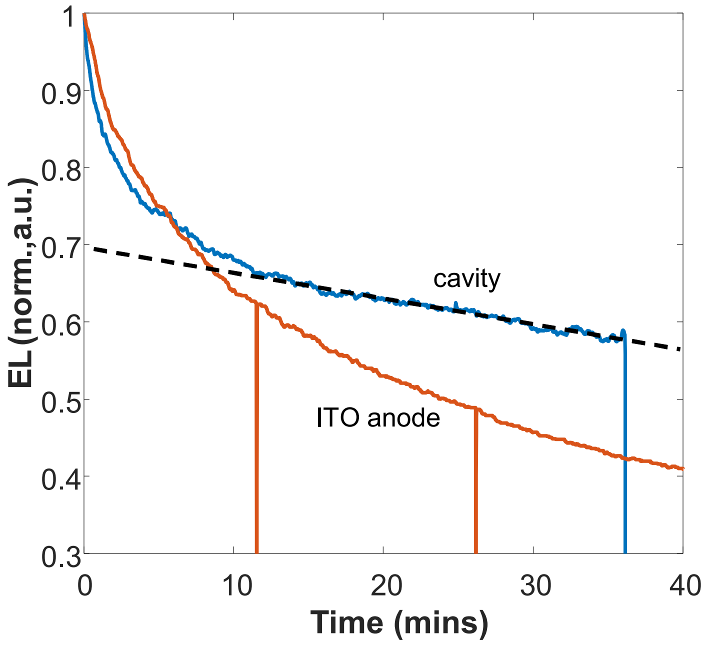
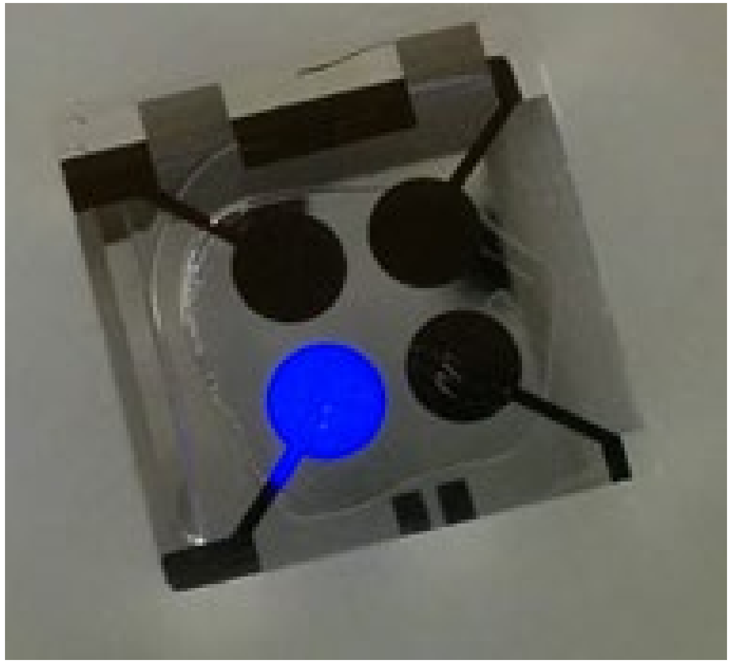
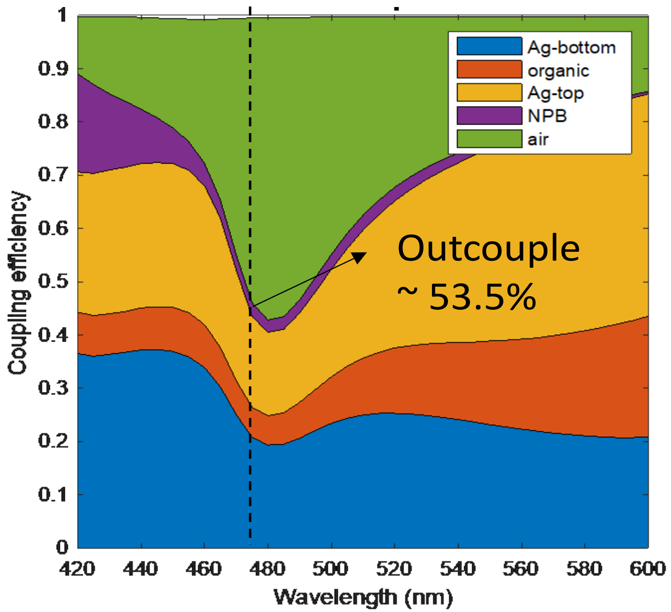
MULTIFUNCTIONAL OPTICAL OUTCOUPLERS FOR EFFICIENT AND STABLE WHITE OLEDS







