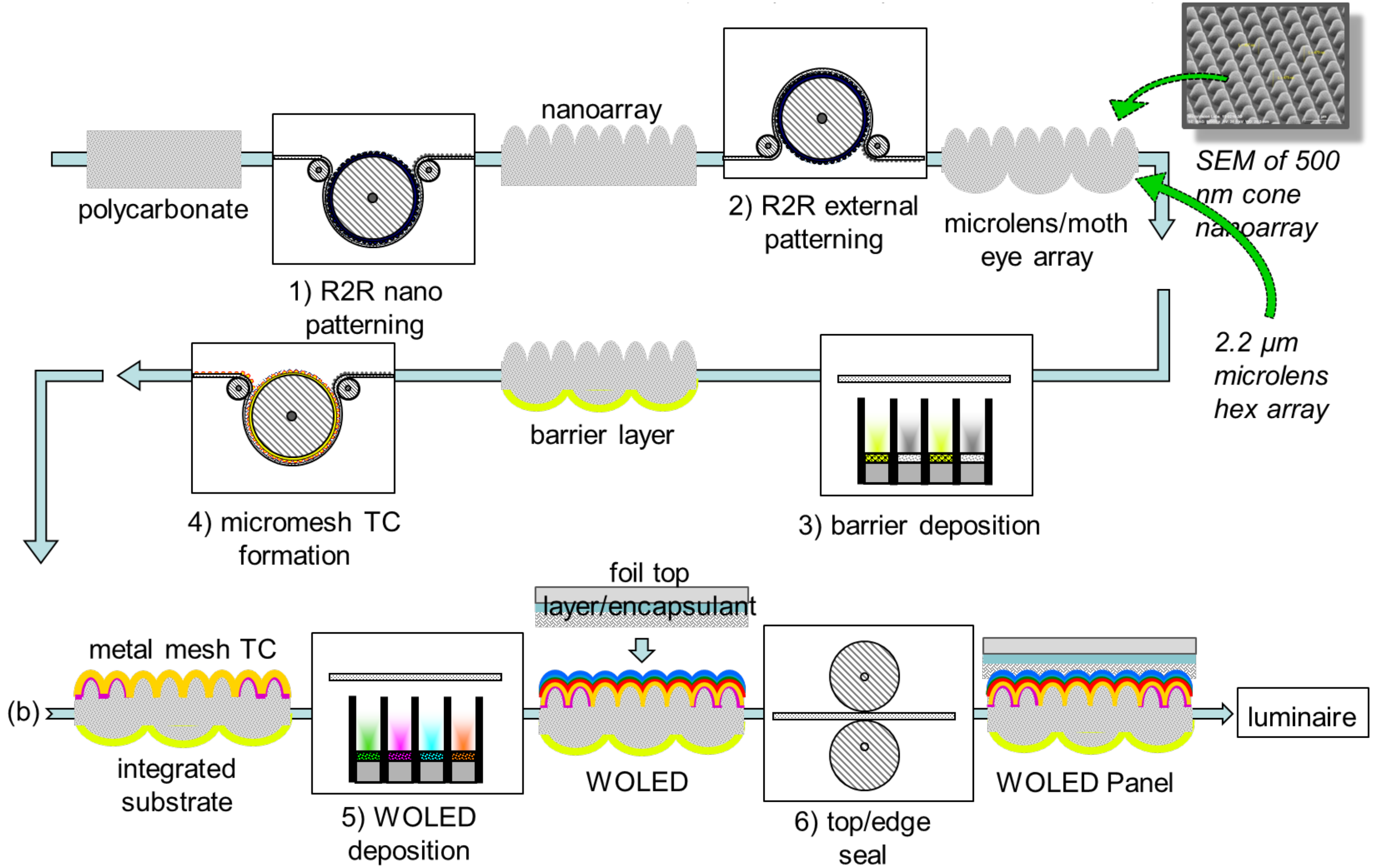




AFM of corrugated polycarbonate (PC) and polyethylene terephthalate (PET)/polymer substrates (10 μm full scale)

MicroContinuum (MCI) substrates

- Cost-effective R2R manufacturing; easily fabricated patterns
- Large area; scalable for high volume production, rapid production
- Versatile, amenable for a variety of structures and substrates
- Multi-level structures: nano-patterns with embedded metal mesh transparent conductor + μLA

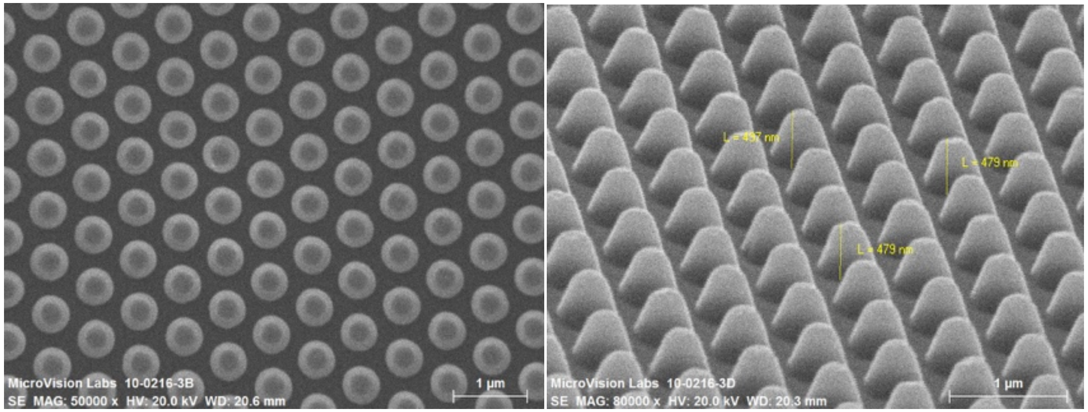


R2R production of integrated OLED substrates. PC: directly imprinted on both sides + an external barrier. (b) OLED deposition & encapsulation steps. (not to scale) Planar internal barriers are also possible.

