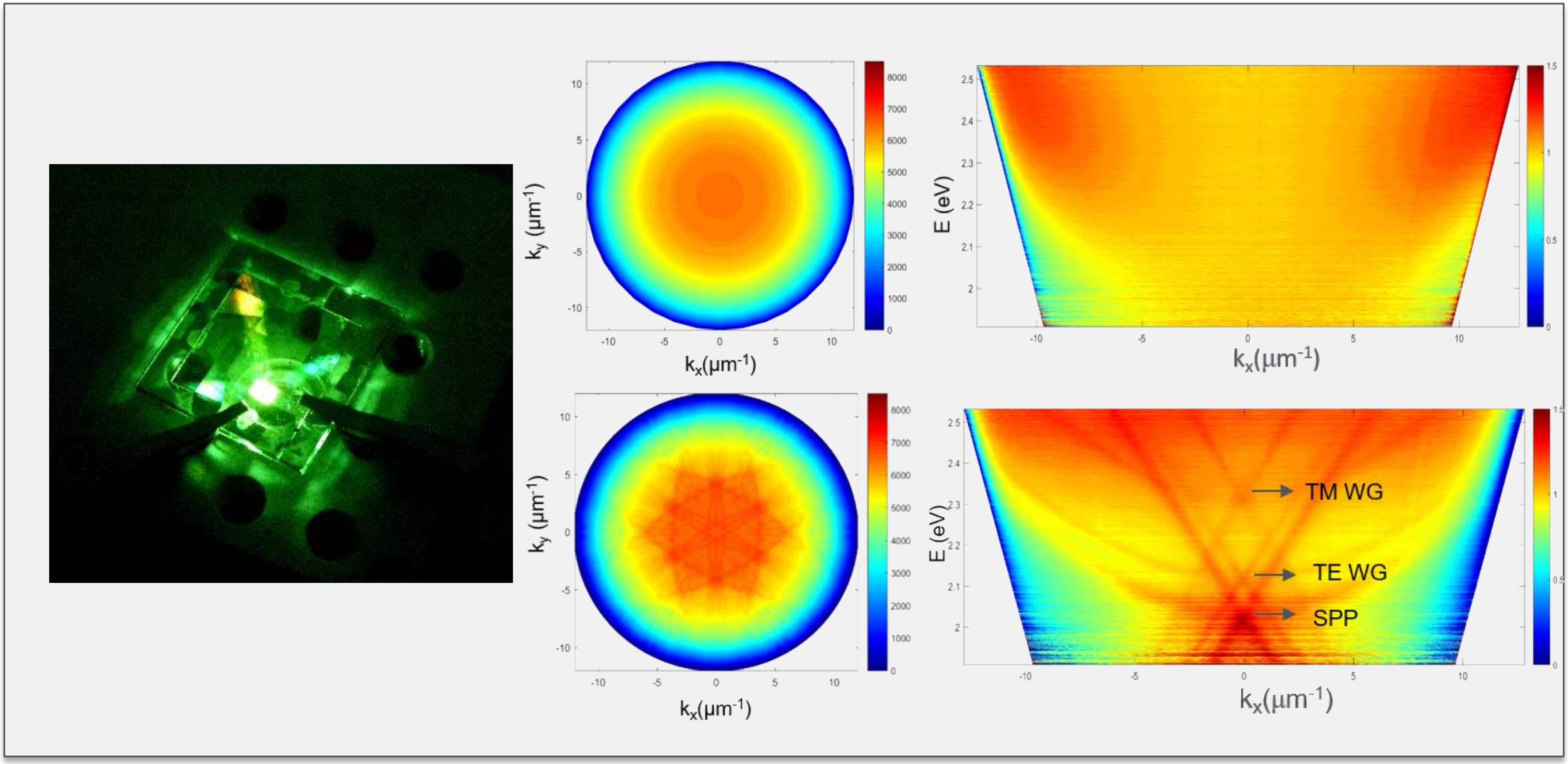
Low Cost Corrugated Substrates for High Efficiency OLEDs

2018 Building Technologies Office Peer Review



U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Project Summary

Timeline:

Start date: Sep, 2016

Planned end date: Sep, 2018

Key Milestones

1. Over 60% EQE with corrugated substrates and macro lens (Apr 2017)
2. Index contrast layer with refractive index < 1.2 (Dec 2017)
3. Further improve EQE to 65% with index contrast layer (Mar 2018)

Budget:

Total Project $ to Date:

- DOE: $258,377
- Cost Share: $133,064

Total Project $:

- DOE: $426,771
- Cost Share: $157,000

Key Partners:

SBA Materials
MicroContinuum

Project Outcome:

The objective of the project is to develop and optimize novel low cost substrates with buffer interlayer materials having a low in index of refraction. The end goal is to demonstrate the technology in an OLED to achieve an external quantum efficiency exceeding 70%.

Purpose and Objectives

Problem Statement: Organic light emitting diode (OLED) is a strong contender for next generation lighting. The external quantum efficiency (EQE) of an OLED is typically less than 25%. Various techniques have been introduced to improve the light extraction efficiency, but finding high efficiency, low cost and large scale manufacturing compatible method remains a challenge.

Target Market and Audience: Solid state lighting is a technology that is envisaged in a new sustainable energy economy. Statistics shows that lighting consumes >700 trillion W-hrs of electricity per year in the United States, which corresponds to 22% of all electricity generated nation-wide.

Impact of Project: In the DOE MYPP, the 2020 goal for novel light extraction of OLEDs approaches is 70% EQE. The PI has previously achieved very high extraction efficiencies by fabricating OLEDs on corrugated sapphire substrate (EQE of 63%). The research aims at developing novel low index materials to be integrated with low cost corrugated glass substrates to achieve the 2020 EQE target by the end of the 2-year program.

Approach

- **Approach**: We use corrugated substrates to extract trapped light from waveguide and SPP modes, and macro lens or microlens arrays to extract light from substrate mode. We recognize the corrugated substrate is ineffective against waveguide modes due to the small refractive index contrast (Δn) between ITO and substrate. We propose to insert a low index ($n < 1.4$) buffer layer at the interface to achieve higher diffraction efficiency. Using this approach, a truly low cost substrate for high efficiency OLEDs with the potential to extract most of the waveguide modes and surface plasmon mode can be realized.

Key Issues: Identify source of extracted light, improve the extraction of waveguide modes by enhancing index contrast

Distinctive Characteristics: Low cost corrugated substrates for high efficiency OLED

Progress and Accomplishments

Accomplishments: We optimized the fabrication of corrugated substrates and obtained 63% EQE with macro lens attached. To understand the source of improved outcoupling, we developed a novel optical study method Angle-Resolved EL Spectroscopy (ARES). With ARES study we were able to identify the limitation to be waveguide mode extraction. With an index contrast enhancement layer inserted between ITO and glass substrate, we were able to further improve the EQE to 65% by enhancing the index contrast by only 0.05. The target EQE of 70% can be achieved with higher index contrast.

Market Impact: The research focuses on using low cost material for high extraction efficiency. We study OLED devices fabricated on low cost glass substrates, which can extend to flexible plastic substrate. The corrugation pattern can be upscaled with roll-to-roll nano-imprinting. The index contrast enhancement layer can be solution processed. In return, the device efficiency is more than doubled, which reduces the power consumption and extends device lifetime in lighting application.

Awards/Recognition: DOE Office of Energy Efficiency and Renewable Energy (Award No. DE-EE0007624)

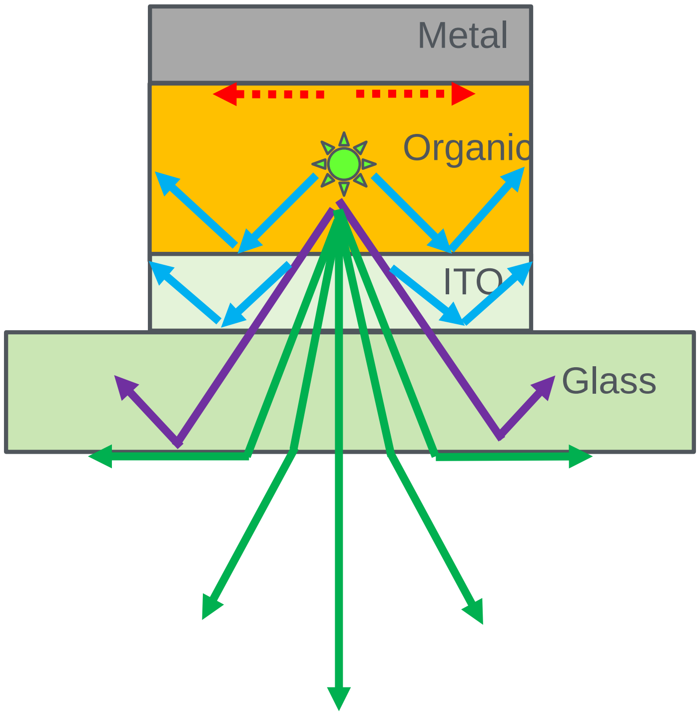
Project Integration and Collaboration

Project Integration: The project receives support on nano-patterns and index enhancement materials from MicroContinuum and SBA materials.

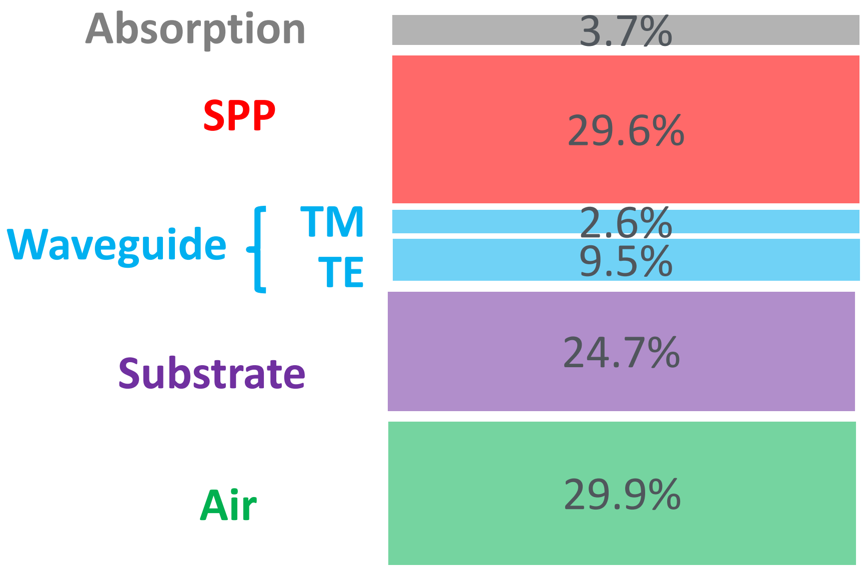
Partners, Subcontractors, and Collaborators: MicroContinuum provides the nano-patterning used for corrugation. SBA Materials provides the research with index enhancement materials.