Massachusetts Institute of Technology
Profs. Marc Baldo, Troy Van Voorhis
baldo@mit.edu, tvan@mit.edu

New program, start April 1, 2020

Project Summary

Timeline:

Start date: April 1, 2020

Planned end date: March 31, 2022

Key Milestones

1. White organic light emitting diode (OLED) incorporating a blue phosphor that achieves > 25× stability (equivalent to LT_{70} = 50,000 hours at 10,000 lm/m^2); March 31, 2022
2. Blue OLED with improved stability vs control & external quantum efficiency > 10%; March 31, 2021

Budget:

Total Project $ to Date:

- DOE: $567,476.01
- Cost Share: $185,939

Total Project $:

- DOE: $1,500,000
- Cost Share: $375,000

Key Partners:

Marc Baldo, MIT
Troy Van Vooris, MIT

Project Outcome:

Blue light emission is the key weakness for solid-state lighting technologies based on organic materials. To realize the cost and energy savings promised by organic SSL, we will stabilize blue OLEDs by speeding up their emission of light, thereby reducing the energy stored with the devices under operation. The goal is a 25x improvement in blue OLED stability.

Team

Marc Baldo
Device engineering

- Expertise in manipulating excited states within organic materials for superior device performance.
- Co-inventor of phosphorescent OLEDs, now commercialized for green & red in displays

Troy Van Voorhis
Physical chemistry

- Expertise in OLED fundamentals, theory, and simulation.

Challenge

- US Department of Energy's efficiency target is 150 lm/W by 2025.

- The corresponding resulting energy savings are estimated to be 276 TBtu per annum, a substantial fraction of total US energy consumption for lighting.

- **No way to hit this target with OLEDs without stabilizing *high efficiency* blue emitters, which presently exhibit < 1000hrs***

LEDs based on light emission from organic materials are uniquely suited for large area, diffuse light sources, even on flexible and curved substrates.

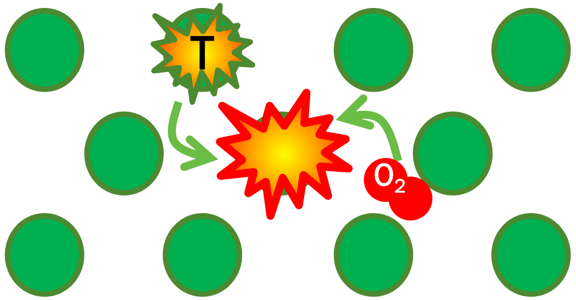
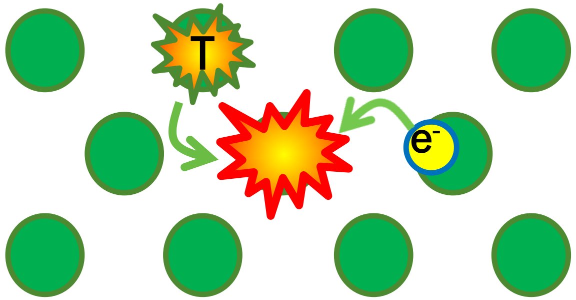
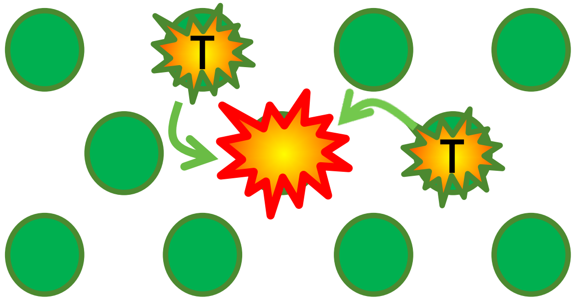
* LT95 = 700 hrs at 1000 cd/m^2 based on archived data from Universal Display Corporation: https://www.oled-info.com/oled-lifetime

Approach

OLED stability usually thought of as a materials problem.

But are there also universal phenomena influencing stability that are common to all materials?