MCI has developed 2 fast, inexpensive methods for producing versatile outcoupling structures

(1) Direct nanopattern formation

- No patterned layer/substrate interface, eliminating peel off & index mismatch losses
- Room temperature production eliminates thermal distortion and/or degradation, reduces production time (no slow heating/cooling cycles as in conventional molding processes)
- Rapid pattern changes and inexpensive tooling costs; pattern amplitude is tunable without new templates (expensive/long turn-around)



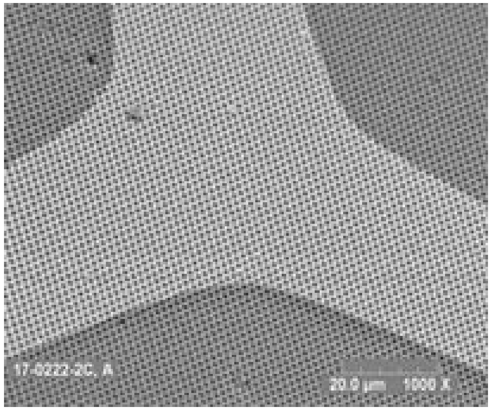
SEM of a nanoarray on PC fabricated by Direct Nanoforming process

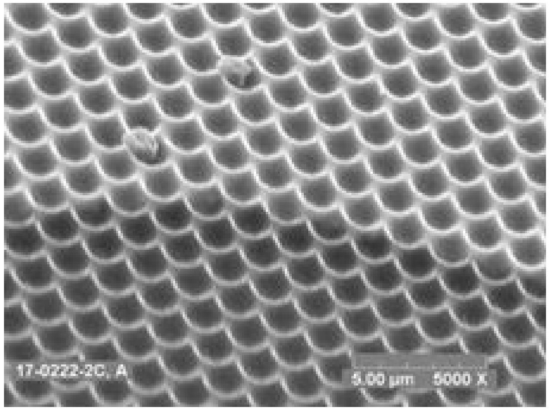
(2) Two layer formulation

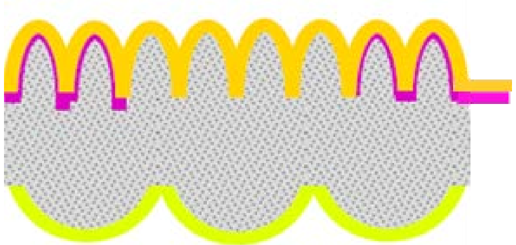
- Pattern and substrate independent optimization, adjusting of the refractive index by material choice + ability to add high index particles

Enhanced Substrates

- **Fully integrated substrates with internal & external extraction features and buried metal mesh**







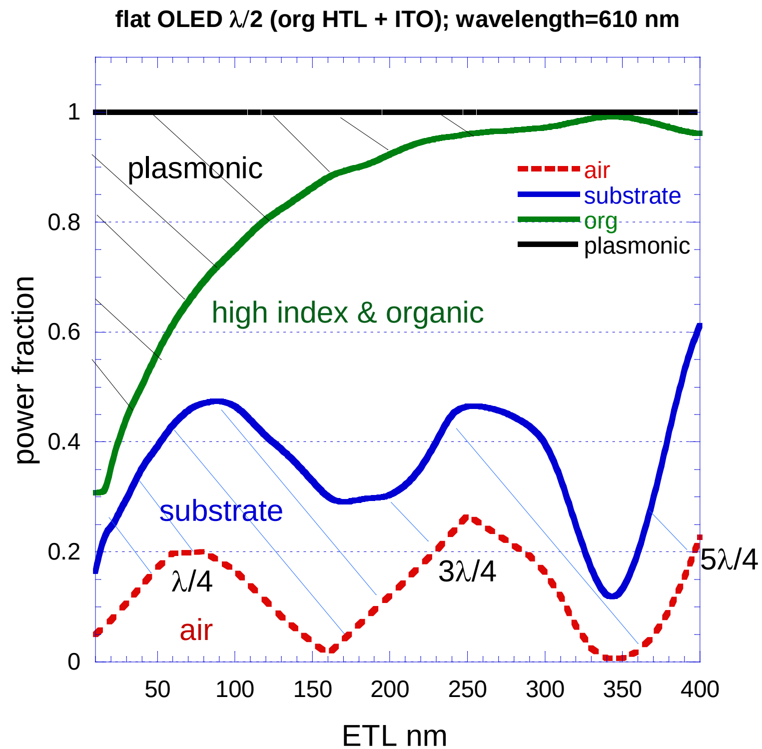
SEM images of an enhanced OLED substrate surface w/hexagonal Cu grid
Left: 1,000x, Right: 5,000x.

- ***The grid, for enhancing thin anode conductivity, is embedded in the corrugation and buried under a thin, continuous ITO layer***

Modelling Simulations of integrated substrates and OLED properties

Computational Approaches: scattering matrix simulations (in Fourier space) and real space finite difference time domain (FDTD) simulation (Lumerical)

Implementing dipole model for flat & conformal corrugated OLEDs

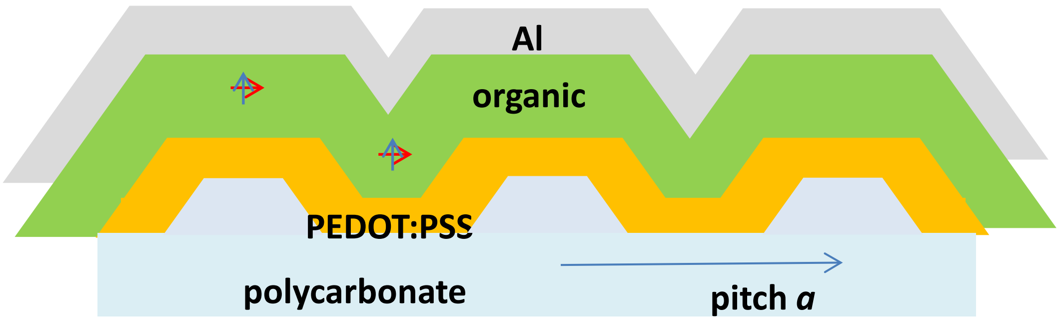


Scattering Matrix Simulations: red emitting

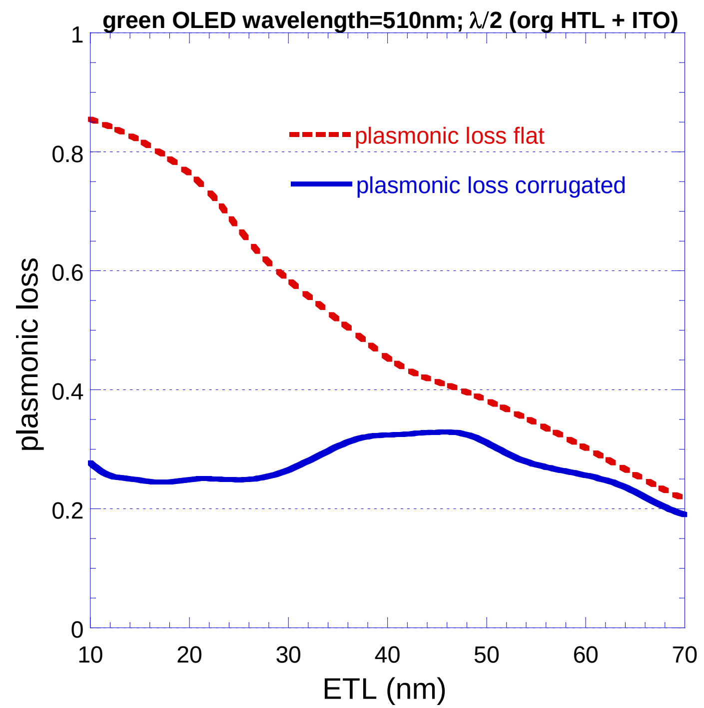
flat OLED glass/ITO/HTL/ETL/Ag

Corrugated OLEDs

Small corrugation height OLED



Schematic of the pattern (not to scale)