Communications: This work was presented in the 2017 SPIE Optics+Photonics conference and 2018 DOE SSL Workshop

Light Trapping in OLEDs

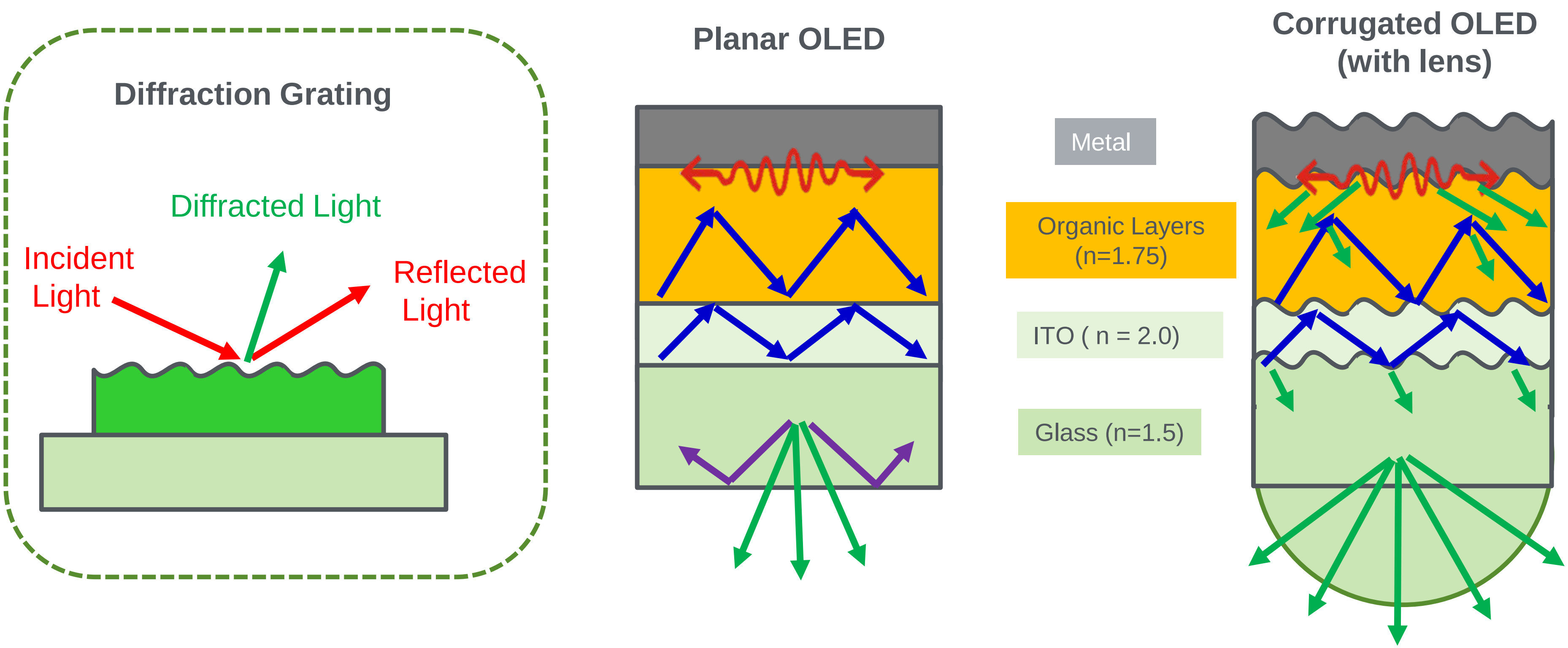


Simulated Mode Distribution



- Light travelling close to the normal direction can escape the device
- Over 70% of the photons are trapped in OLEDs in optical modes
  - Eventually dissipate as heat

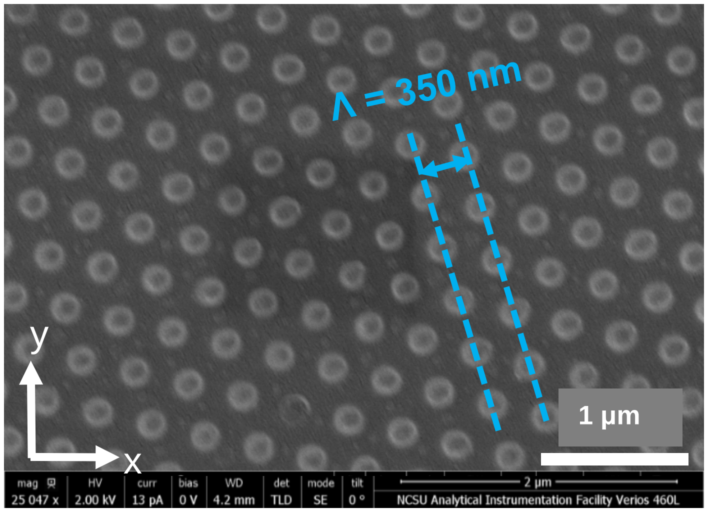
Light Extraction with Corrugation and Lens



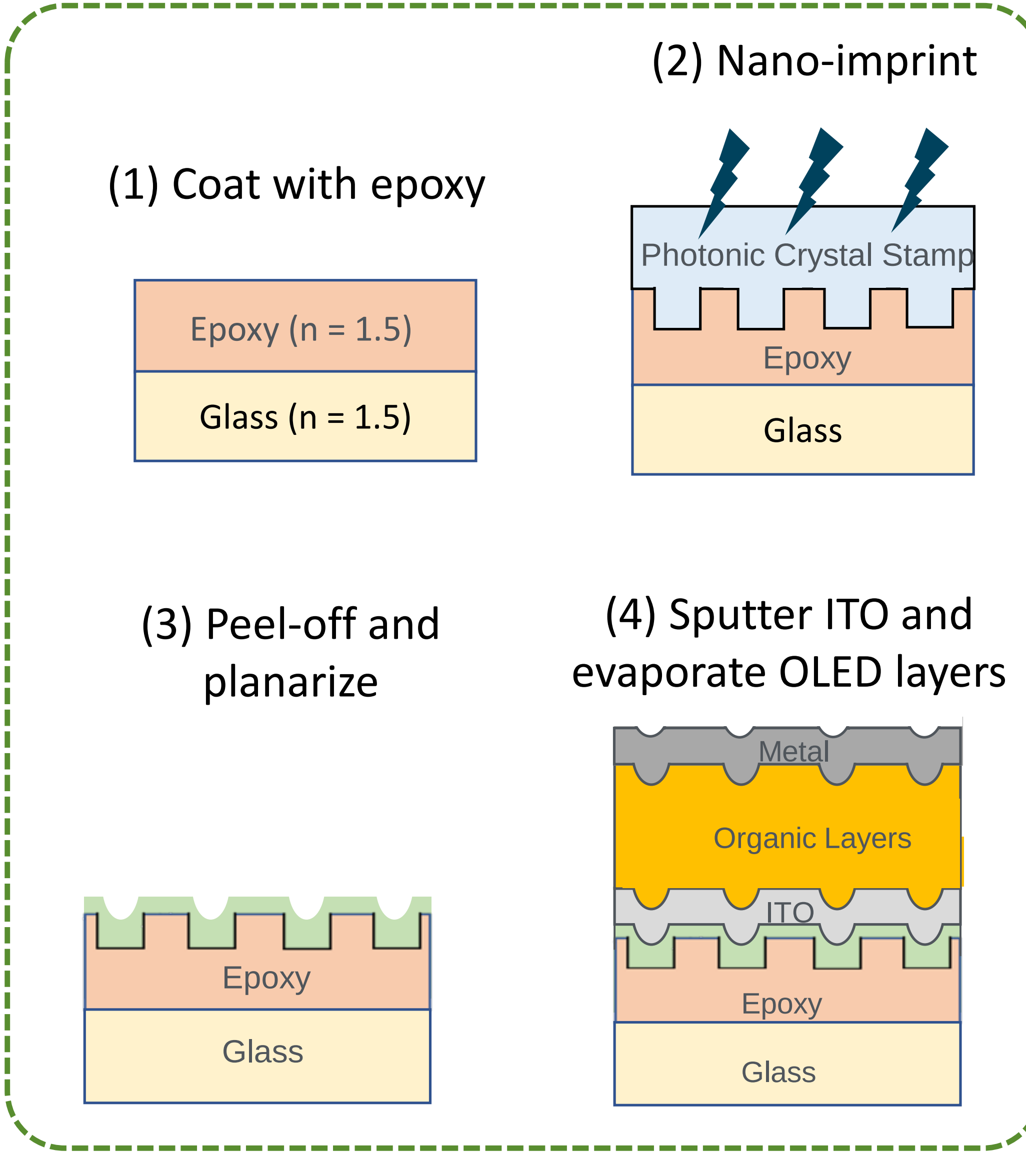
- Corrugation acts as diffraction grating and diverts photons towards the normal direction
- Lens eliminates total internal reflection and extracts substrate mode

Fabricate Corrugated OLED with Photonic Crystals

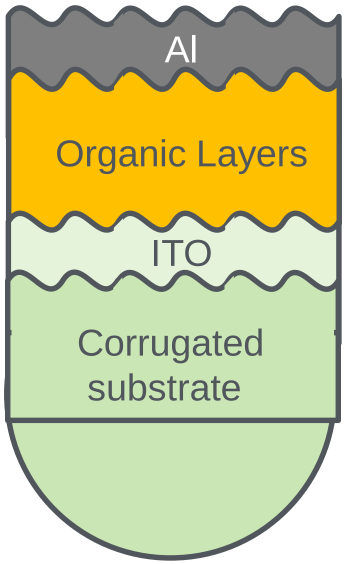
Photonic Crystal Mold

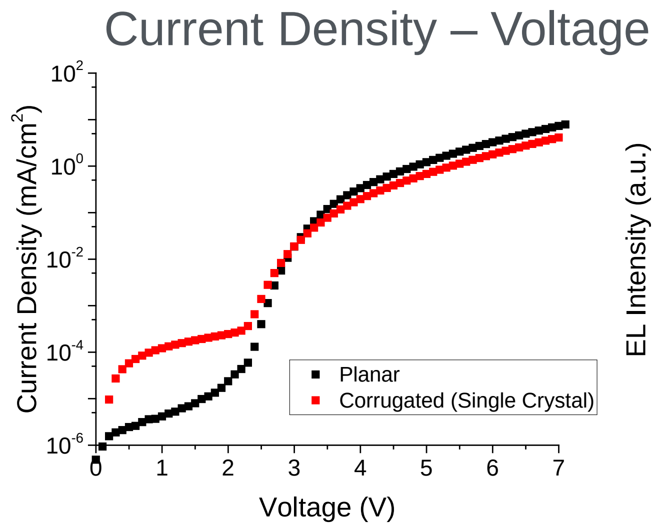


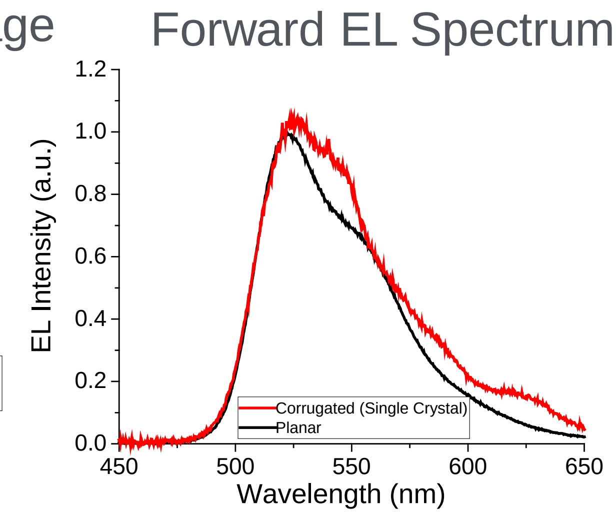
- Single crystal hexagonal lattice
- Λ = 350 nm
- d = 160 nm (85 nm after planarization)