G: pump rate (*e.g.* current density), τ : exciton lifetime

	Triplet-Impurity Interaction	Triplet-Charge Interaction	Triplet-Triplet Interaction
Defect generation mechanism			
Defect generation rate	$\propto G\tau$	$\propto G^{1.5}\tau$	$\propto G^2\tau^2$

Ha, Tiepelt, *et al*. Adv Opt Materials 2019, **7**, 1901048

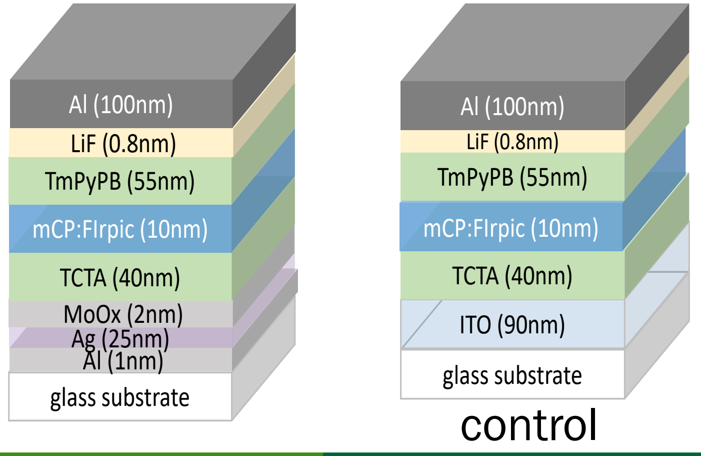
Approach

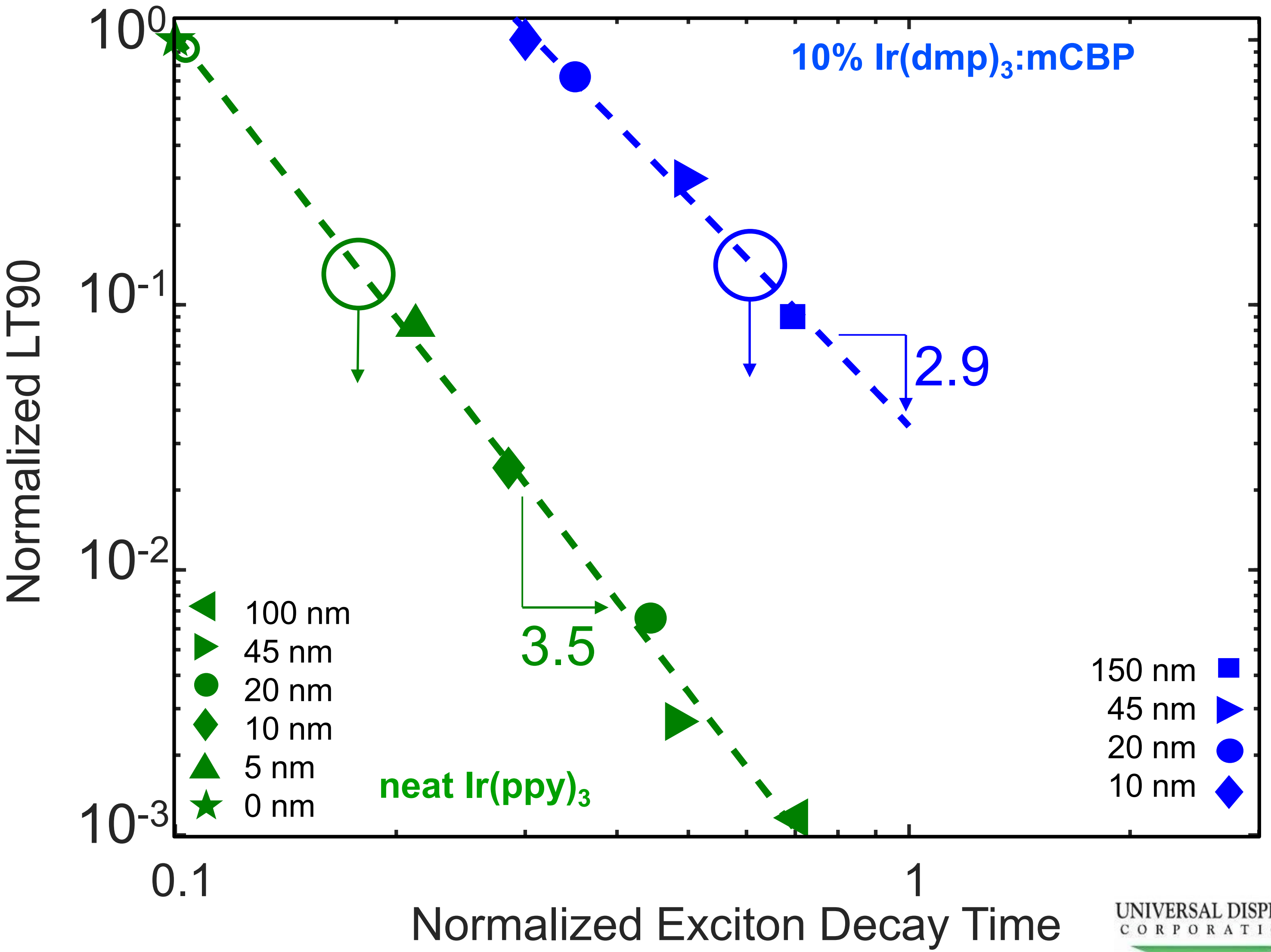
A new concept for OLEDs:

- Reduce the energy stored within an OLED to reduce degradation rate.
- *Get the light out faster*

Preliminary work with UDC showed strong effect for *optically* excited materials: More than 1000X modulation in stability.

To implement in devices, we build optical cavities with silver mirrors at the anode.

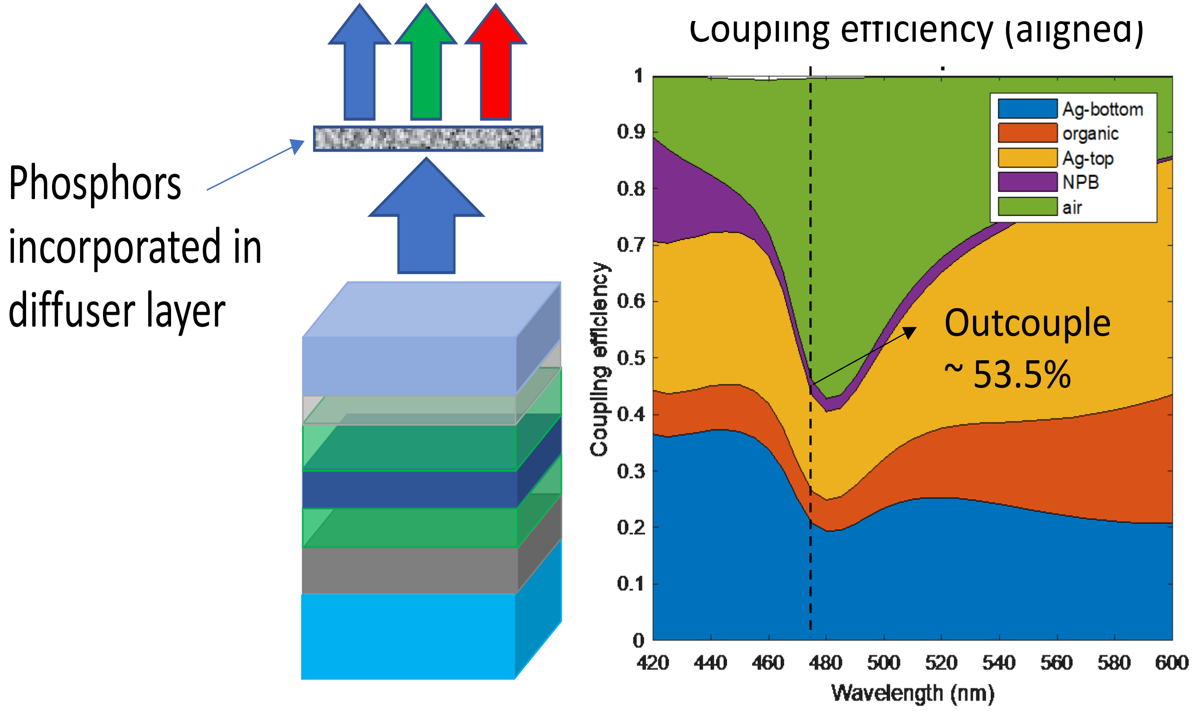




Ha, Tiepelt, *et al*. Advanced Optical Materials 2020

Impact

- Current blue OLEDs present a tradeoff:
  - High efficiency materials are very unstable (>30% photons/electron, LT95<1000hrs at 1000cd/m^2)
  - Lower efficiency materials cannot reach DOE efficiency targets but are more stable (~10% photons/electron, exact lifetimes are proprietrary, but appropriate for use in displays). *So, et al. Nature Comms, 10, 2305 (2019)*
- Stabilizing a high efficiency blue would allow us to hit DOE's 2025 goal of 80% internal quantum efficiency 3 years earlier.
- Better blue enables simpler device design that doesn't need incorporation of red and green OLEDs in a stack.