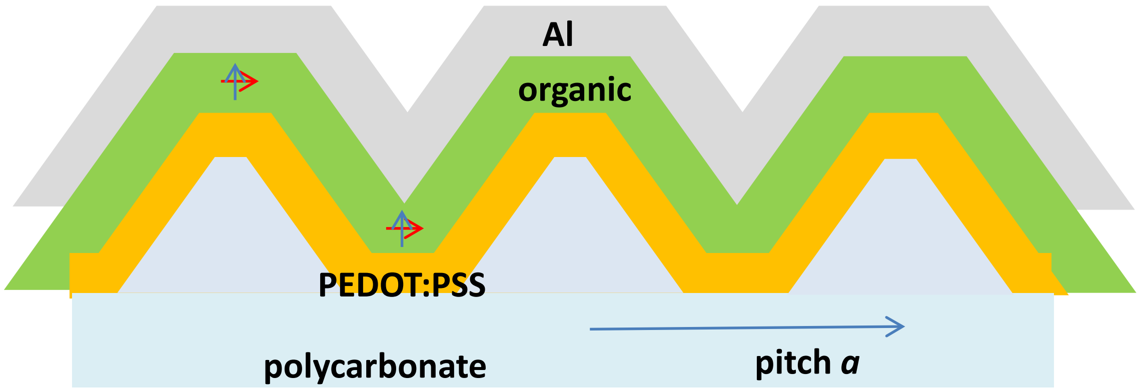
Preliminary Simulations: corrugated green OLED vs flat OLED

h = 50 nm, *a* = 750 nm

- Flat OLEDs have very high plasmonic loss at small ETL thickness
- Plasmonic loss decreases for corrugated structures for thin ETL
- Thicker ETL provides reduced plasmon loss

Corrugated OLEDs

Large corrugation height OLED



- Cathode *overlaps* anode
- Internal waveguiding is disrupted
- Two positions of the dipole emitter shown

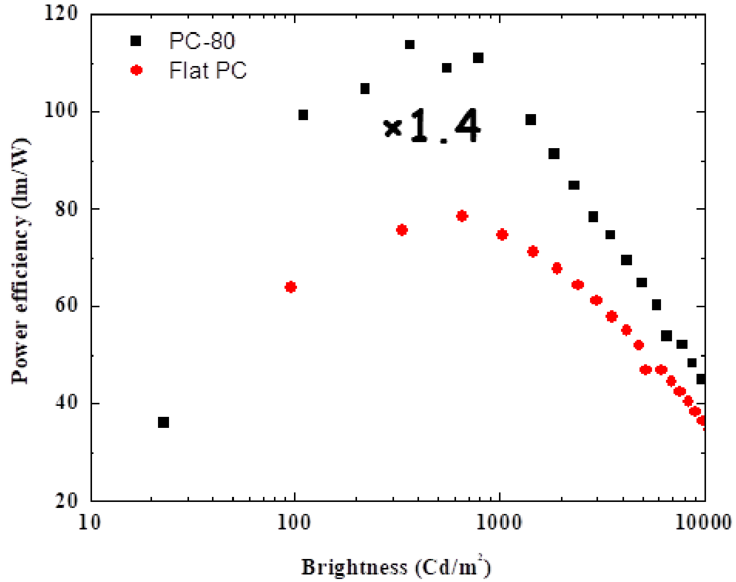
Schematic of the pattern (not to scale)

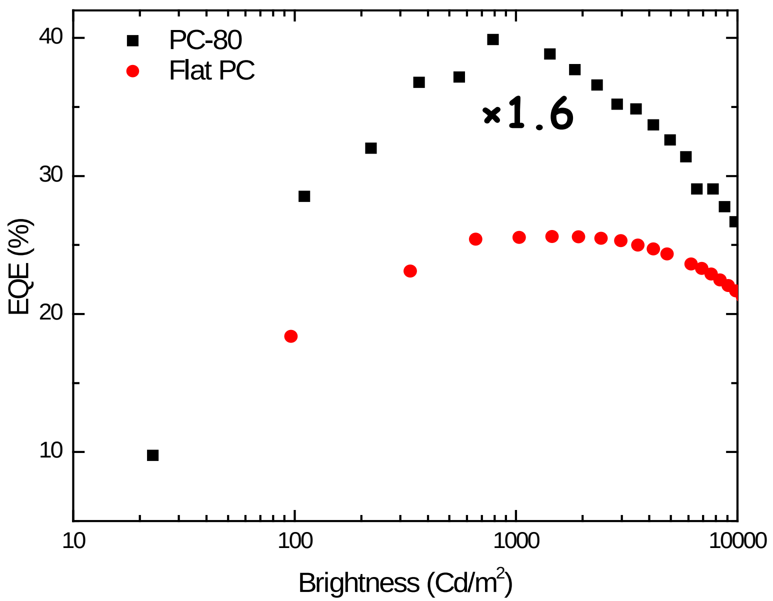
Results

- Large *h* causes strong diffraction
- Internal waveguide & surface plasmon modes, and possibly some substrate mode are extracted into air
- 500 - 750 nm pitch and 200-400 nm pattern height enhance OLEDs
- Preliminary simulation results indicate 50-60% outcoupling

Green PhOLED (*h* ~80 nm, *a* ~750 nm)