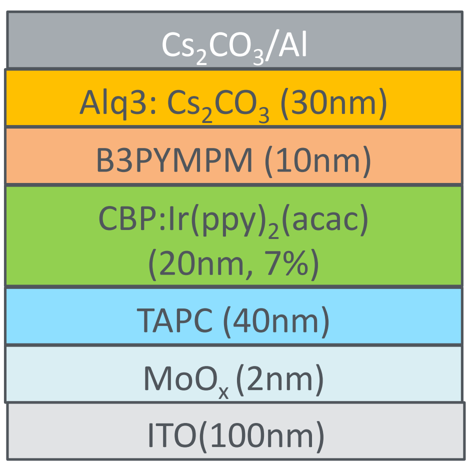


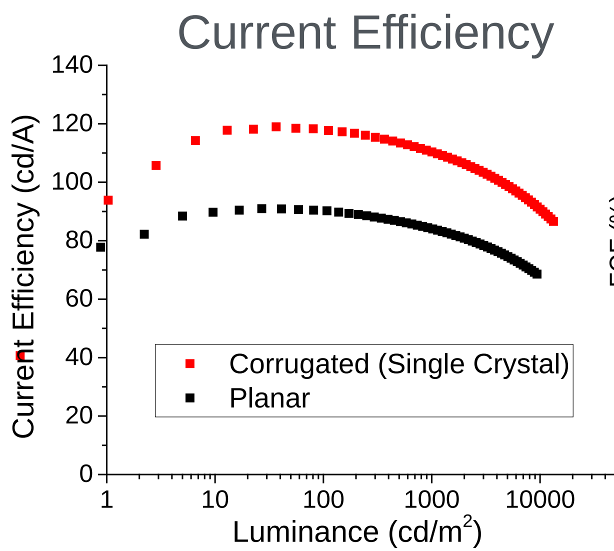
Corrugated OLED Performance

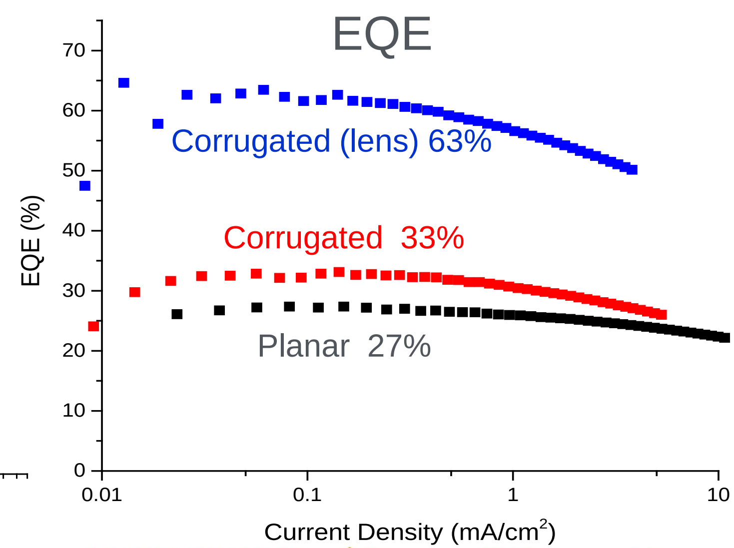












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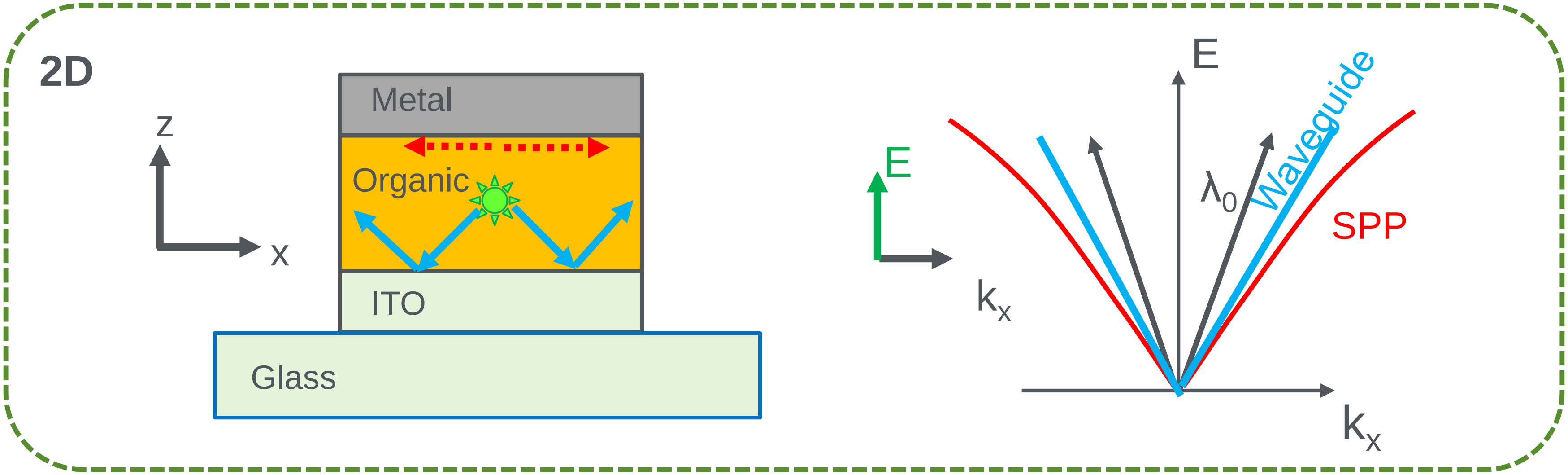
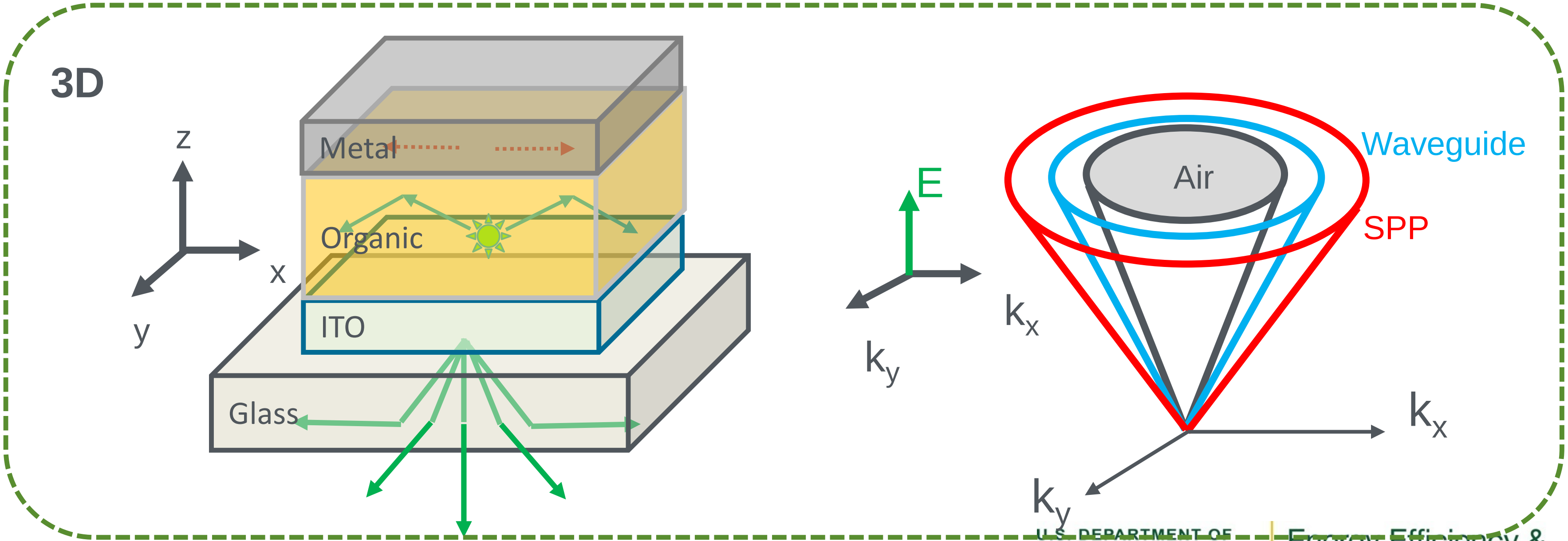
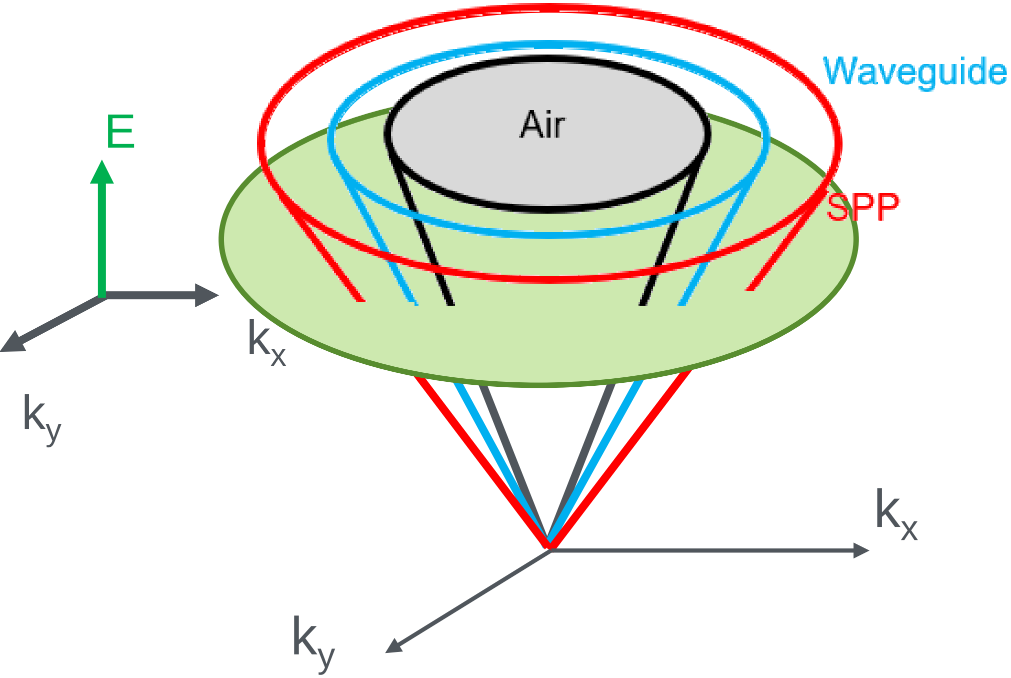
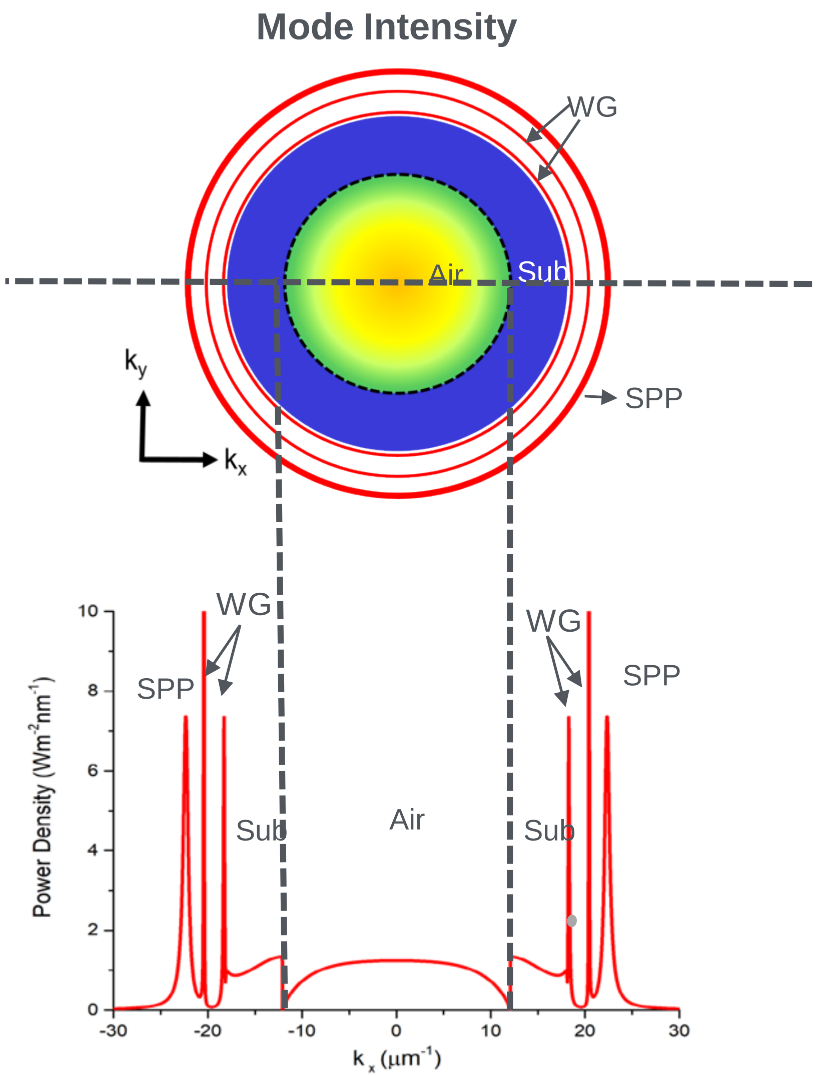
3D Optical Modes in OLEDs





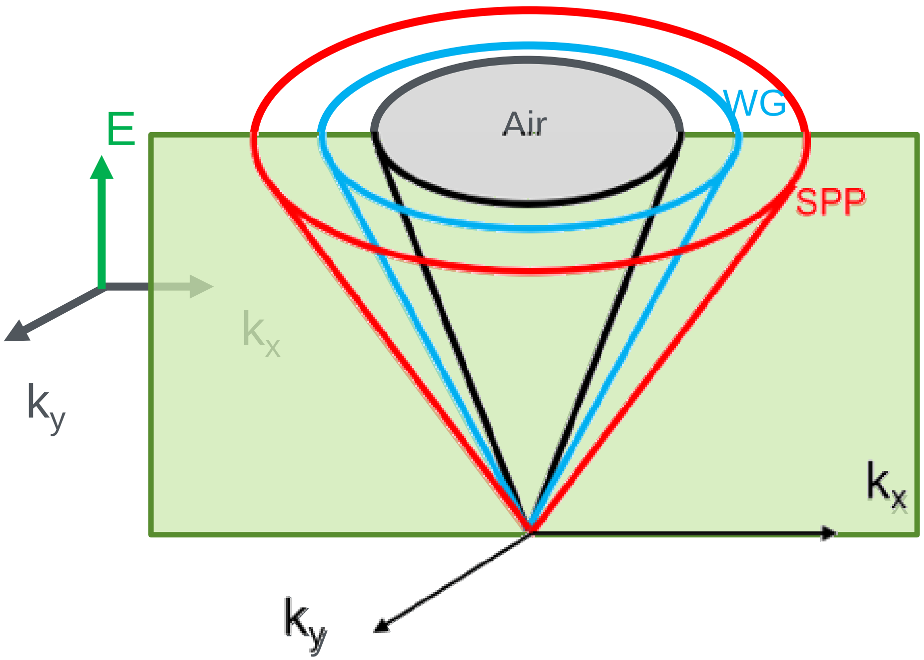
Dissecting 3D Optical Modes - Far Field Emission