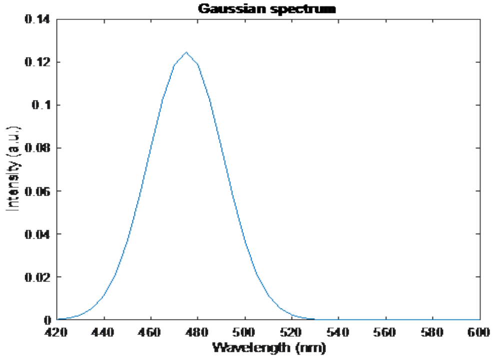
Aim: build blue OLEDs good enough to be used with down converters for green & red

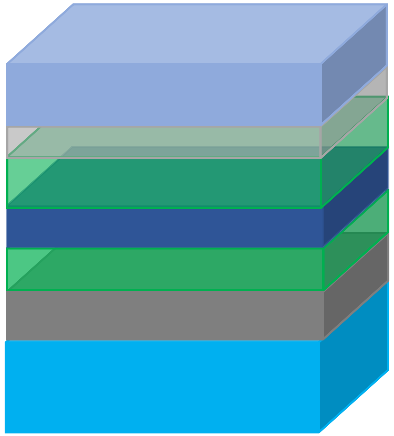
Progress: Design

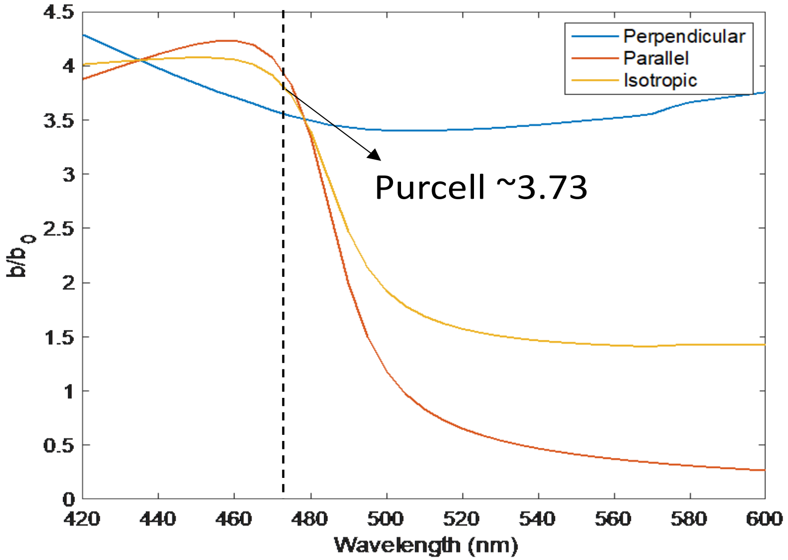
At 15 months (of 36 months)