60 nm ETL

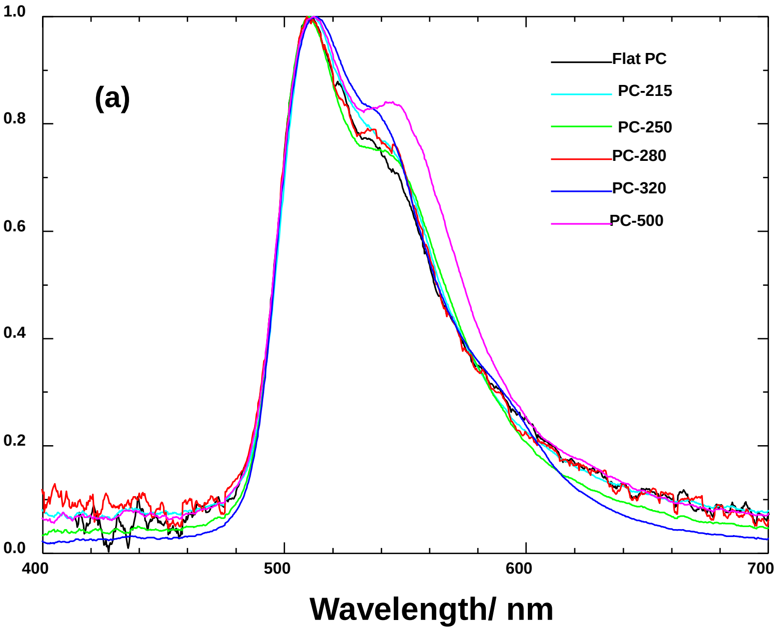


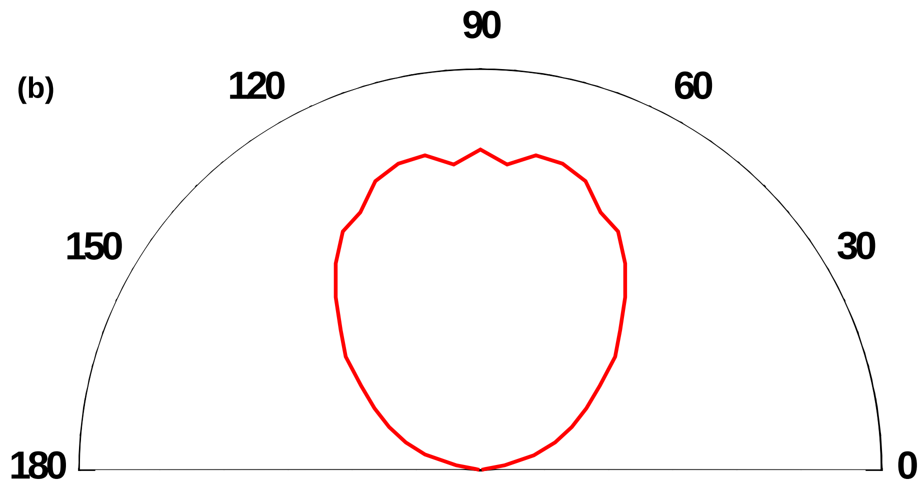


PC/PEDOT:PSS/HAT-CN (5 nm)/10% MoOx:TAPC (60 nm)/TAPC (20 nm)/6% $Ir(ppy)_3$:mCP (20 nm)/TmPyPb (20 nm)/20% CsF:TmPyPb (40 nm)/LiF (1 nm)/Al (100 nm)

The enhancement is due to disrupting both the surface plasmon & waveguide modes

Optical Attributes





Ideal Lambertian Distribution (black)

Angular Dependence with Patterned PC (red)

PEDOT:PSS/MoO_x(1 nm)/10% MoO_x:NPB (22.5 nm)/NPB (22.5 nm)/6% $Ir(ppy)_3$:CBP (11 nm)/ BPhen (40 nm)/LiF (1nm)/Al (100 nm)

PC-320: the EQE increased ~1.6 fold from ~22 to 36%

Enhanced OLEDs (non-encapsulated devices)

Green PhOLEDs

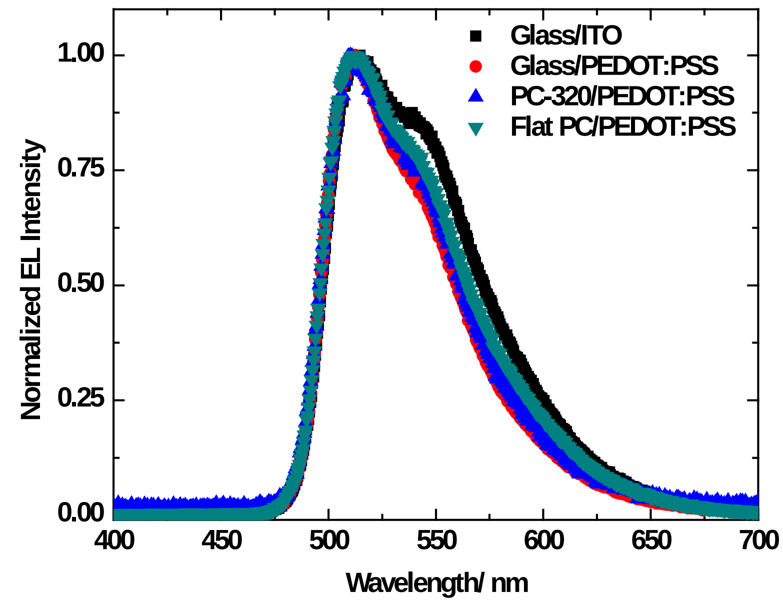
Device Structure: Anode/HAT-CN (5 nm)/10% MoOx:TAPC (120 nm)/TAPC (20 nm)/6% $Ir(ppy)_3$:mCP (20 nm)/TmPyPb (20 nm)/20% CsF:TmPyPb (40 nm)/LiF (1 nm)/Al(100 nm)

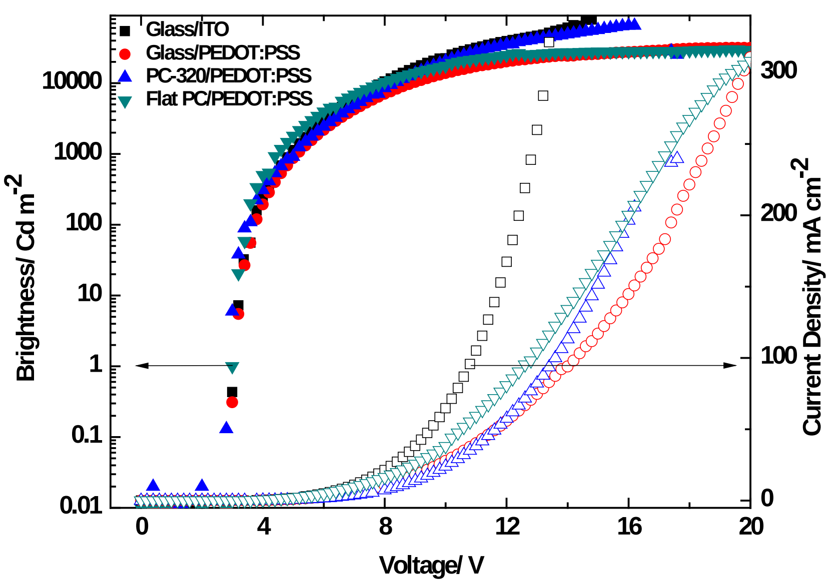
Anodes:

1. Glass/ITO
2. Glass/PEDOT:PSS
3. PC-320/PEDOT:PSS

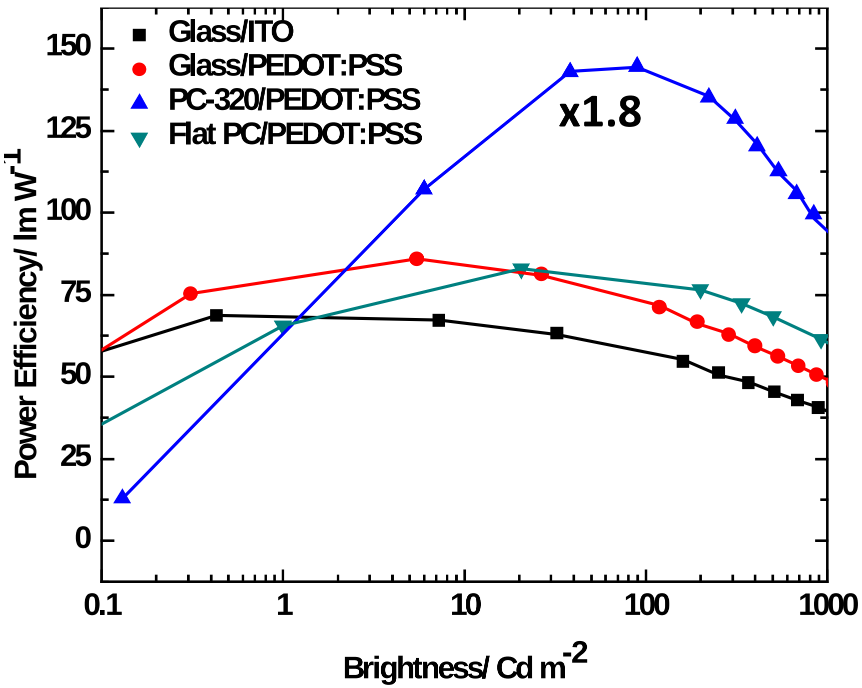
(*h* ~320 nm; pitch ~750 nm)

4. Flat PC/PEDOT:PSS



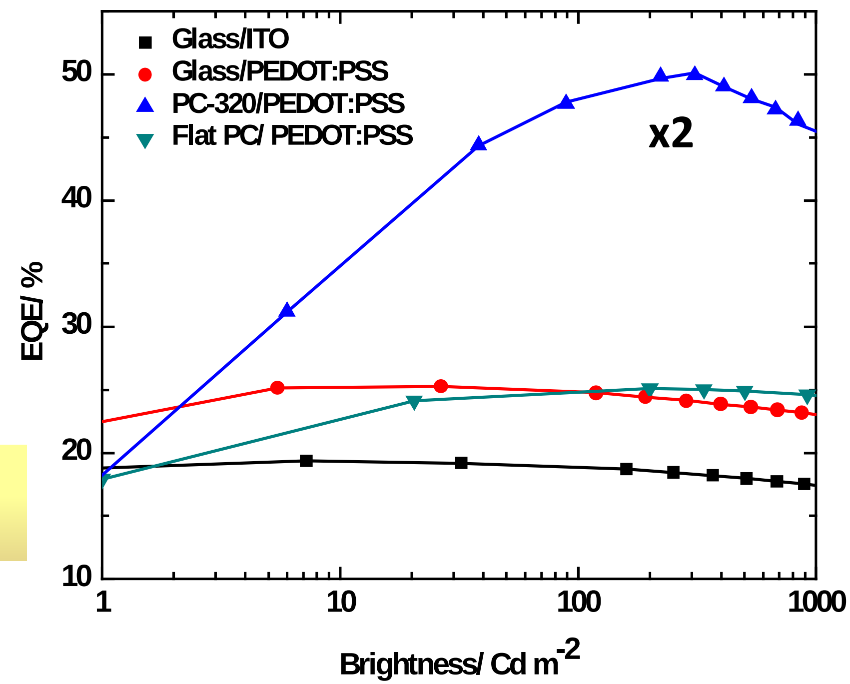


Experimentally: optimal corrugation ~200-400 nm height; ~750 nm pitch consistent with modeling results



Adv. Opt. Mater. (2018)

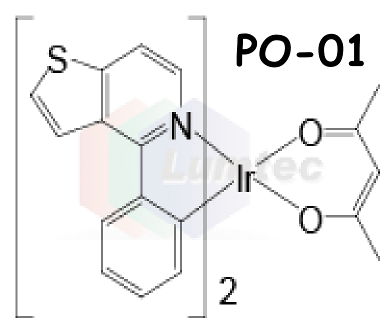
DOI: 10.1002/adom.201701244



EQE = 50% @ ~300 cd/m²; $\eta_{out} \geq 50\%$

White PhOLEDs

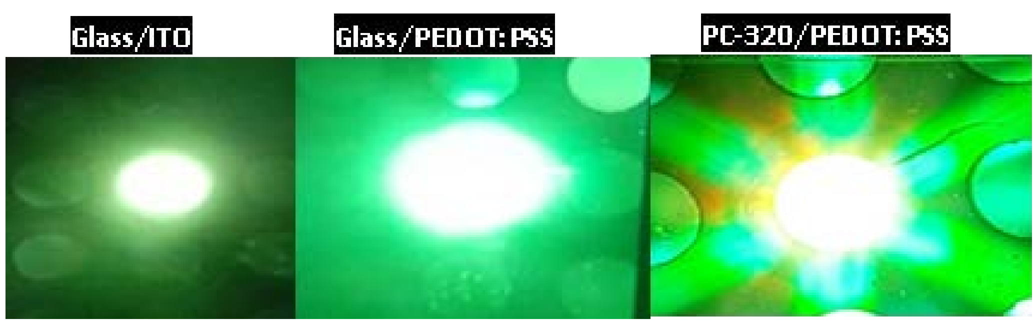
- ~x1.4 increase in EQE of patterned OLED (32%) vs planar (23%)
- PO-01 and FIrpic emitters



PO-01

Substrate/anode	Luminous efficiency (Cd/A)	Power efficiency (lm/W)	EQE (%)	Enhancement factors (relative to glass/ITO; glass/PEDOT:PSS; flat PC/PEDOT:PSS
Glass/ITO	68	~65	19	
Glass/PEDOT:PSS	88	86	25	
Flat PC/PEDOT:PSS	88	82	25	
Corrugated PC/PEDOT:PSS	164 (at 300 cd/m^2)	145 (at 100 cd/m^2)	50 (at 300 cd/m^2)	Luminous efficiency: x2.4; x1.9; x1.9 Power efficiency: x2.2; x1.7; x1.8 EQE: x2.6; x2.0; x2.0

Green PhOLEDs (λ_{peak} = 512 nm) with thin PEDOT:PSS anode on corrugated PC are consistently superior to those on glass or flat PC, or on glass/ITO.

