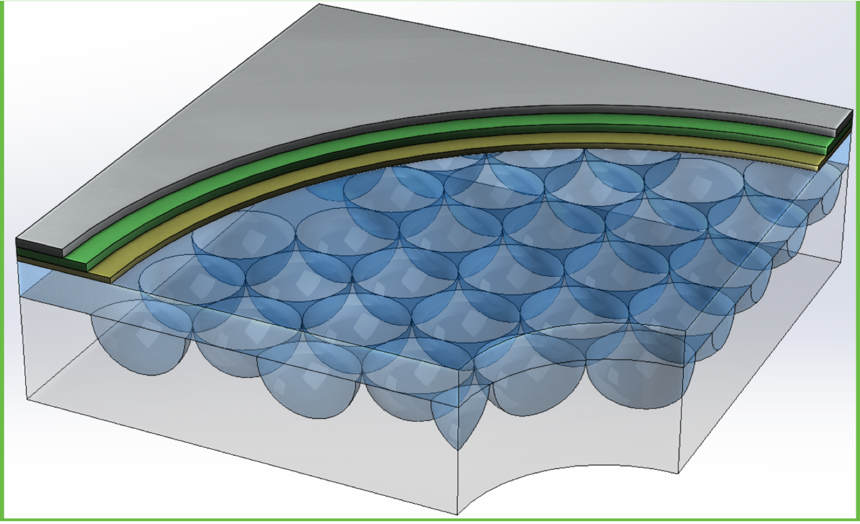
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Eliminating Plasmon Losses in High Efficiency White Organic Light Emitting Devices for Light Applications



University of Michigan

Stephen R. Forrest, Professor / Principal Investigator

Tel: (734) 647-1147; stevefor@umich.edu

Project Summary

Timeline:

Start date: 9/1/2016

Planned end date: 8/31/2018

Key Milestones

1. Down-select to two from three methods proposed: (eliminated grating-based methods: 8/31/2017
2. Demonstrate SEMLA structure with 70% outcoupling: 12/2017
3. Demonstrate very low cost outcoupling with >60% efficiency: 1/2018.

Budget:

Total Project $ to Date:

- DOE: $632,110
- Cost Share: $44,468

Total Project $:

- DOE: $900,001
- Cost Share: $195,722

Key Partners:

Universal Display Corp.

Project Outcomes:

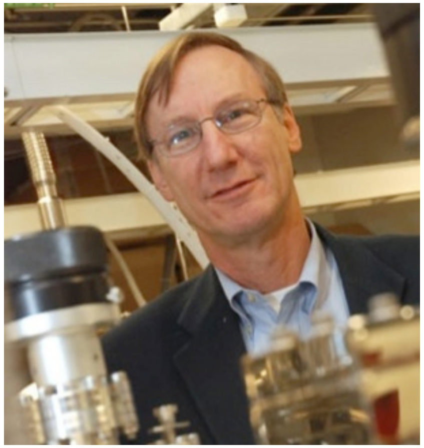
- Demonstrate at least 70% outcoupling efficiency with scalable technologies that have the following attributes:
  - Potentially low cost
  - Viewing angle and wavelength independent
  - Not invasive of the OLED structure
- Protect and disseminate result to the lighting community

Team

P.I.; **Stephen Forrest**

(Prof., EECS, Physics, MS&E)

- Project leader
- 35 years experience in organic electronics and photonics



Yue Qu

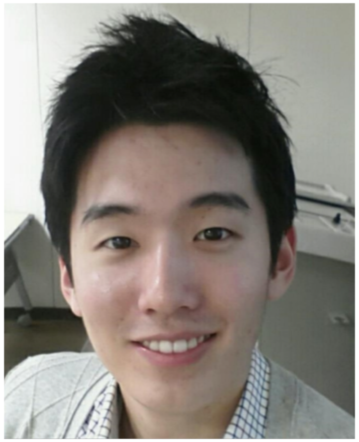
(PhD student, Physics)

- Sub anode grids/lenses
- Modeling

Jongchan Kim

(PhD student, EECS)

- Diffusers
- Modeling



Xiahen Huang

(PhD student, EECS)

- Diffusers, thin substrates
- Modeling

Challenge

Problem Definition:

The internal quantum efficiency of phosphorescent OLEDs (PHOLEDs) is 100%, making this an ideal source of high efficiency lighting. However, only 20% of the light leaves the substrate due to losses in:

- Substrate modes
- Waveguide modes
- Surface plasmon polaritons
- Metal losses

Approaches:

Acceptable solutions must have the following properties

- Low cost
- Viewing angle and wavelength independent
- Non-invasive of the OLED structure

We seek solutions that outcouple > 70% of the emitted light

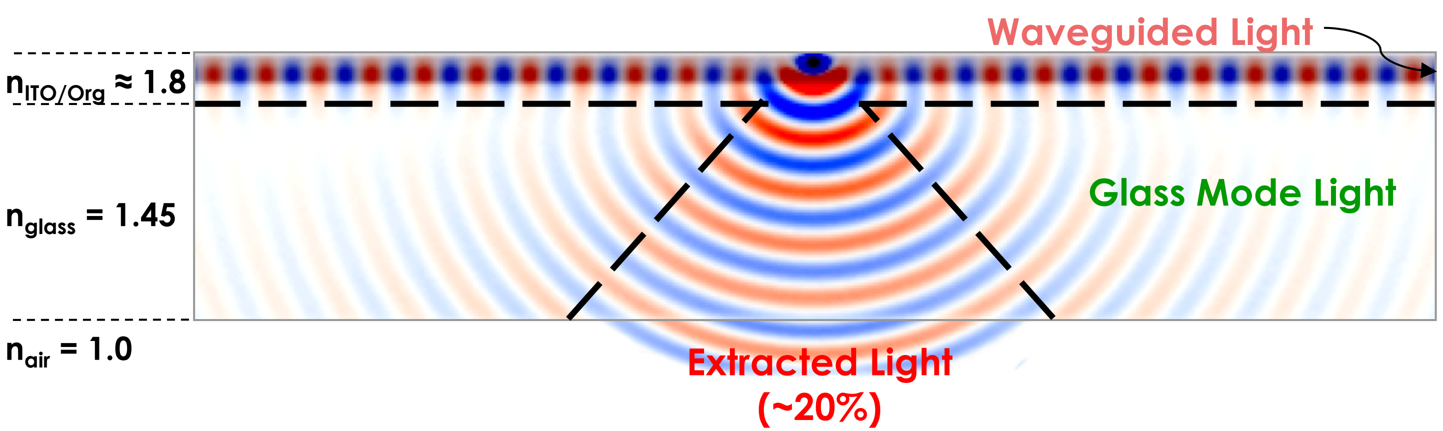
Gain a fundamental understanding of the limitations facing outcoupling