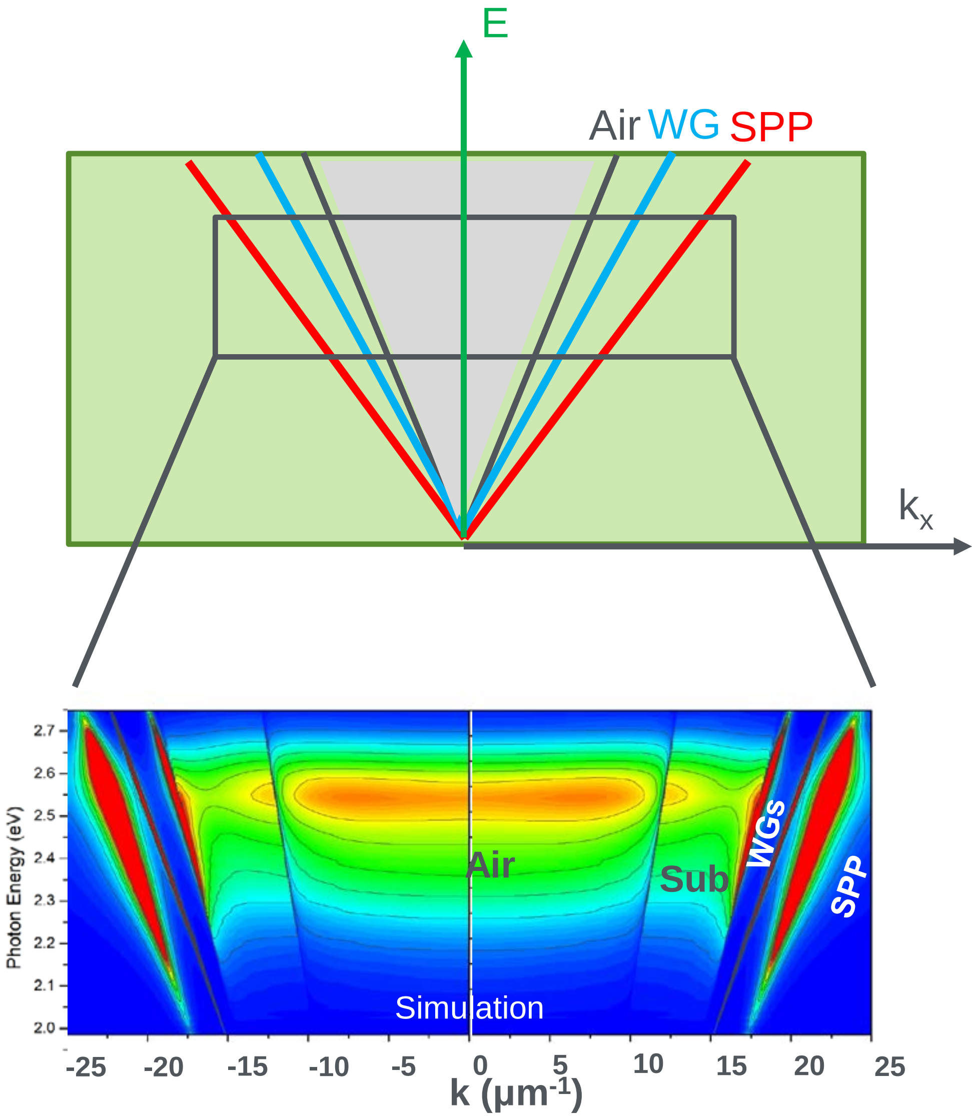




- All k directions
- Single wavelength

Dissecting 3D Optical Modes - Mode Dispersion





- Single k direction
- Multiple wavelengths

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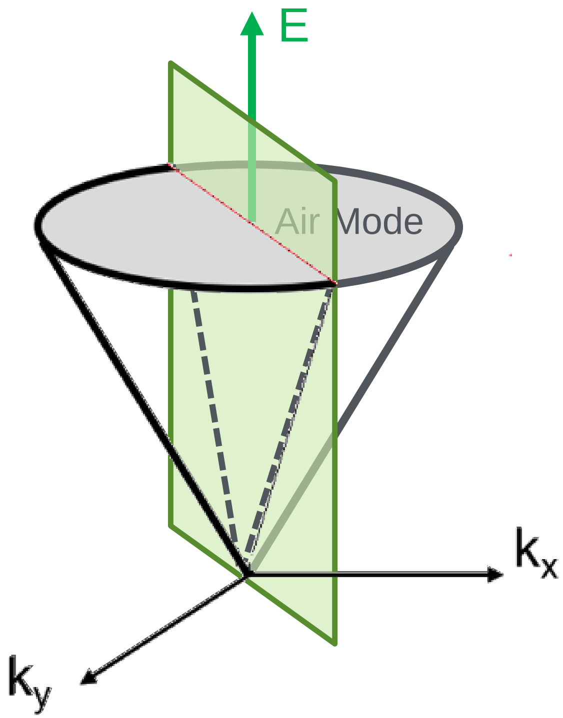
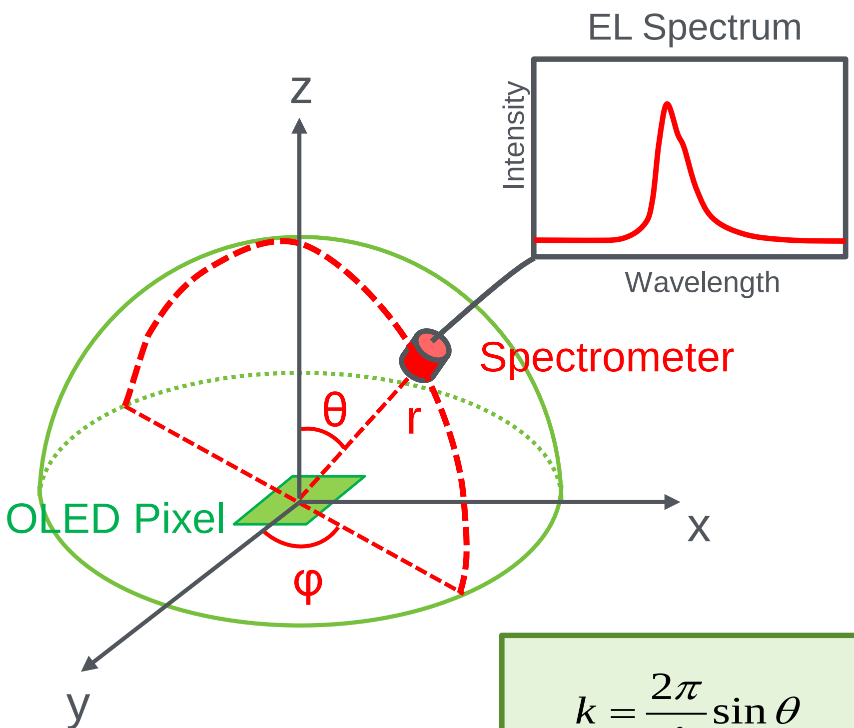
Angle Resolved EL Spectroscopy





$$k = \frac{2\pi}{\lambda} \sin\theta$$

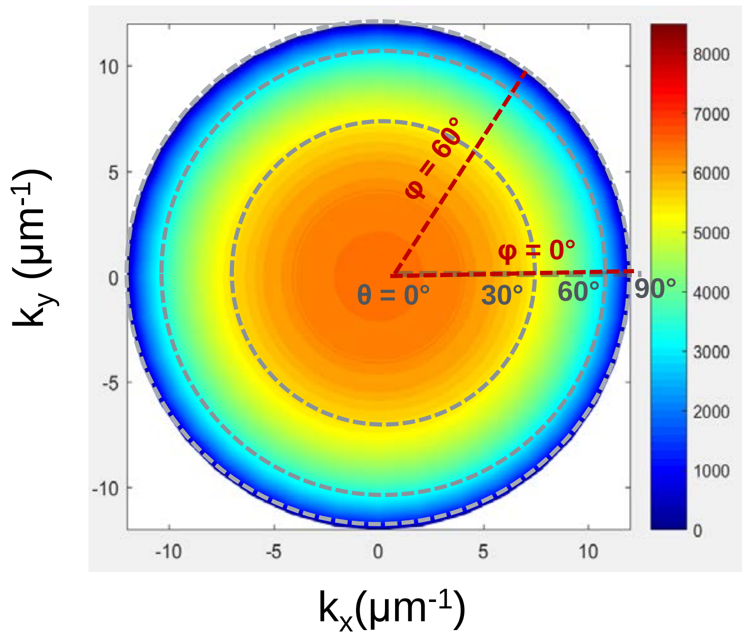
$$E = h\nu = \frac{hc}{\lambda}$$

ARES measurement

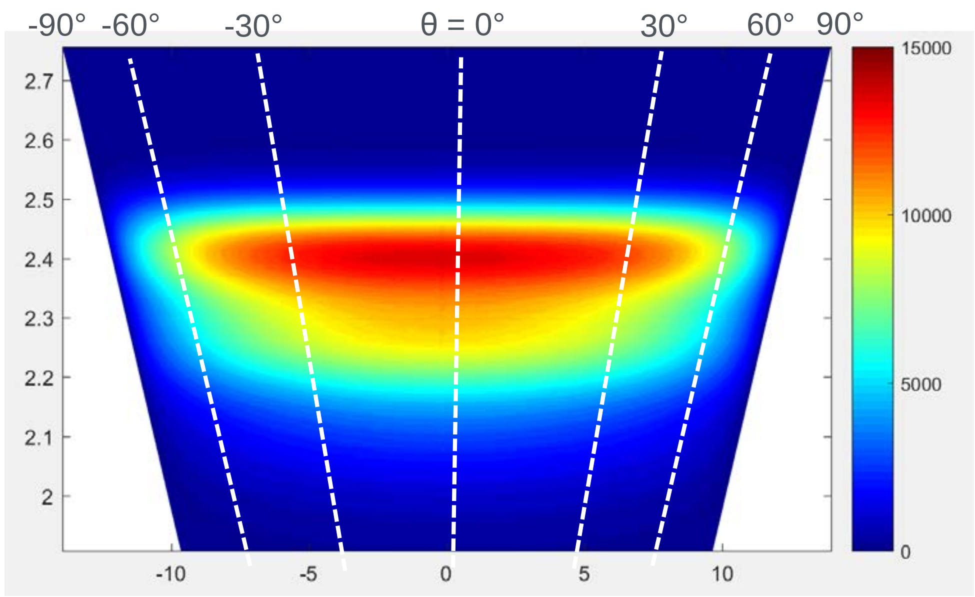
- Collect EL spectra of an operating OLED device from all the forward solid angles
- Convert $I_{EL}(E, \varphi, \theta)$ to $I_{EL}(E, k_x, k_y)$ to get 3D air mode

ARES Study of Planar OLED

Far Field Emission (λ=520nm)