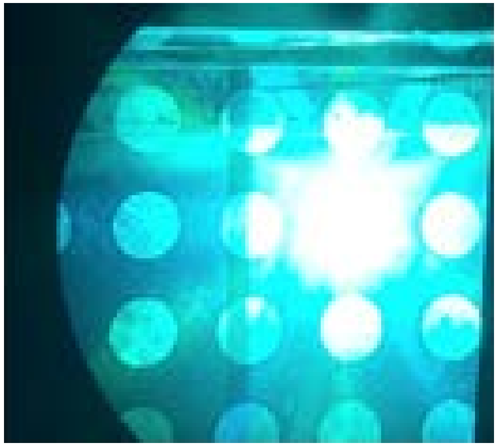


Blue PhOLEDs

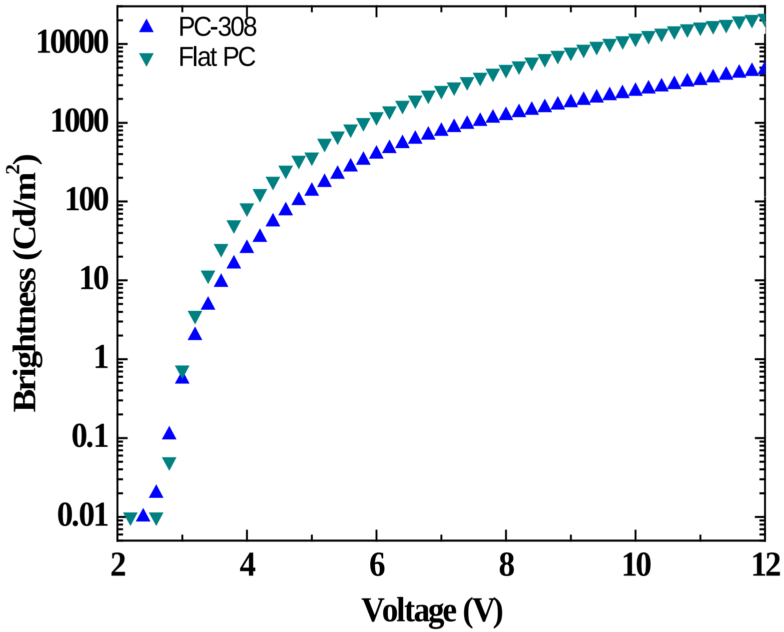
Device structure:

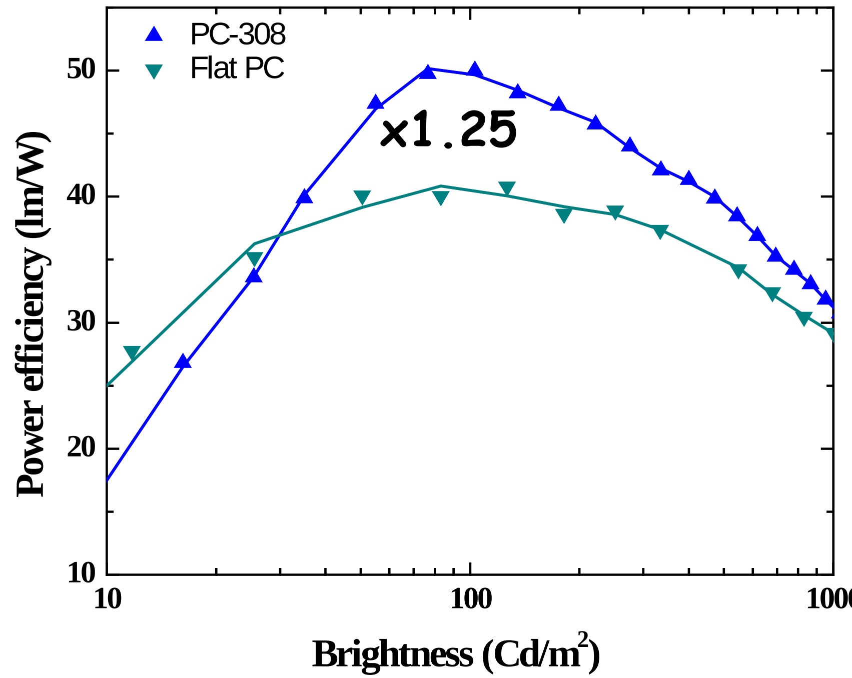
PEDOT:PSS/HAT-CN (5 nm)/10% MoOx:TAPC (60 nm)/TAPC (20 nm)/8% Firpic:mCP (20 nm)/TmPyPb (20 nm)/20% CsF:TmPyPb (40 nm)/LiF (1 nm)/Al (100 nm)