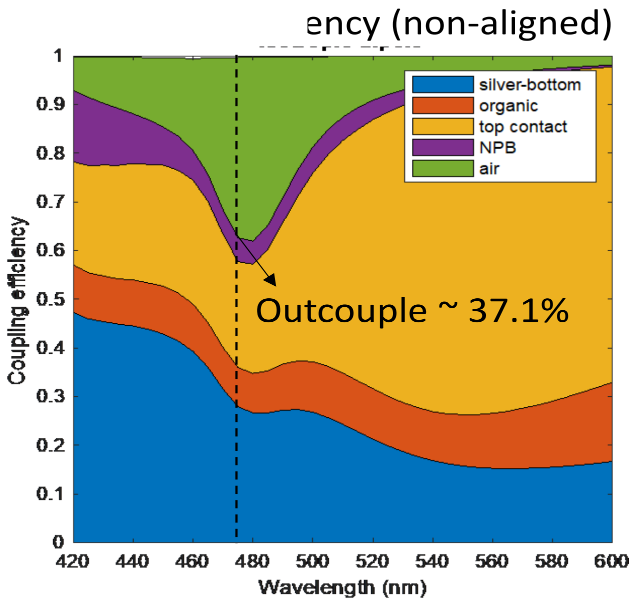
Initial design work for blue

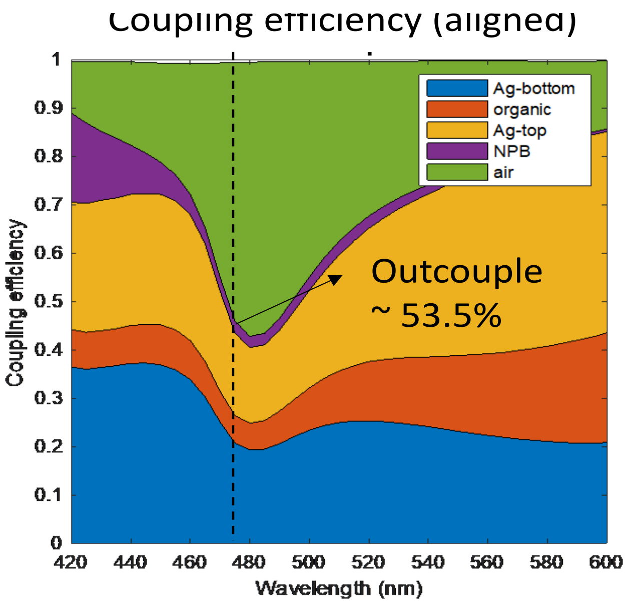
- Designed top emitting & bottom emitting devices.
- Purcell factor measures speed up.
- Top emitting device has highest projected efficiency but slightly lower speed up.