Demonstrate scalability of the methods investigated.

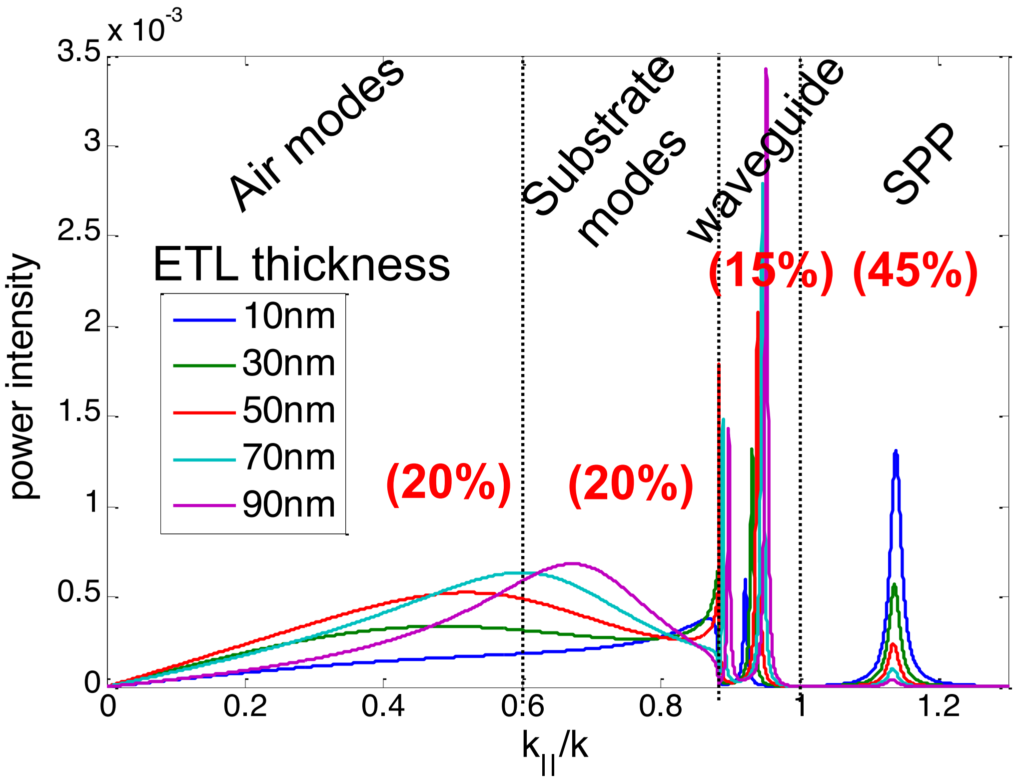
Approach

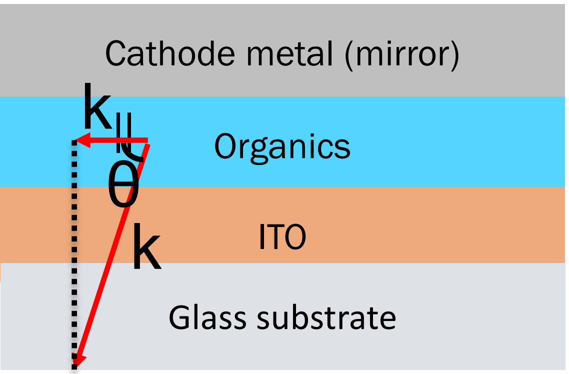
– Internal quantum efficiencies (η_{IQE}) have reached ~100%
– But extraction efficiency (η_{Ext}) is a major limit on the external efficiency (η_{EQE})
– $\eta_{EQE} = \eta_{IQE} \times \eta_{Ext} \approx 20\%$ due to TIR and other losses

- Refractive index differences at interfaces lead to trapped light due to total internal reflection at the glass-air interface ("glass modes")
  – In the high-index ITO and organic layers ("waveguided")
  – Trapped at the metal cathode interface ("Surface plasmonic")



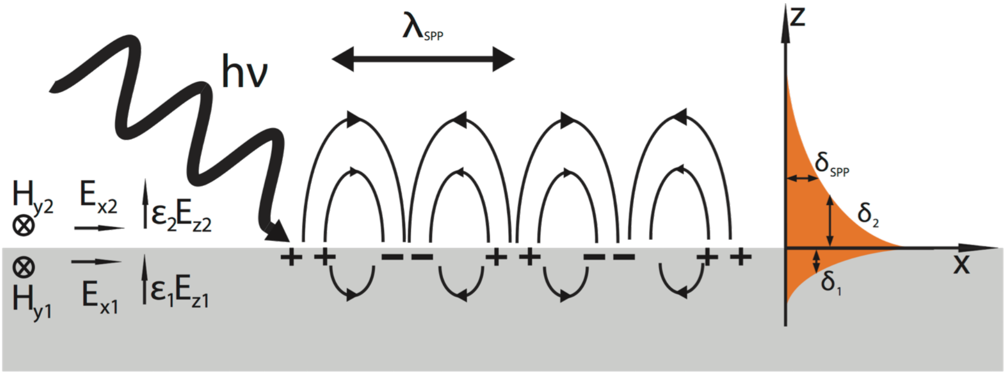
Where do all the photons go?