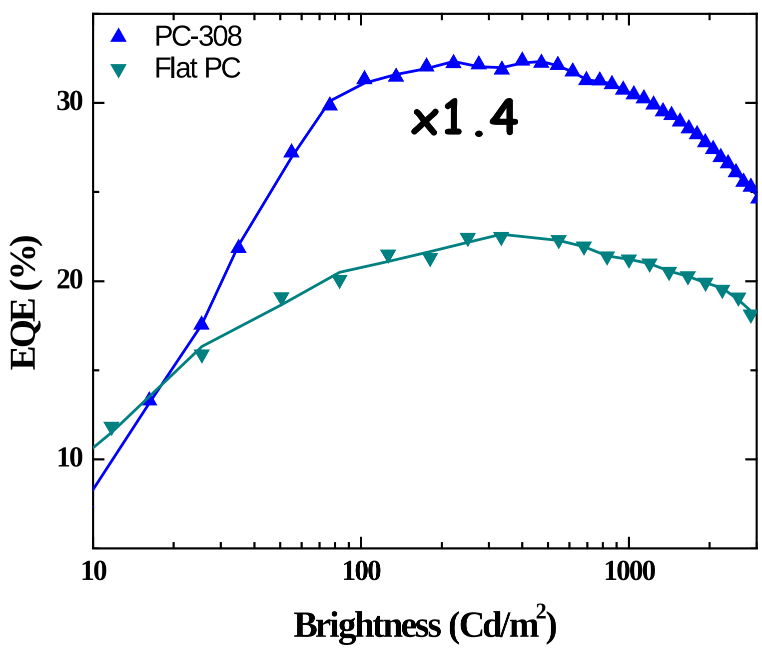
Flat PC



Corrugated PC-308



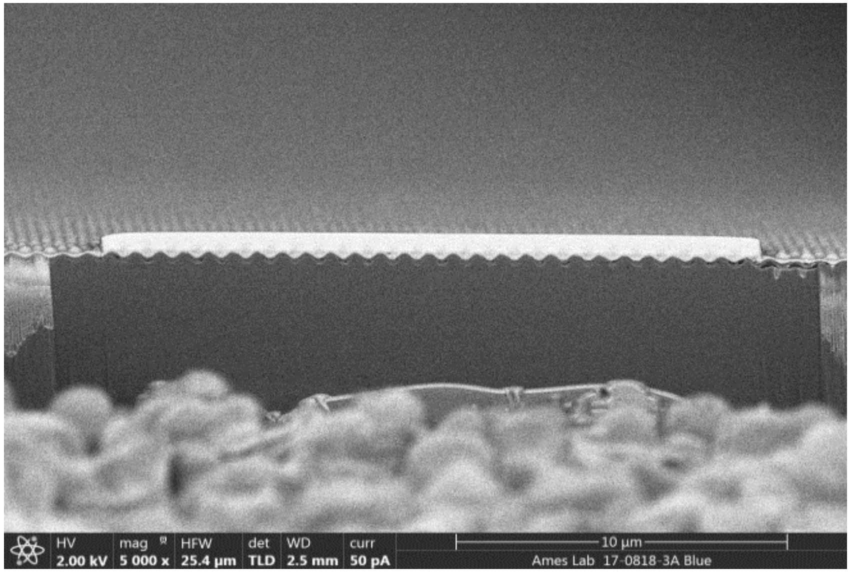


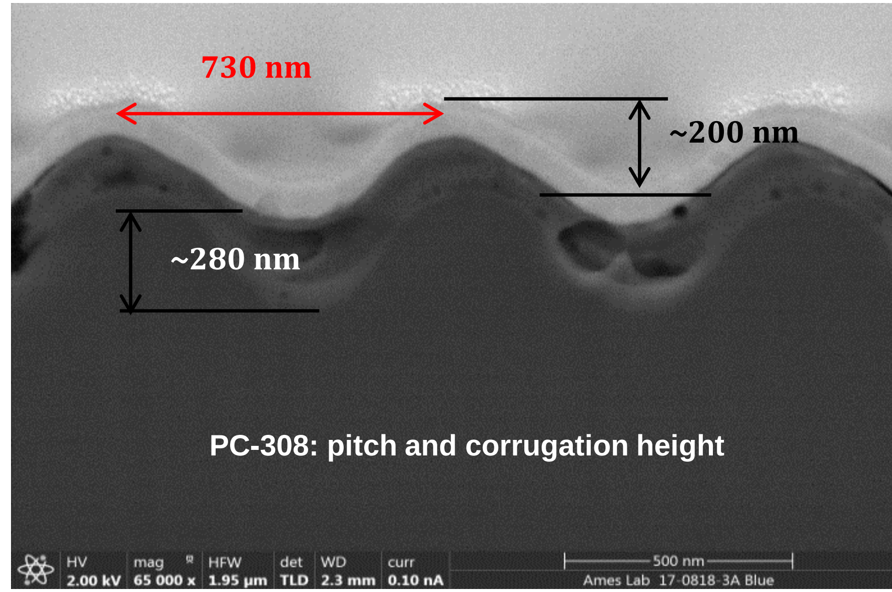


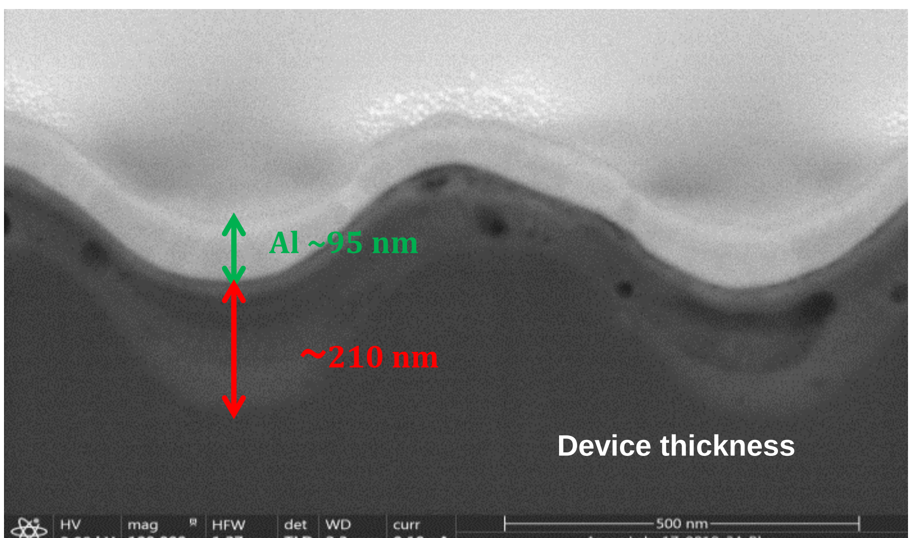
Characteristics of blue PhOLEDs on flat & corrugated PC-308 substrates

- Luminous efficiency – x1.4 enhancement
  80 vs 57 cd/A
- EQE – x1.4 enhancement
  32.5 vs 22.5%
- Power efficiency x1.25 enhancement
  50 vs 40 lm/W

Patterned OLED: FIB Analysis





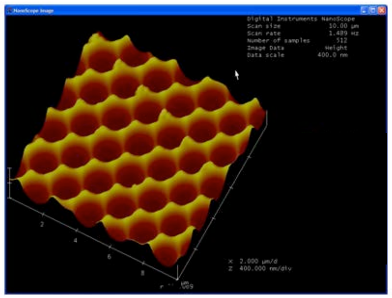


- Total FIB measured thickness: ~305 nm
- Device thickness: ~295 nm; ~265 nm, measured with the thickness monitor + ~30 nm PEDOT:PSS thickness
- Corrugation height at the Al ~180-200 nm