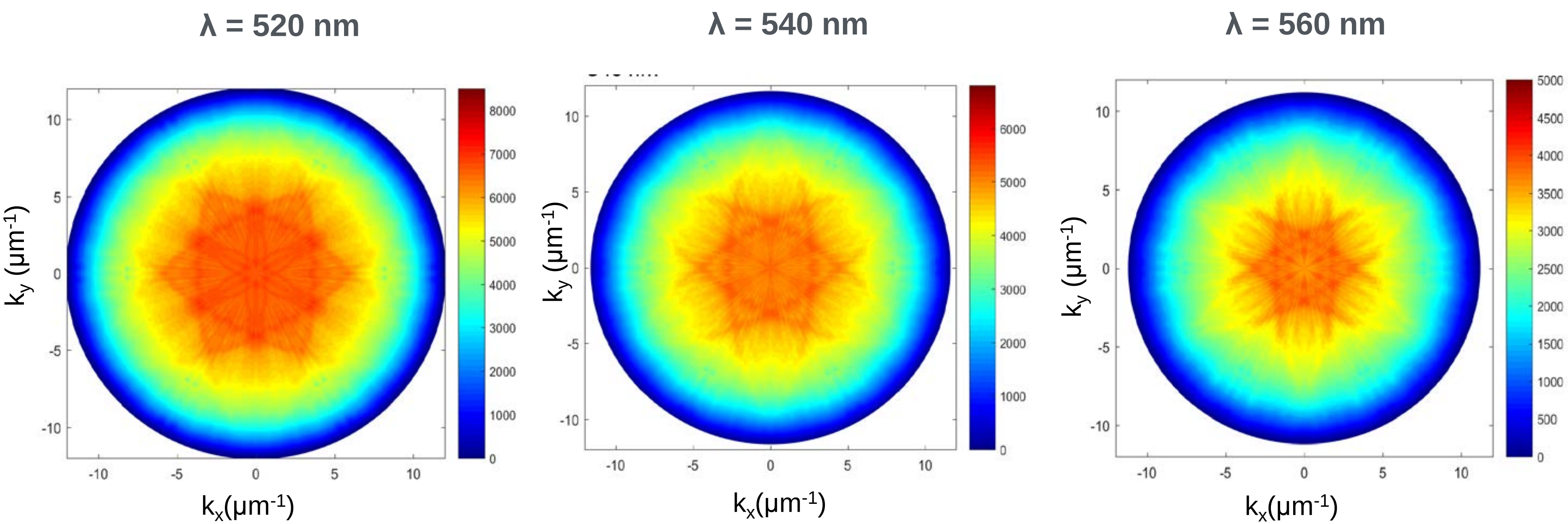


Mode Dispersion (any φ)



- For a planar OLED, mode dispersion and far field emission is independent on φ

ARES Study of Corrugated OLED – Far Field Emission



- For a corrugated OLED, far field emission shows flower-shaped patterns with hexagonal symmetry

The features in mode dispersion and far field emission plots correspond to extracted light.

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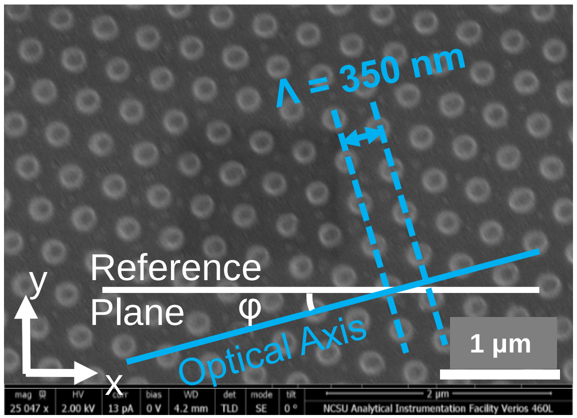
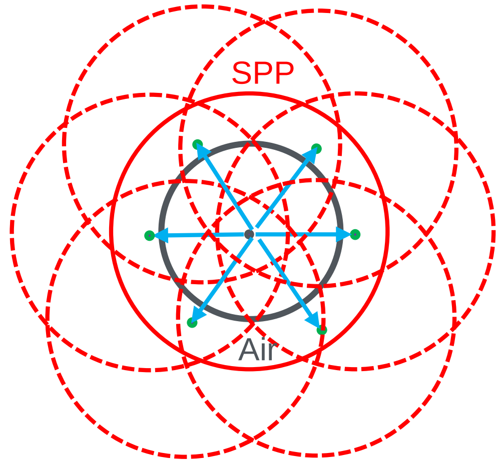
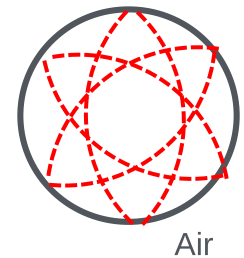
Explain Far Field Emission with Simulation



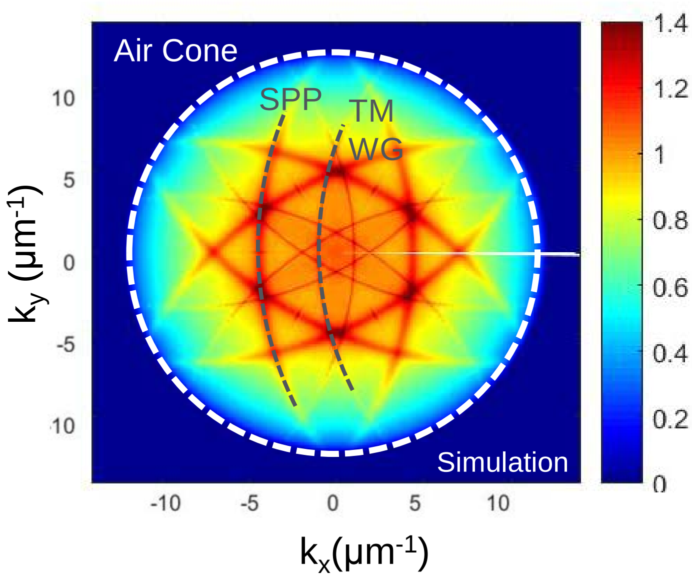


Far field emission

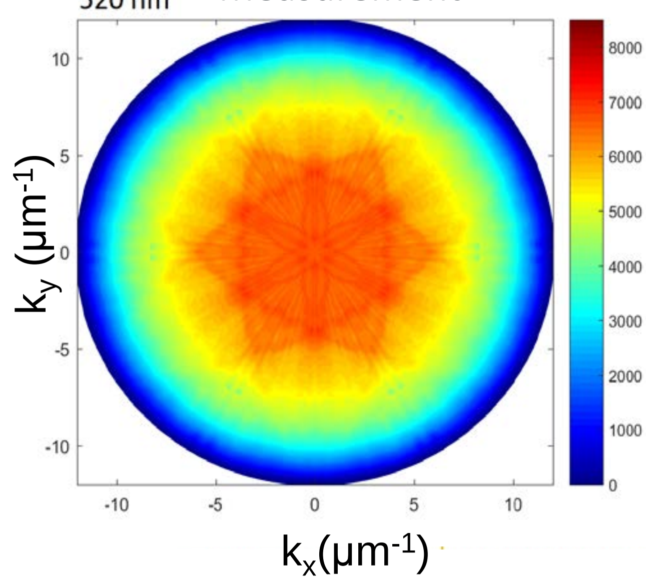
($E = E_0$)



Simulation



Measurement



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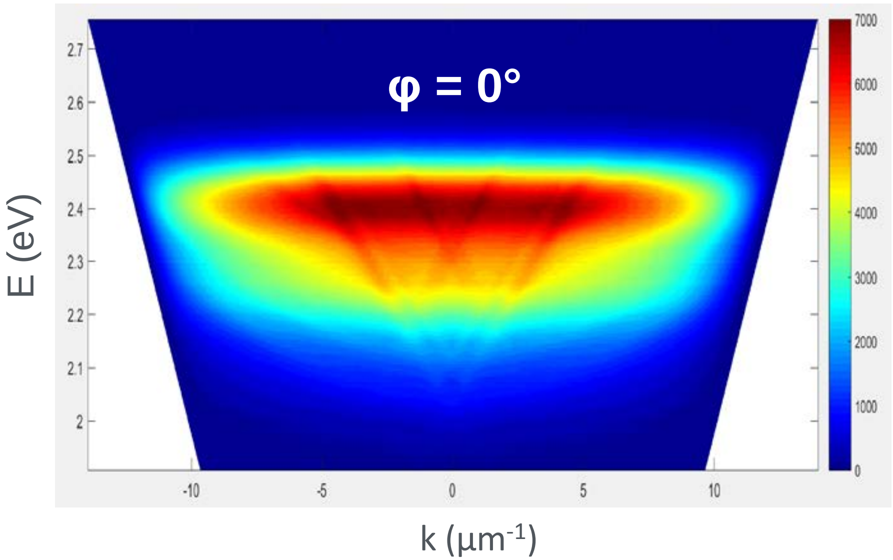
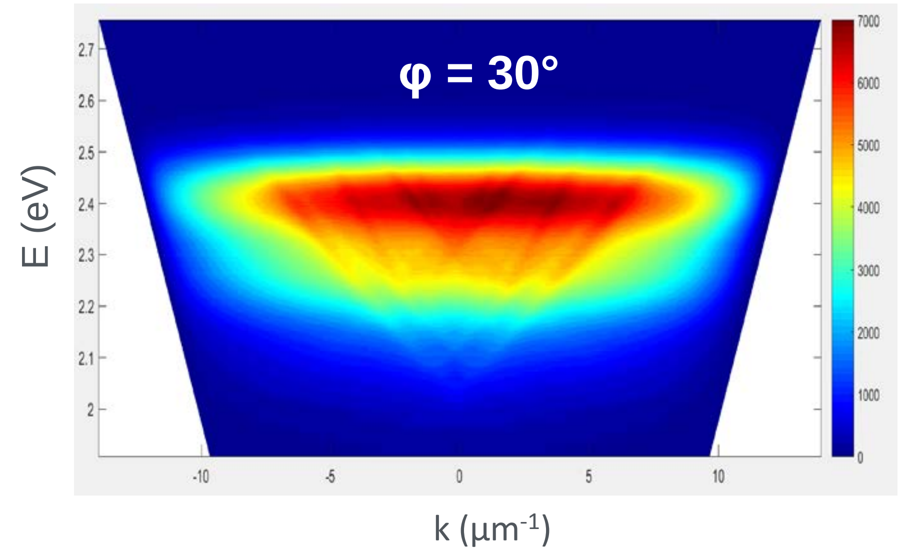
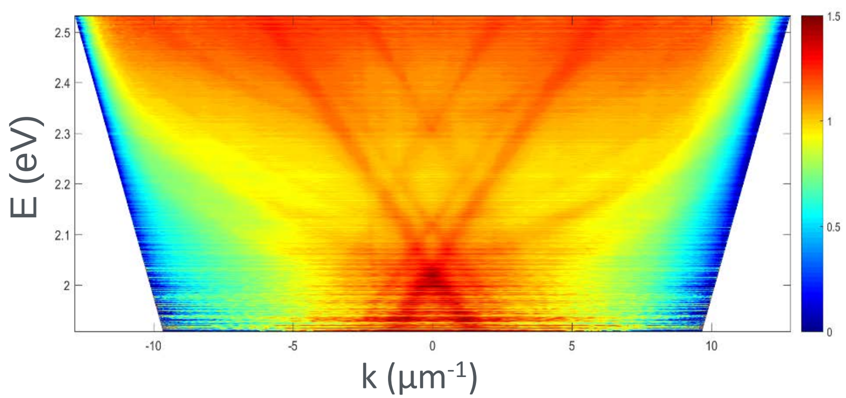
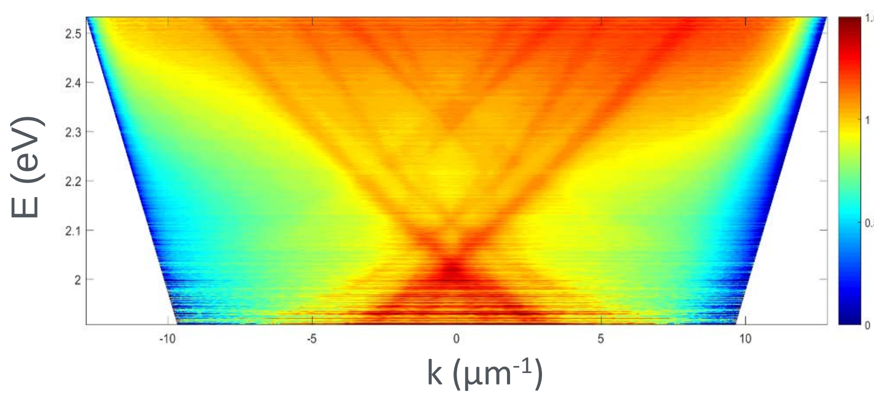
ARES Study of Corrugated OLED – Mode Dispersion