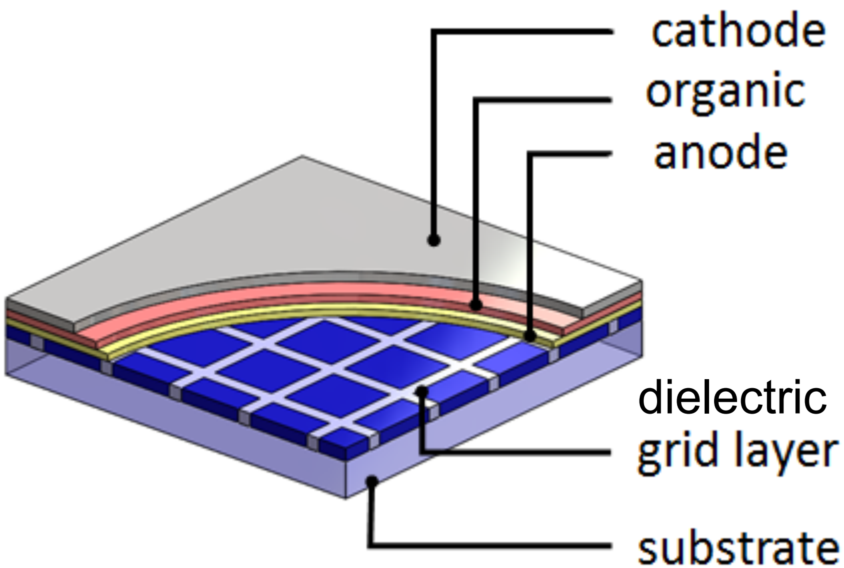


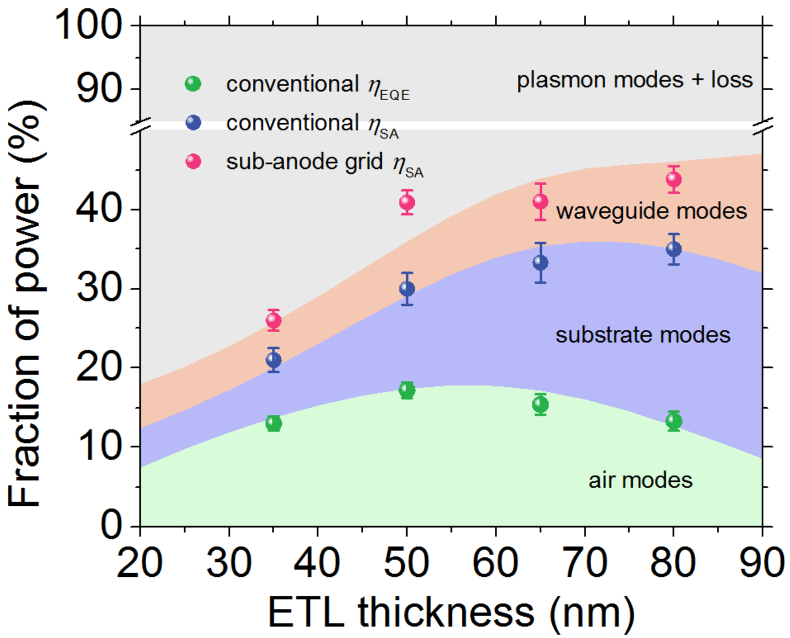
- **Air modes**: EQE first increases, then decreases with ETL thickness
- **Waveguide modes**: Only one waveguide mode TE_0 due to thin ETL (<30nm). TM_0 appears when >50nm.
- **Surface plasmon polariton modes:** Reduced with ETL thickness
- Both waveguide and SPP modes are quantized

Surface plasmons: Significant loss mode



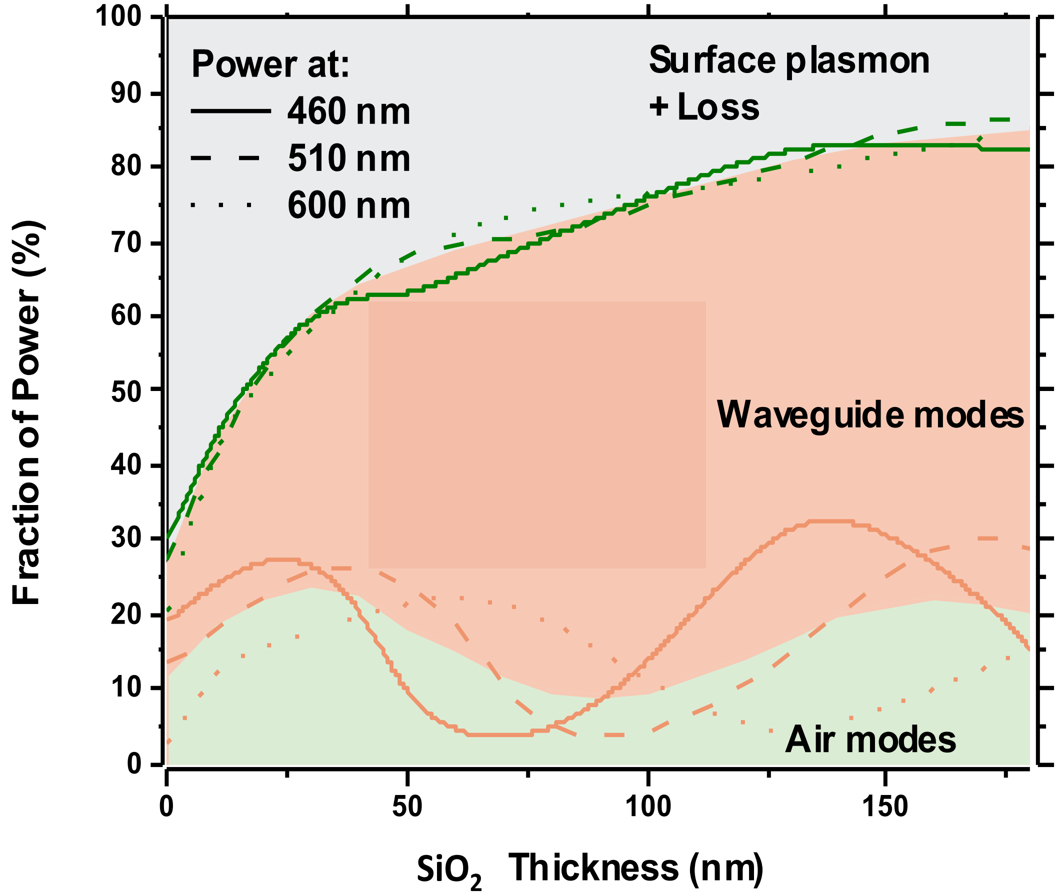
Early example of outcoupling waveguide modes:
Sub-anode grid