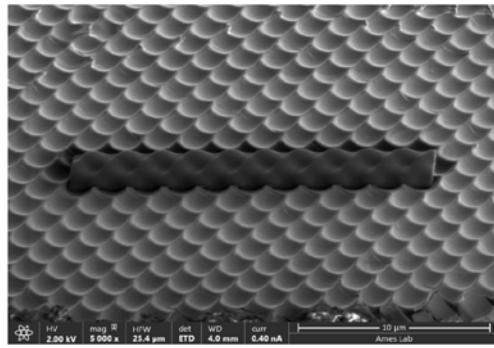
Patterned OLED: FIB Analysis

ITO Anode

White PhOLED:
PET/ITO/20 nm MoOx/126 nm organics/1 nm LiF/100 nm Al



Substrate AFM image



SEM images of PET/CAB/ITO patterned surface

Backscattered electron image

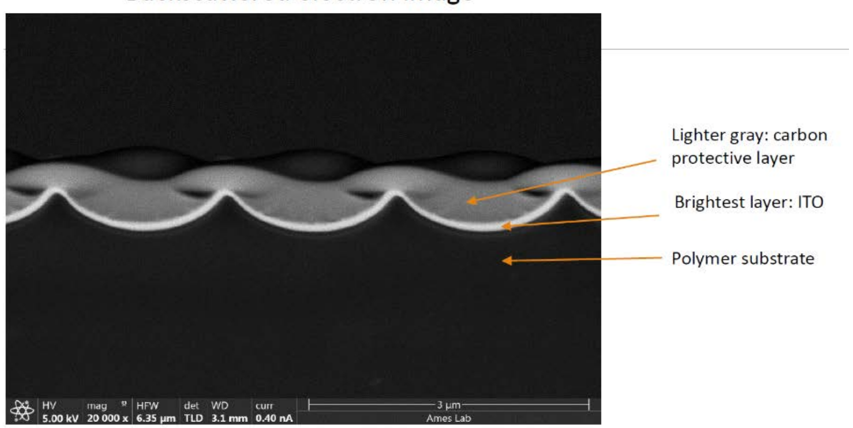
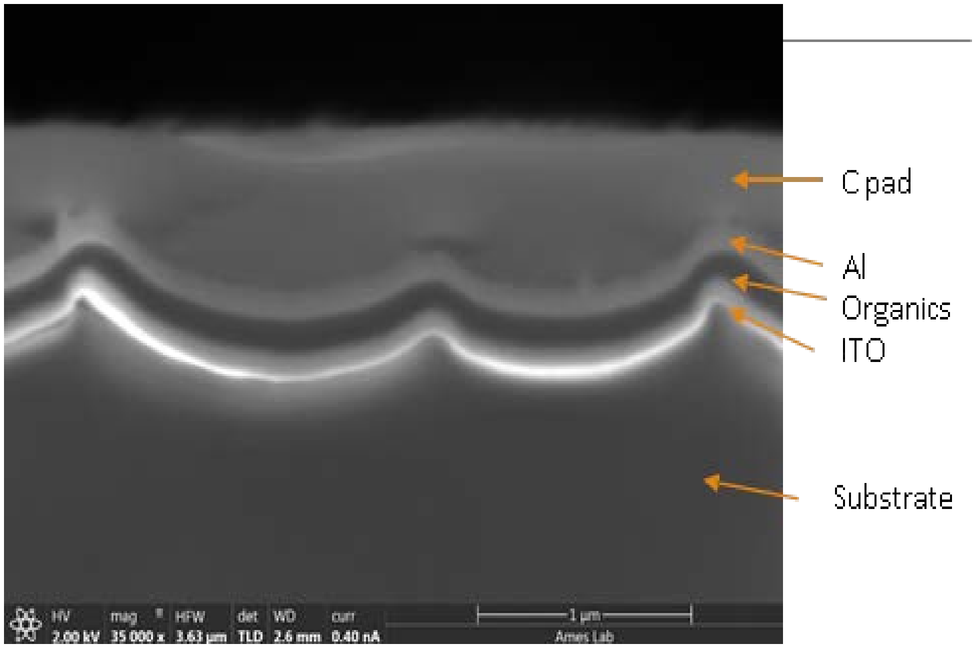


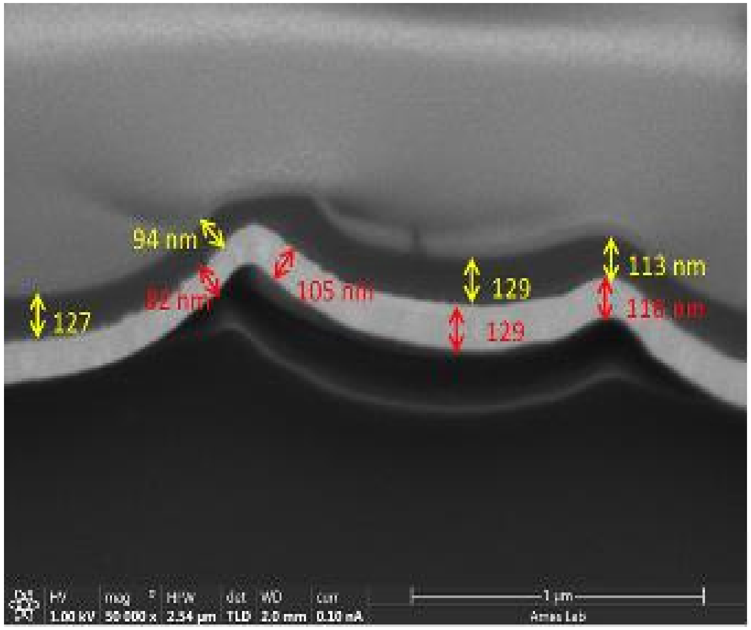
Image of conformal ITO on patterned PET/CAB (h ~250 nm; pitch ~2 μm)

The pad on the top right image is a protective carbon layer through which milling in the FIB measurement is performed

Conformal OLED on Patterned Substrate/ITO

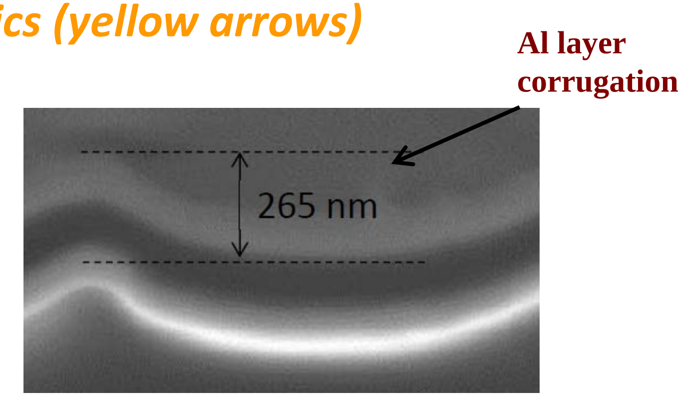
PET/CAB with concave features; *h* ~250 nm and pitch ~2 μm





FIB images of the OLED layers on PET/CAB and thicknesses at various locations of the ITO (red arrows) and organics (yellow arrows)

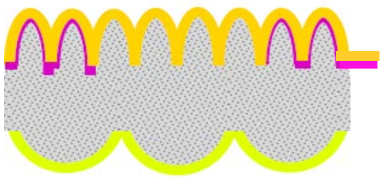
The OLED structure appears largely conformal up to the Al electrode with some thickness variations across the features



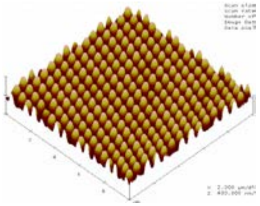
Acknowledgement: DOE EERE program

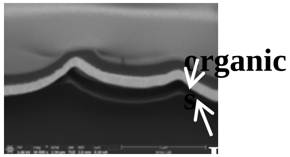
Concluding Remarks

- A periodic nanopatterned flexible substrate was used successfully to extract light trapped in the anode+organics and photons lost to surface plasmon excitation
  - EQE ~50% was obtained for green PhOLEDs



- OLEDs were largely conformal with the corrugation, likely dependent on the pattern's pitch to height ratio
  - R2R coating will likely be beneficial for coating uniformity
- An integrated metal micromesh with continuous field conductor improves the anode electrical conductivity
- The corrugation and OLED design were supported by modeling





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