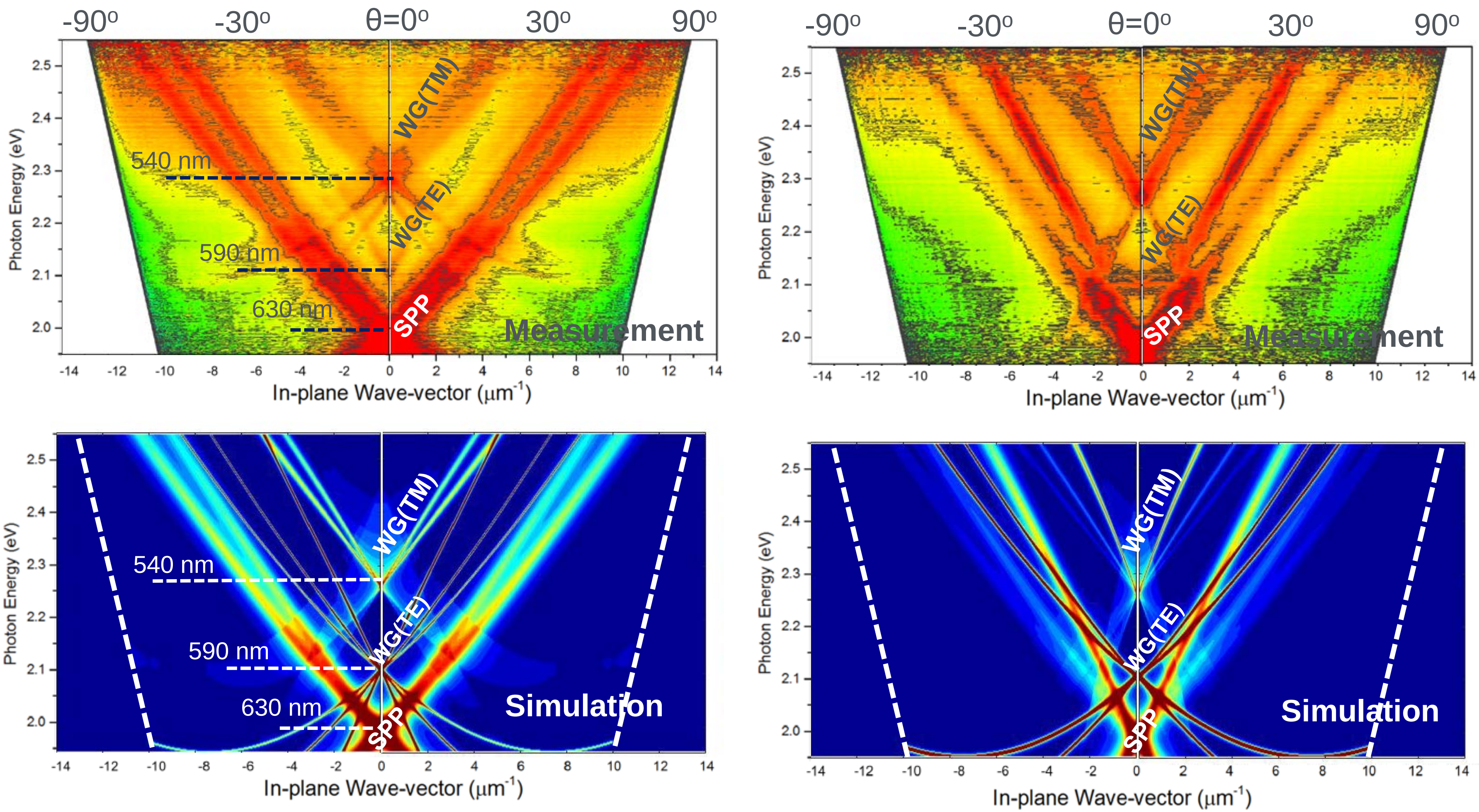


- For a corrugated OLED, mode dispersion is dependent on φ
- After eliminating the effect of emitter EL spectrum, linear features are revealed

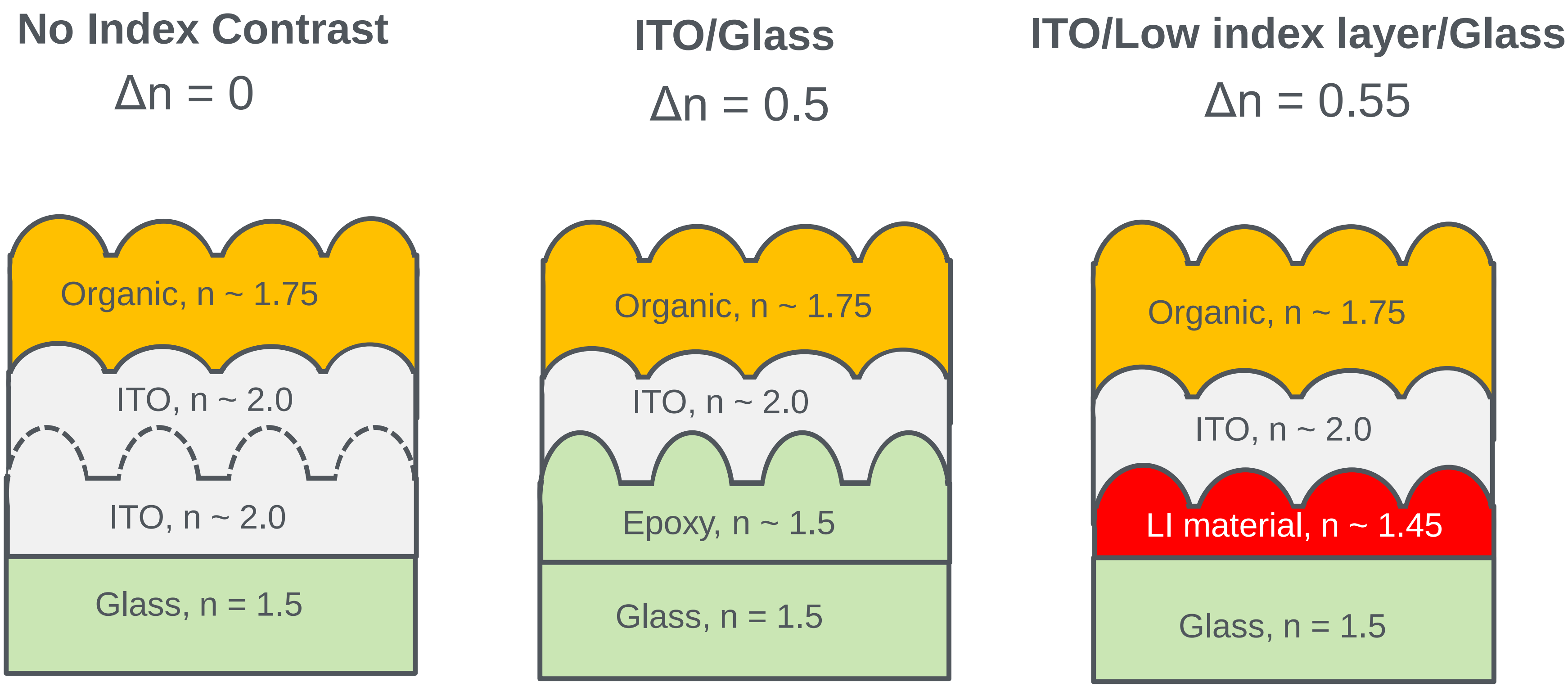
Explain Mode Dispersion with Simulation

Φ=5°

S Light **P Light**

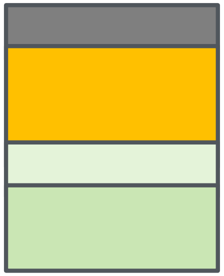
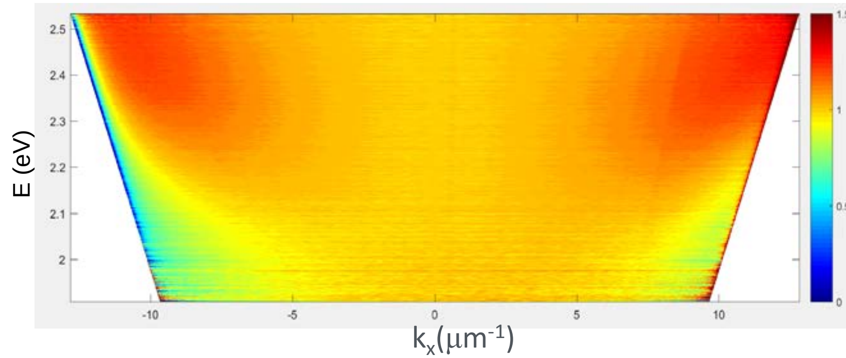
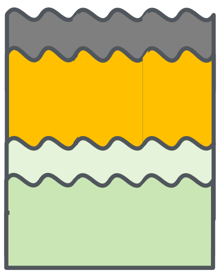
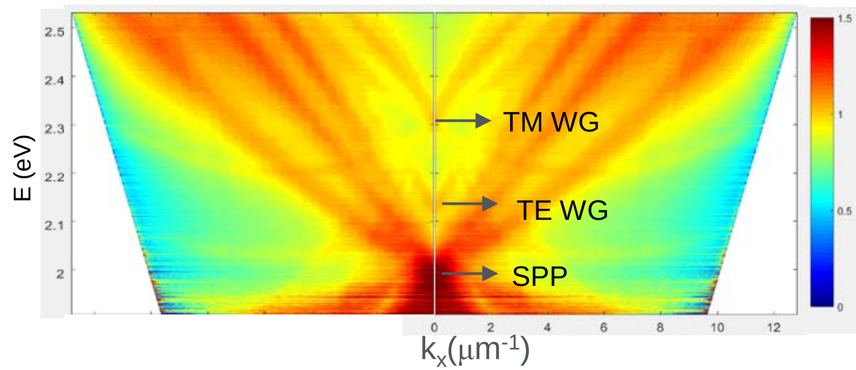
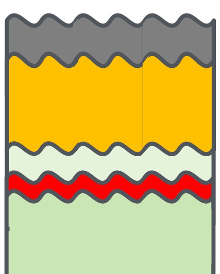
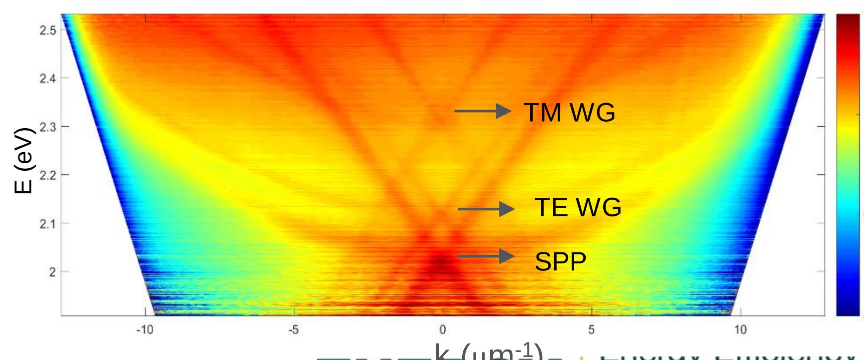


Extract TE WG Mode with Low Index Layer



- TE waveguided mode is trapped in ITO layer
- Index contrast between ITO and underlying layer determines TE waveguided mode extraction

Corrugated OLED with LI Layer

Structure		EQE	ARES Measurement
Planar		27% 46% (w/ lens)	
Corrugated		33% 63% (w/ lens)	
Corrugated (with LI layer)		35% 65% (w/ lens)	

Remaining Projects

Optimize Index Contrast Enhance Layer for >70% EQE

- Optimize the processing procedure of index contrast layer to achieve $\Delta n > 0.8$ and further improve TE waveguide extraction

Substrate Mode Extraction with Microlens Arrays

- Use microlens arrays (MLAs) with diameter smaller than 15 µm to replace bulky macro lens
- Study the extraction efficiency with different pitches, depths and configurations (square-shaped, hexagonally close packed, honeycomb)