Y.Qu, S.R. Forrest, et al., *Nature Photonics, 2015*

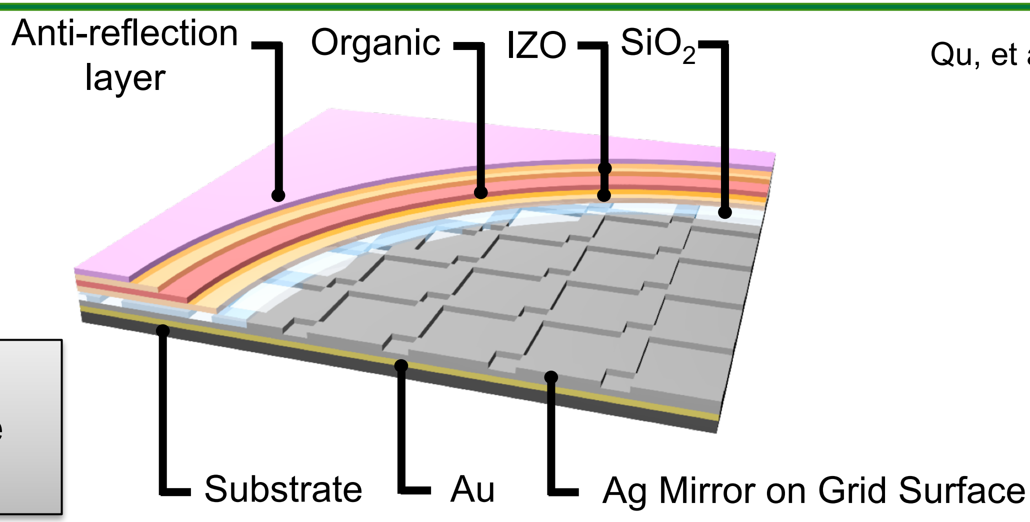
Optical modelling is the roadmap to solution



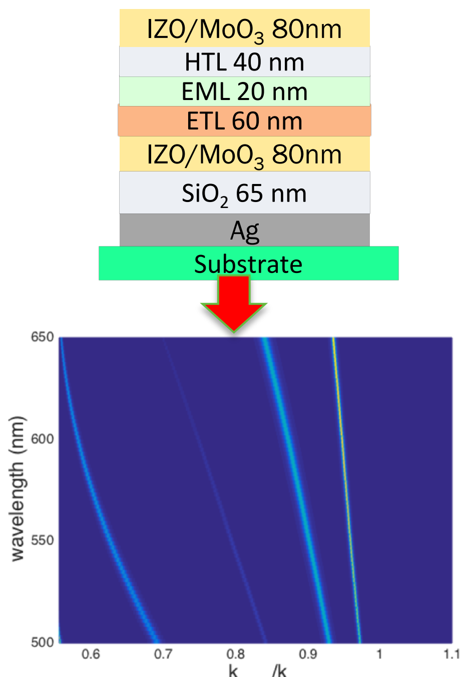
- Simple design that does not interfere with OLED structure
- Only substrate processing
- Extracts all wavelengths approximately equally
- 80-90% extraction within reach!

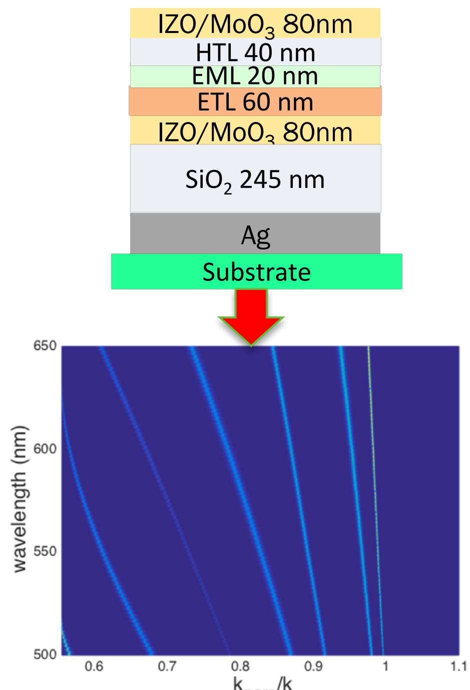
Solution #1: Sub anode grid + mirror

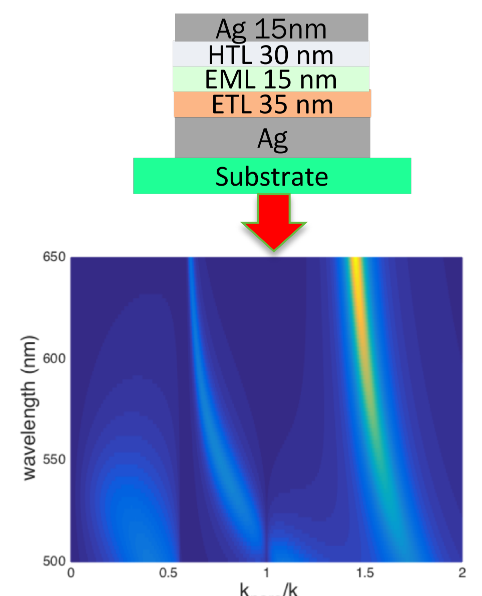
Qu, et al. ACS Photonics, 2017



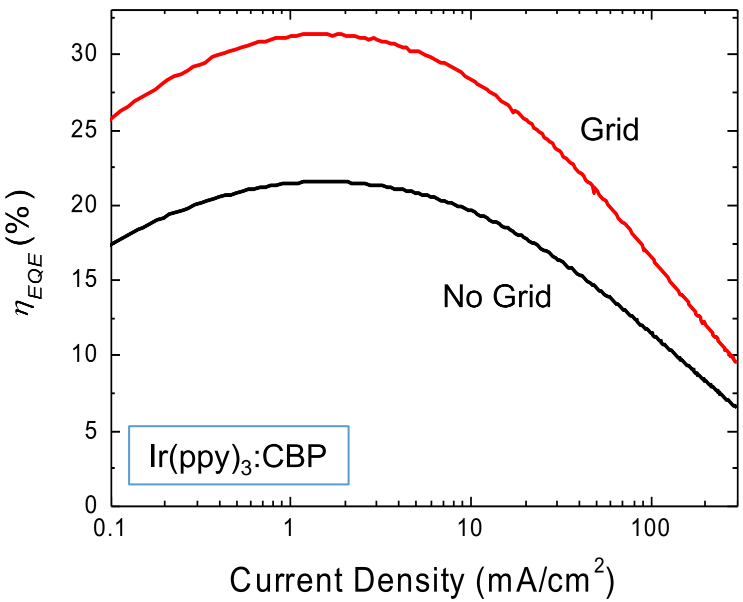
Variable Waveguide Widths Prevent Mode Propagation