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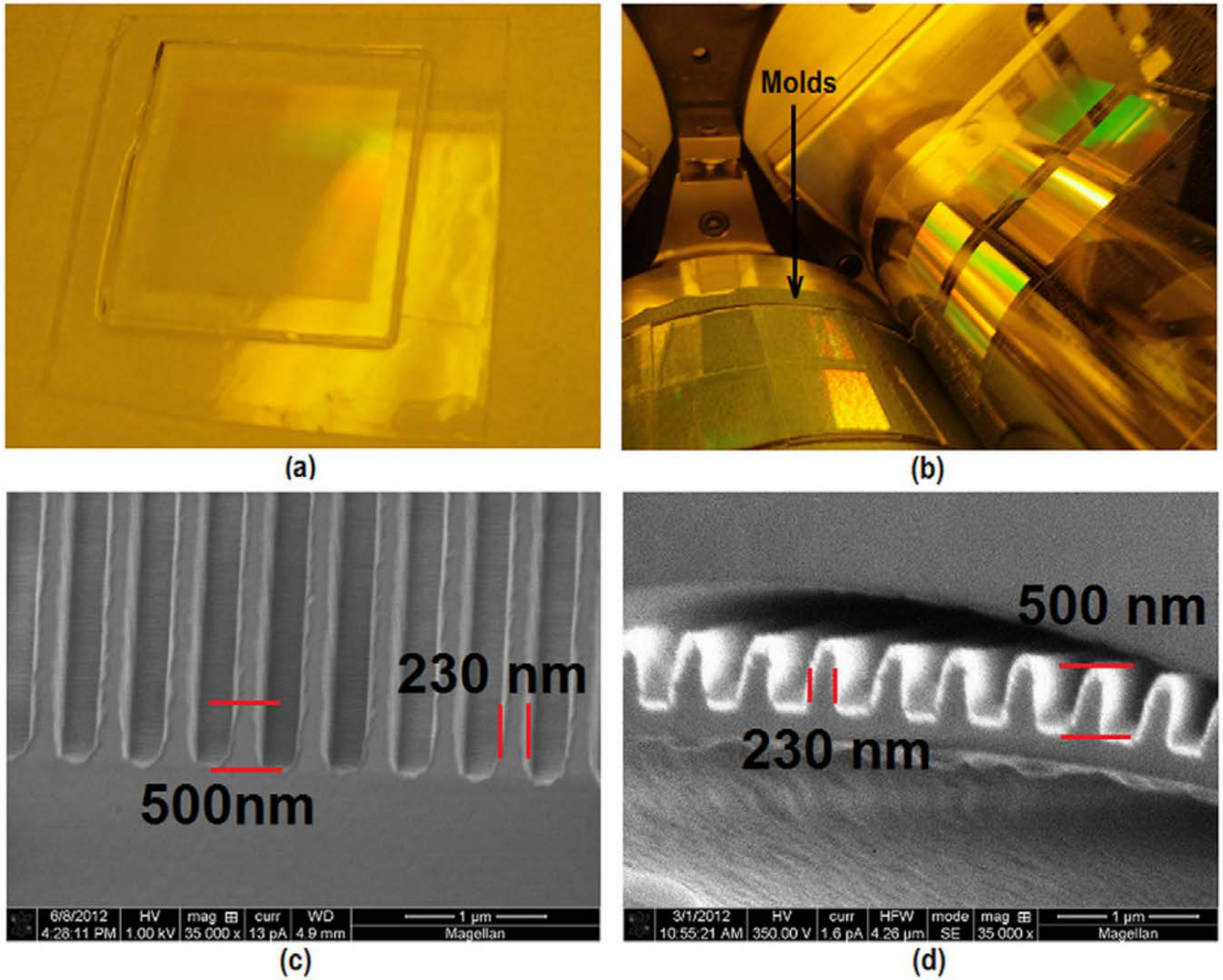
REFERENCE SLIDES

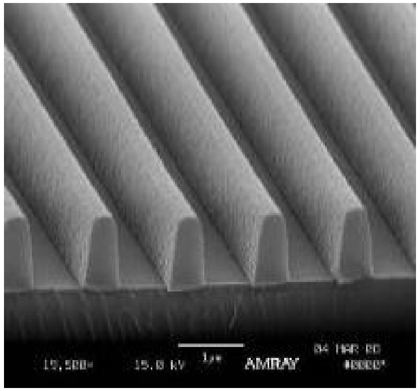
Roll-to-roll Imprinting of Photonic Crystals

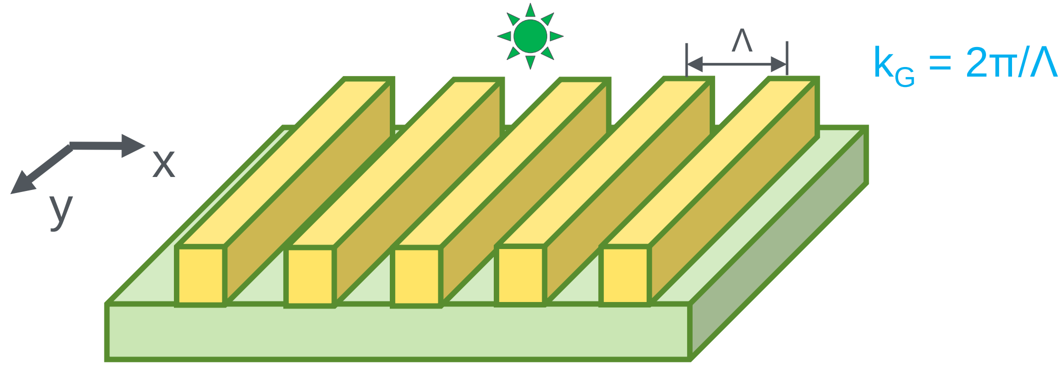


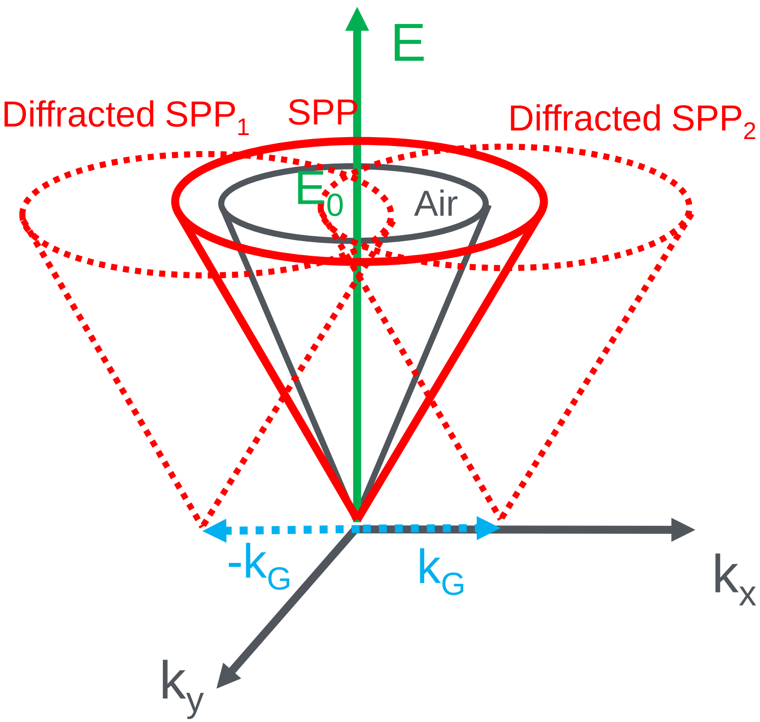
- A photonic crystal mold can be used for large scale roll-to-roll nano-imprinting with high quality

Nanotechnology 24 (2013) 505307 (9pp)

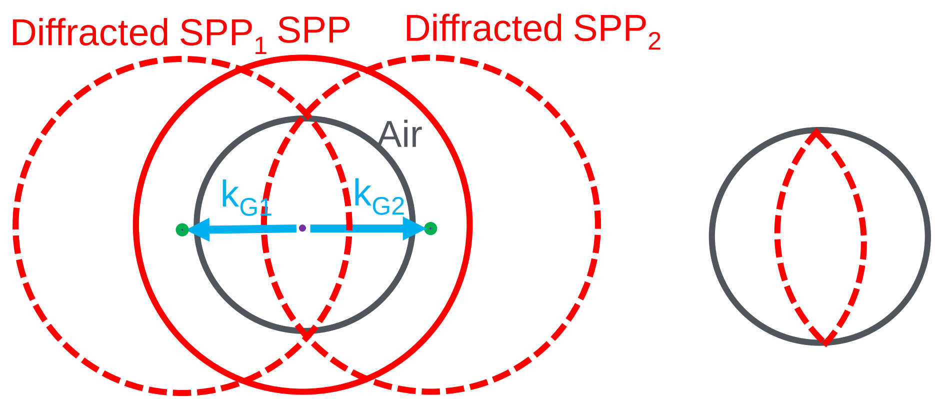
Mode Diffraction with 1D Gratings





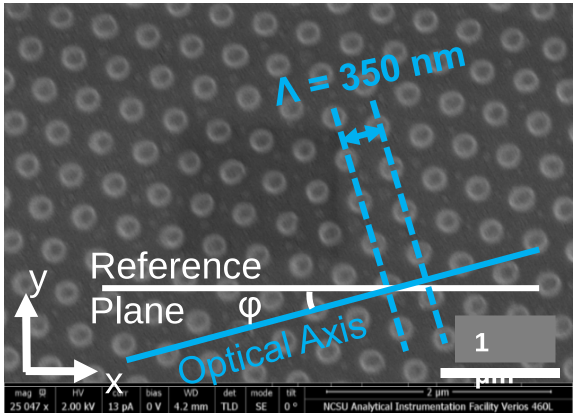


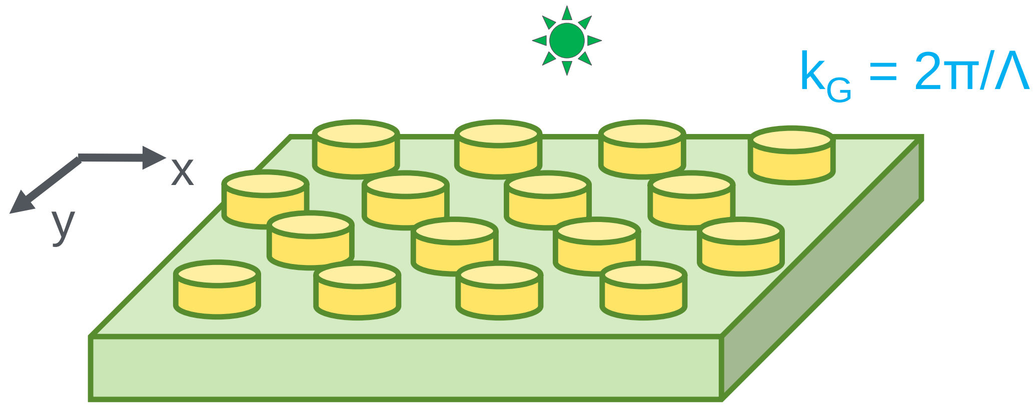
Far field emission ($E = E_0$)

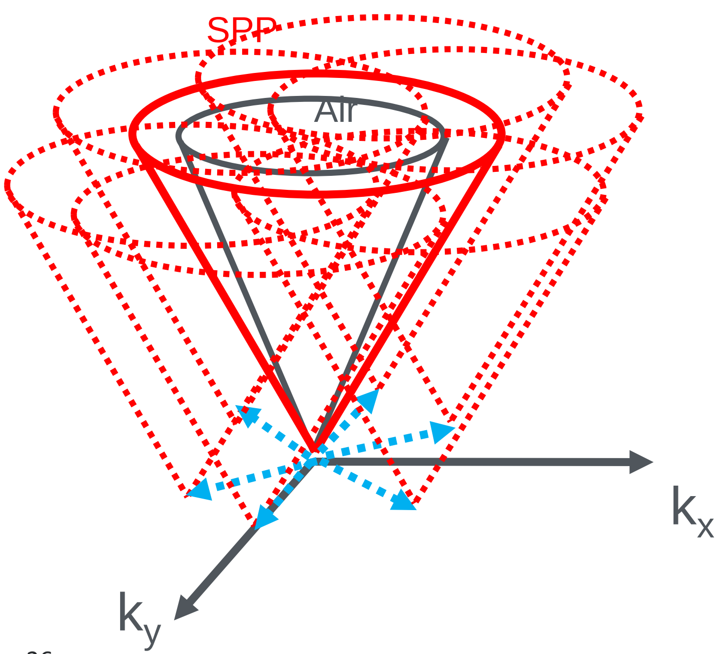


$$k' = k + m \cdot k_G$$

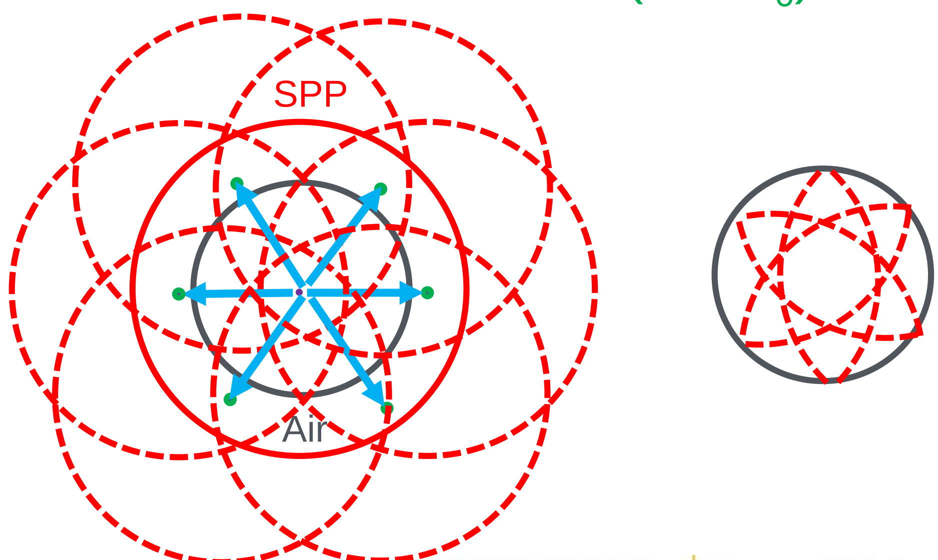
Mode Diffraction with Hexagonal Photonic Crystals