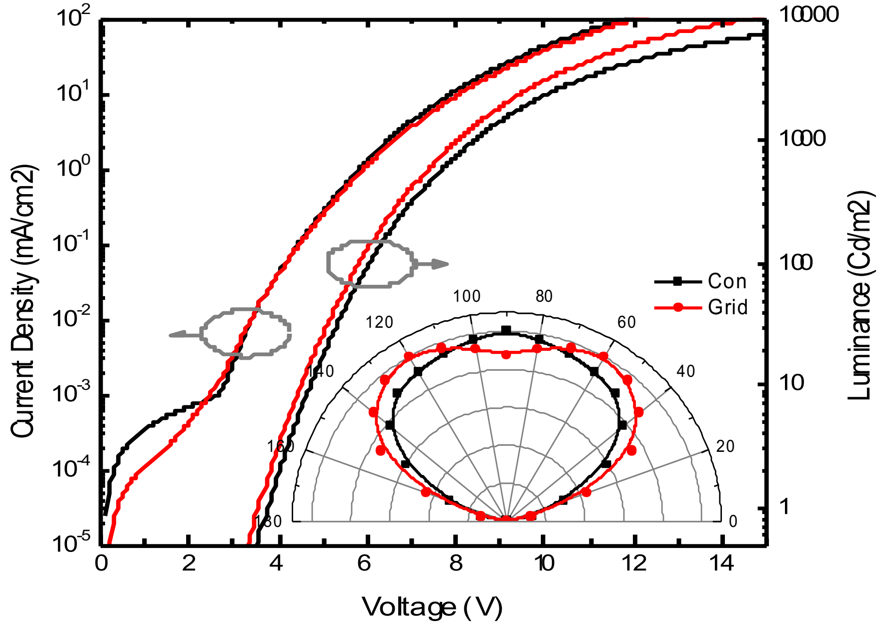


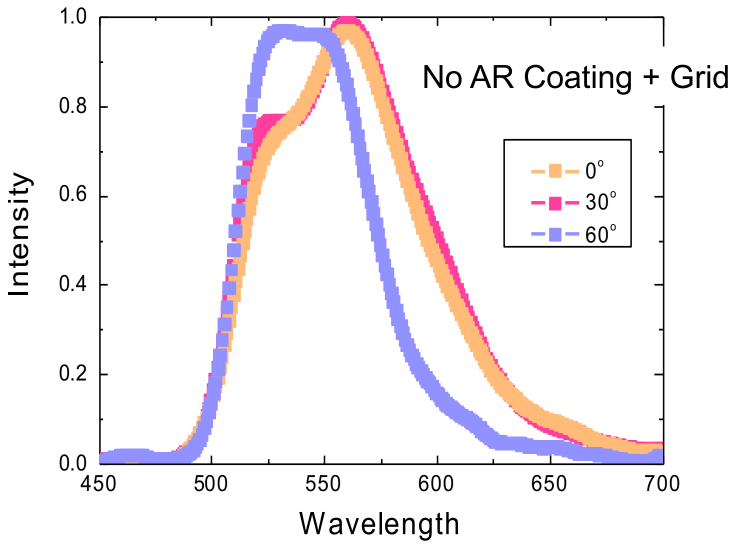


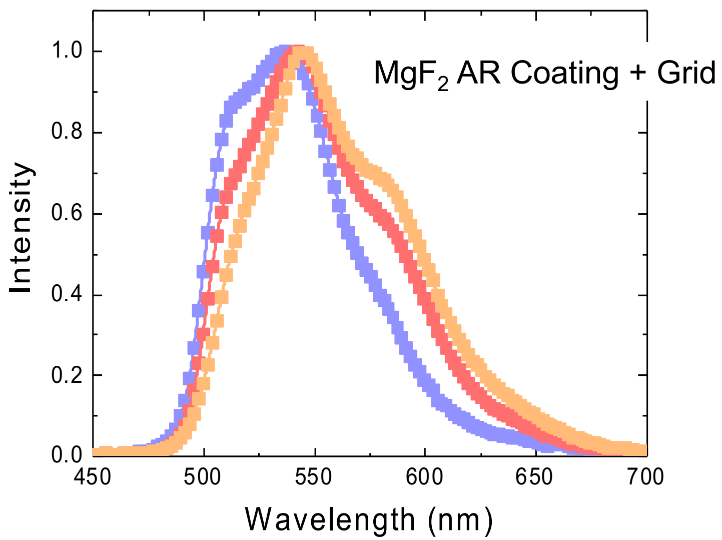


Performance with and w/o grid + mirror

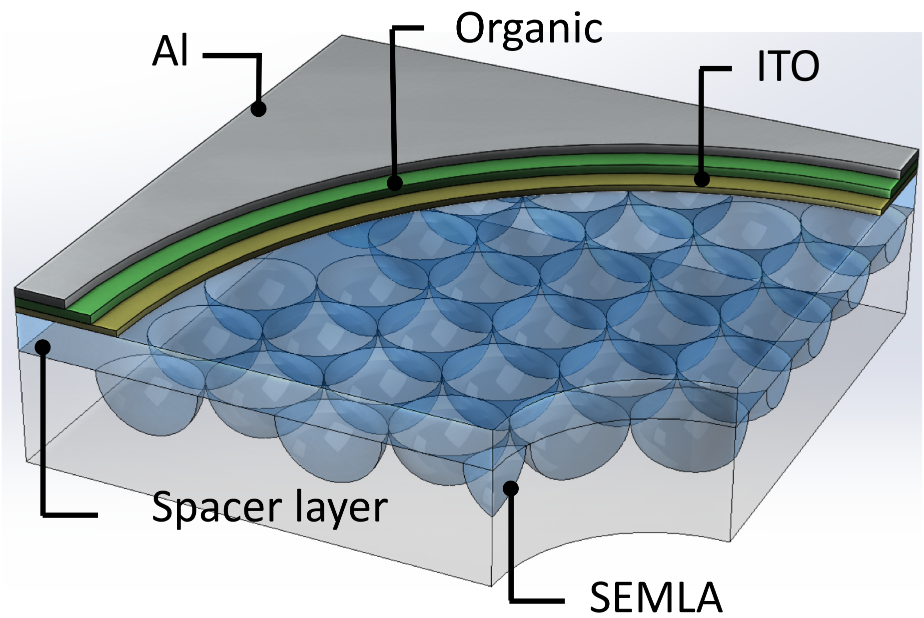








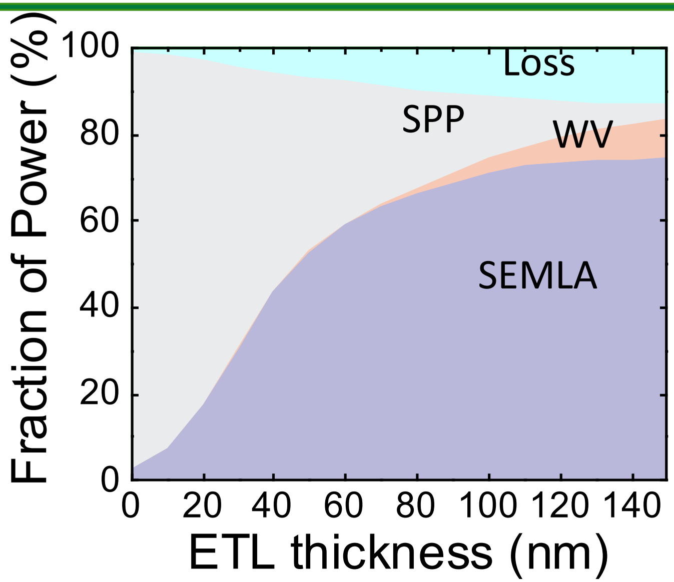
Solution #2: Subelectrode microlens arrays



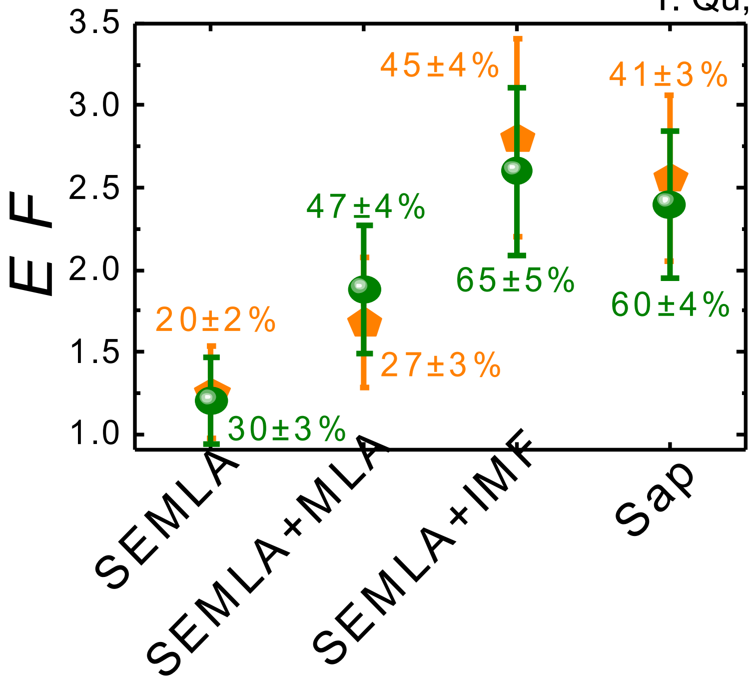
High index microlens arrays and spacer layer below OLED:

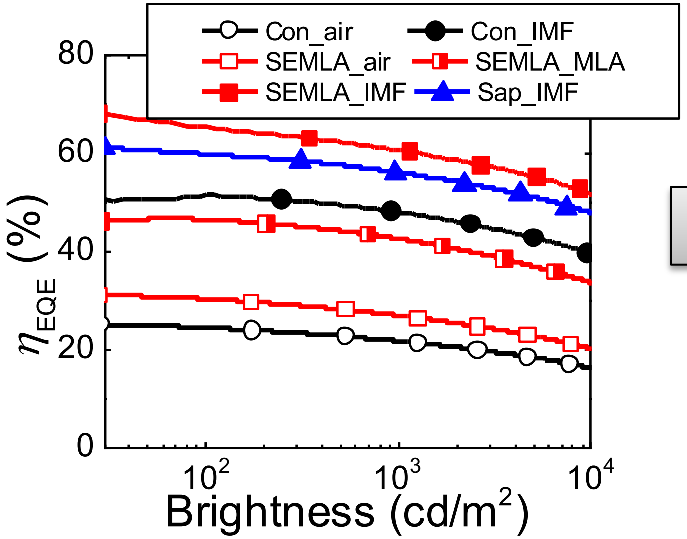
- All waveguide modes move into spacer and are refracted into substrate
- Non invasive of OLED
- No fine features: low cost
- No SPPs

Analysis of SEMLA and Results

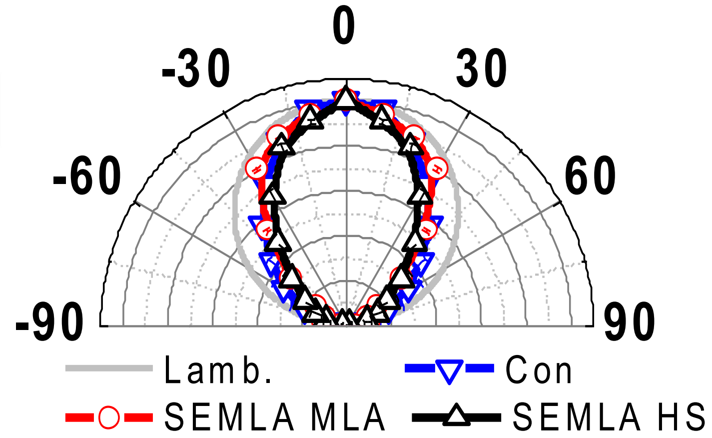


Y. Qu, in press (2018)



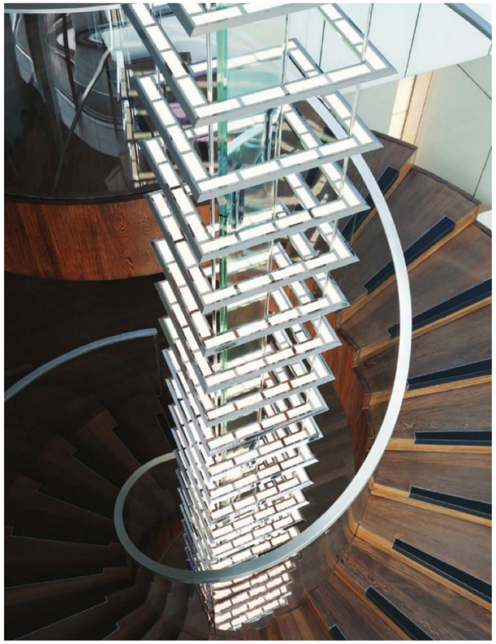


~70% EQE



Impact

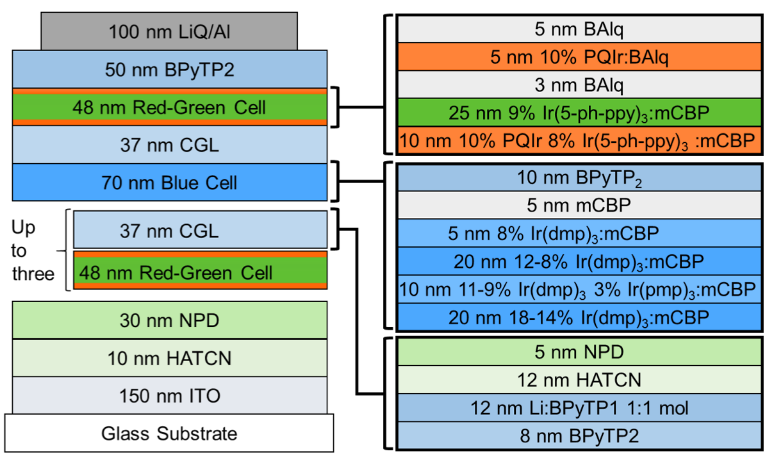
- **OLED lighting offers ultrahigh efficiency, architecturally pleasing light, but it remains too expensive at too low efficiency**
- **Harvesting 70% of the emitted light at low cost can make this an important addition to high efficiency lighting**
- **Our work if successful will help to develop and maintain a U.S. manufacturing opportunity with Universal Display Corp and Partners.**
  - UDC in discussions with a U.S. based OLED lighting panel manufacturer
  - UDC's phosphorescent emitter materials are made by PPG Industries (Pittsburg, PA) and Adesis (DL)
- **OLED lighting panels now made overseas are being imported back into the U.S. and incorporated into luminaires at several U.S. lighting companies.**
- **OLED lighting could potentially reduce the need for imported energy, reduce energy-related emissions including greenhouse gases, improve energy efficiency in buildings, and promote U.S. technical leadership for advanced energy technologies.**



Progress: 18 mo. of 24 mo. program

- **Demonstrated multiple outcoupling schemes that meet the following criteria**
  - Potentially low cost
  - Wavelength and viewing angle independent
  - Non-invasive of the OLED structure

- **Focus has been on SPP elimination**
- **At least one method (maybe more) outcouple >70% of emitted light**
- **Techniques are scalable**
  - Applying techniques to stable, very high efficiency all phosphorescent WOLEDs



- Max Luminance > 200,000 nits
- 50 lm/W max
- CCT = 2780K
- CRI=89

Coburn, et al. ACS Photonics (2018)

Stakeholder Engagement

- All results shared with Universal Display Corp.
  - Holds global rights to IP generated
  - Works closely with domestic and global manufacturers to bring PHOLED lighting to the market
  - Works closely with chemical companies and partners in US to provide materials and other technologies developed by our group to the market in the shortest time possible
- Support for associated R&D provided by UDC
- Attend DOE workshops and international meetings where results are shared with community
- Publish all relevant results in the refereed, open literature

Remaining Project Work

- **Combine outcoupling methods with highest efficiency, high reliability white PHOLEDs**
  - Use previously demonstrated 5-stack device with 80,000/14,000 hr (L_0 = 1000/3000 nit) lifetime
- **Demonstrate scalability on larger** (10 cm^2) **substrates**
- **Complete demonstration of new, ultra-low-cost high efficiency schemes not discussed here.**
- **Determine practical outcoupling limits from fundamental optics perspective**

Thank You

University of Michigan
Stephen R. Forrest, Professor / Principal Investigator
Tel: (734) 647-1147 email: stevefor@umich.edu

REFERENCE SLIDES

Project Budget

Project Budget: The original budget allocated $450k per year with 20% cost share on behalf of UM
Variances: The variances to date have been within normal tolerances. Some of the cost shared equipment has been ordered but not invoiced yet.
Cost to Date: To date, approximately 70% of the budget has been expended
Additional Funding: UDC is funding synergistic aspects of this project

Budget History					
9/1/2016– FY 2017 (past)		FY 2018 (current)		FY 2019 – 8/31/2018 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
321,897	80,474	310,213	44,467	267,891	70,781

Project Plan and Schedule

Milestone	Description	Verification Process	Date
Budget Period 1			
Milestone number	Description and Metrics	Test Methods	Month of completion
1.1.1	Develop theory of outcoupling of SPPs, compare results with existing OLEDs with accuracy to 10%	Measure outcoupling and compare with theory	3
1.2.1	Demo fabrication of texture by OVPD and stamping with pillar dimensions ~10 nmX100 nm with 40% filling	Microscopic analysis	6
1.3.1	Demo decrease in SPPs by >20%, within 10% from prediction, <10% change in opt/elec OLED perf.	Measure outcoupling and compare with theory	9
2.1.1	Meas. 80% grating diffraction eff. across the visible	Optical characterization	8
2.2.1	SPP & waveguide mode decr. by 50% in outcoupling eff. With diffuser, show DCIE<3% from conven. OLED	Optical characterization	10
3.1.1	Sub-anode grid surface features <5 nm from planar.	Microscopic analysis	8
3.2.1	Show no delamination of grid from metal mirror with reflectivity of 95%.	Optical and microscopic characterization	10
3.3.1	SPP & waveguide mode decr. by 50% in outcoupling eff. & <10% opt/elec perf. change from conven. OLED. Demo top emitting OLED at 5000 nits for >100 hrs	Optical and electrical characterization	12
3.3.2 G/NG	Show at least one Approach with decrease in SPP coupling by 50%.	Optical characterization	12
Budget Period 2			
4.1.1	Select at 1 - 2 approaches for optimization	Analysis, data review	13
4.2.1	Fabricate WOLEDs with EQE>30%, CRI=90	Optical characterization	15
4.3.1	Optimize outcoupling for PHOLED yields >90% over 50 cm^2 areas, <10% performance variation	Optical and electrical characterization	18
4.4.1	Demo WOLEDs with outcoupling >70%, EQE=110%, CRI=90 with <10% spectral shifts with angle and conv. WOLED. Compare to <10% with analysis.	Optical and electrical characterization	21
4.5.1	Demo WOLEDs on 25cm^2 packaged outcoupling substrates with outcoupling eff. >70%. Validate at UDC	Optical and electrical characterization	24

Publications

- Elimination of plasmon losses and enhanced light extraction of top emitting organic light emitting devices using a reflective sub-electrode grid," Yue Qu, Caleb Coburn, Dejiu Fan and Stephen R. Forrest, *ACS Photonics,* **4**, (2), pp. 363-8, 2017. DOI: 10.1021/acsphotonics.6b00847

- "Elimination of plasmon losses and enhanced light extraction of electrophosphorescent, top emitting organic light emitting devices using a metallic sub-electrode grid," Yue Qu, Caleb Coburn, Dejiu Fan and Stephen R. Forrest, *MRS Spring Mtg,* Poster ED8.7.15 (Apr. 17, 2017)

- "Efficient, Non-Intrusive Outcoupling in Organic Light Emitting Devices Using Embedded Microlens Arrays," Yue Qu, Jongchan Kim, Caleb Coburn and Stephen R. Forrest, *ACS Photonics*, in press (2018).

New Disclosures and Patent Filings

- "Top emitting organic light emitting devices using a reflective sub-electrode grid," Stephen R. Forrest and Yue Qu
  - Disclosed 1/27/17 (UM7369)
  - US PTO Application 15/724,055 filed 10/3/17
- "Method of spacing emission layer and metal cathode," Stephen R. Forrest and Yue Qu
  - Disclosed 10/16/17 (UM7746)
- "Ultra-thin flexible substrate for organic light emitting devices with enhanced light extraction efficiency,"
  - Disclosed 1/9/18 (UM 2018-0248)
- "Top emitting organic light emitting devices using a low refractive index dielectric and high refractive index microlens array," Stephen R. Forrest and Yue Qu
  - Disclosed 1/30/17 (UM7371)
- "Organic light emitting devices with no plasmonic losses," Stephen R. Forrest and Jongchan Kim
  - Disclosed 2/10/17 (UM7396)
- "Sub-electrode microlens arrays enhance light extraction efficiency for organic light emitting devices," Stephen R. Forrest and Yue Qu
  - Disclosed 5/10/17 (UM7536)