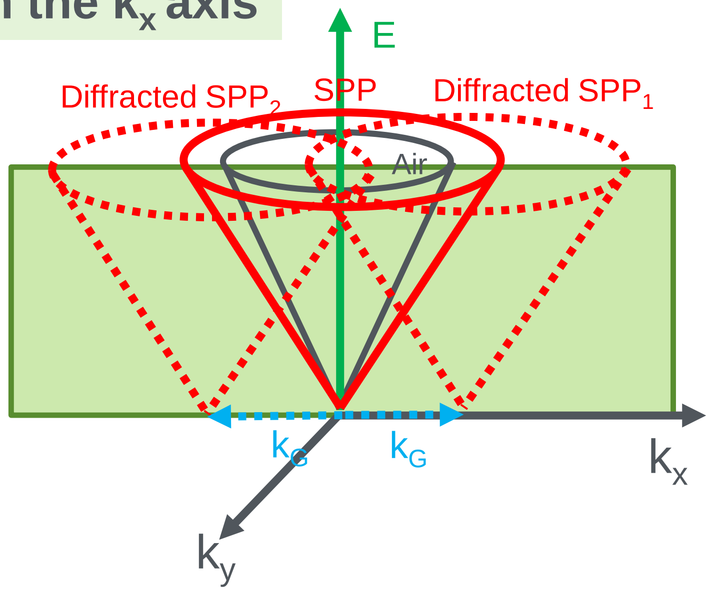


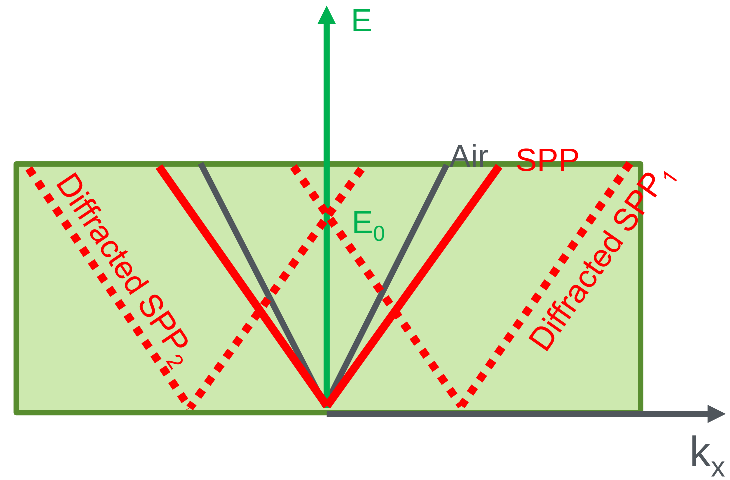
Far field emission ($E = E_0$)



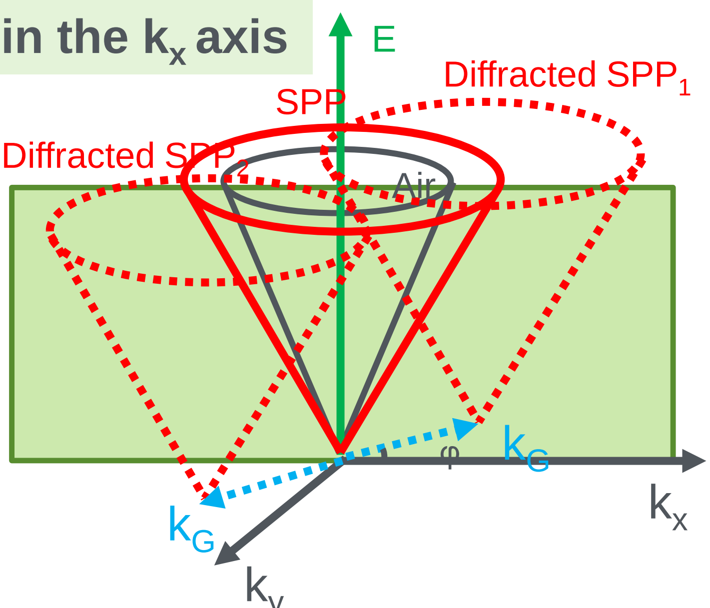
ARES Study – Mode Dispersion

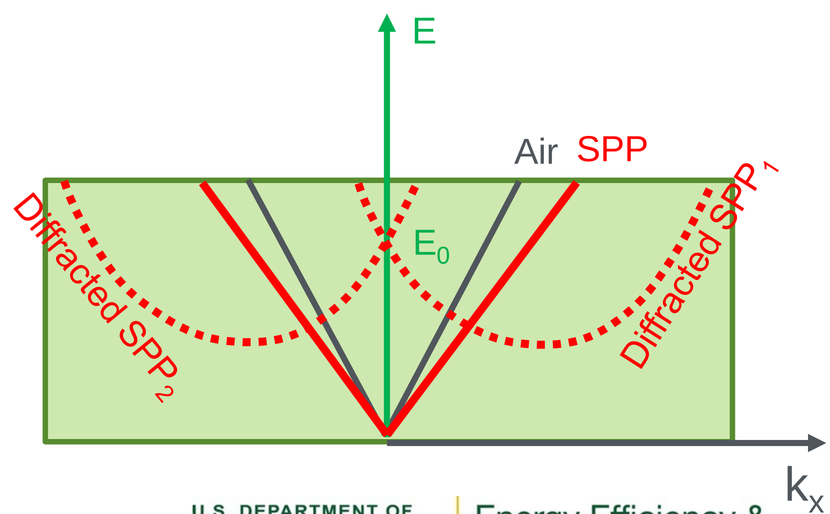
k_G in the k_x axis



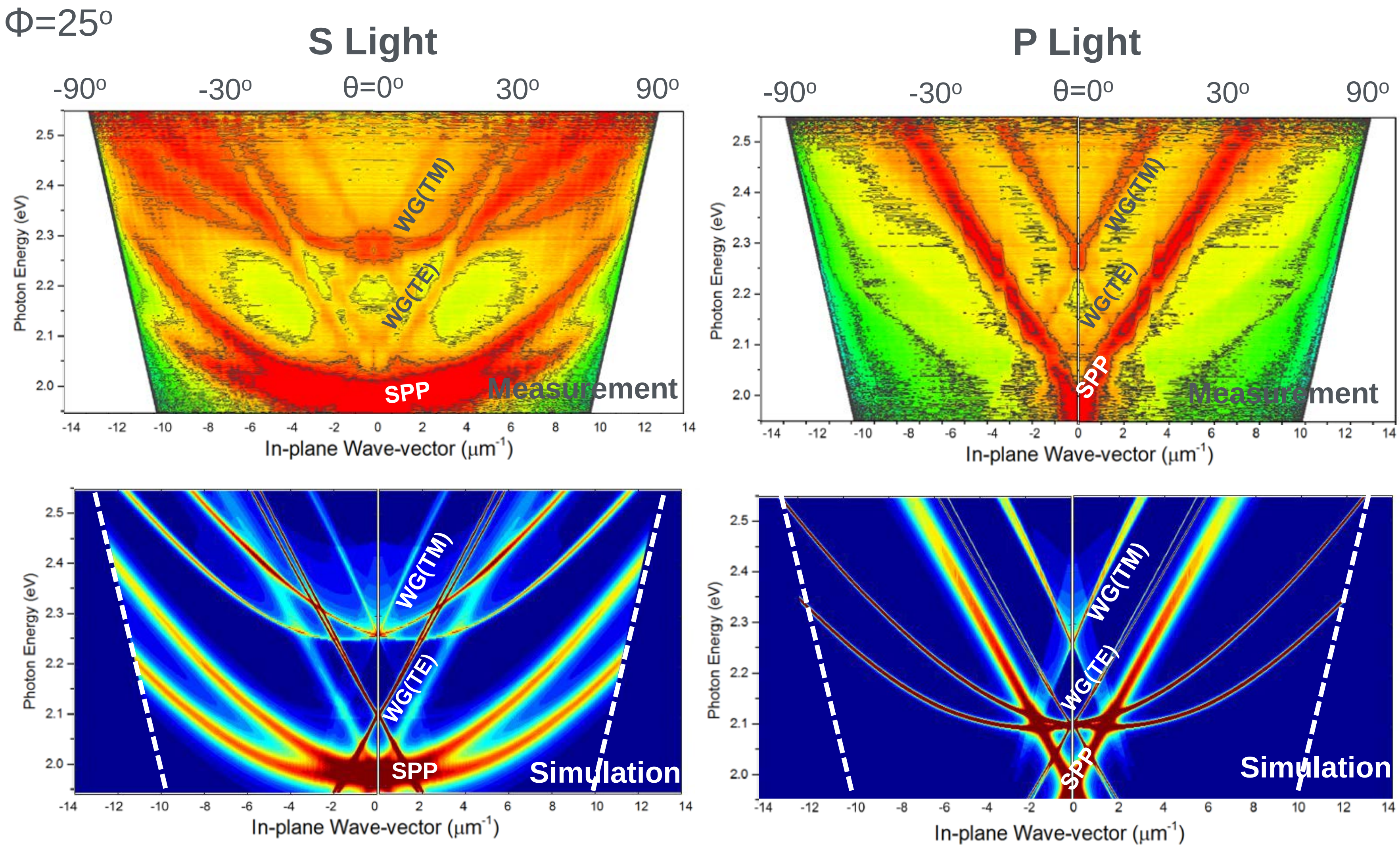


k_G not in the k_x axis





Explain Mode Dispersion with Simulation



Project Budget

Project Budget: Table below
Variances: N/A
Cost to Date: DOE share $407,042.85; Recipient share $126,912.69
Additional Funding: N/A

Budget History			
FY 2016 – FY 2018 (past)		FY 2018 (planned)	
DOE	Cost-share	DOE	Cost-share
$583,771	$157,000	$258,377	$133,064

Project Plan and Schedule

- The project started in Sep 2016 and has met every milestones to date. The optimized corrugated device shows 63% EQE, and corrugated device with low index layer shows 65% EQE. With a focused and well-informed research plan, we are heading towards 70% EQE with macro lens by the end of project (Sep 2018). The remaining research will maximize EQE with low index layer and replace macro lens with microlens arrays tailored for extracting substrate mode.

Project Schedule

Project Start: Sep 2016	Completed Work
Projected End: Sep 2018	Active Task (in progress work)
	◆ Milestone/Deliverable (Originally Planned)
	◆ Milestone/Deliverable (Actual)

	FY2016				FY2017				FY2018			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Fabrication of corrugated substrates 70 nm depth					◆							
Fabrication of corrugated substrates OLED device performance EQE > 60%					◆							
Use of low index material and its n < 1.2								◆				
Use of low index material and its optical transmittance > 90%								◆				
OLED on low index buffer layer and corrugation profile										◆		
Microlens profile and OLED with microlens array										◆		
Current/Future Work												
OLED on low index buffer layer and device performance												
Device performance of OLED with microlens array												
Device performance of OLED with microlens array + low index material												