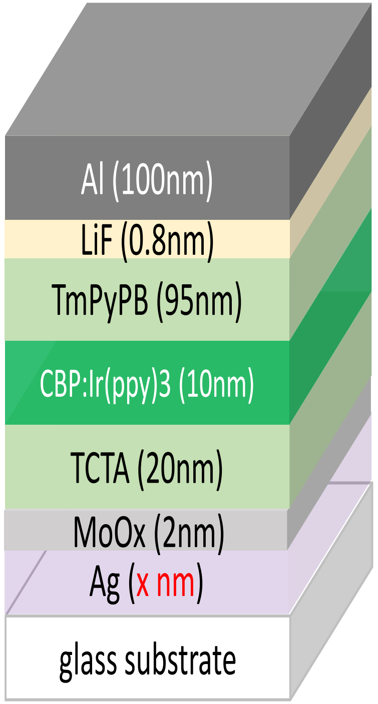


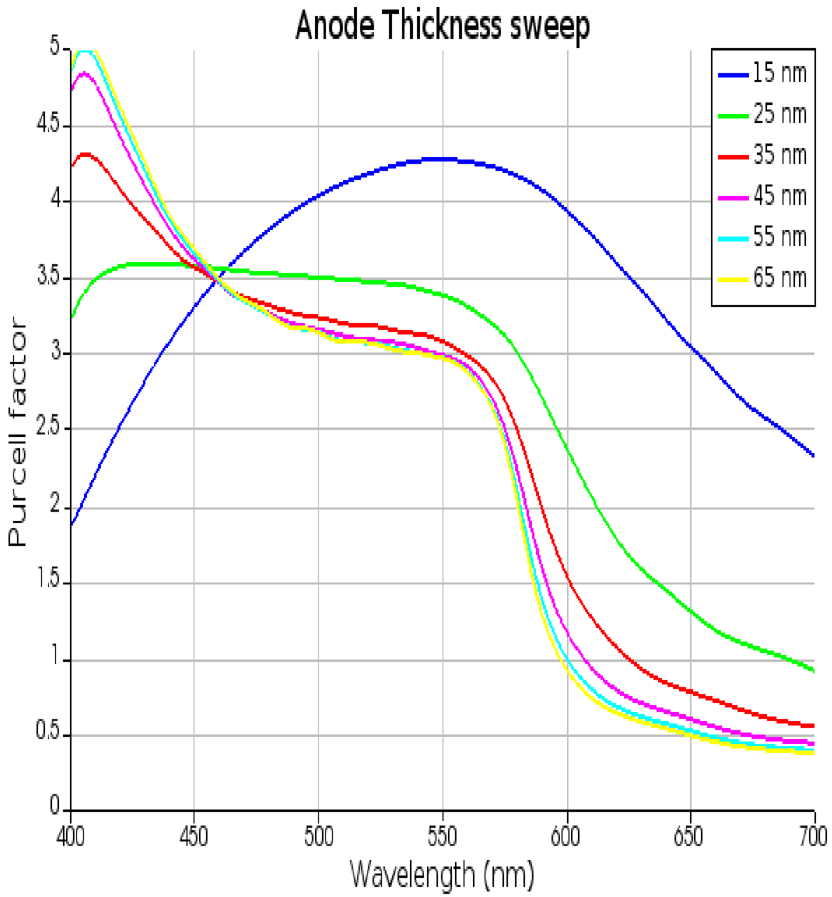


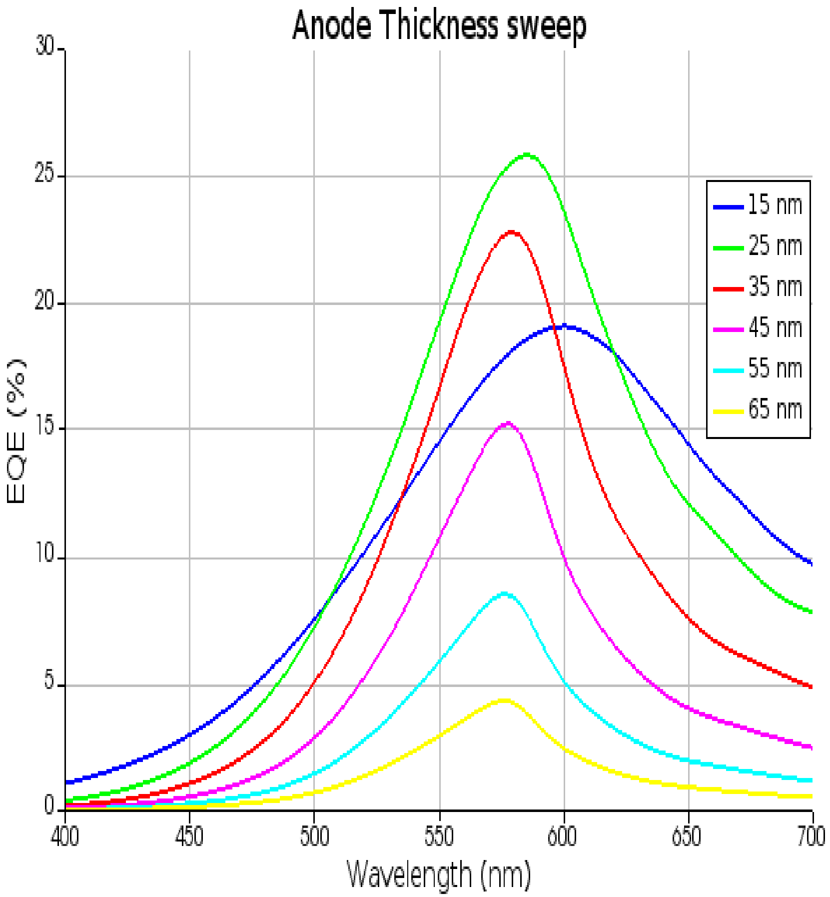


Progress: Design

Speed vs efficiency tradeoff:
Vary thickness of Ag anode.
thicker = faster but less ‘transparent’





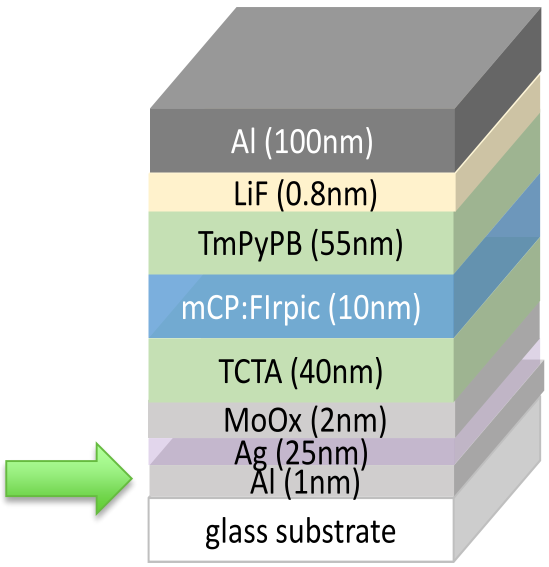


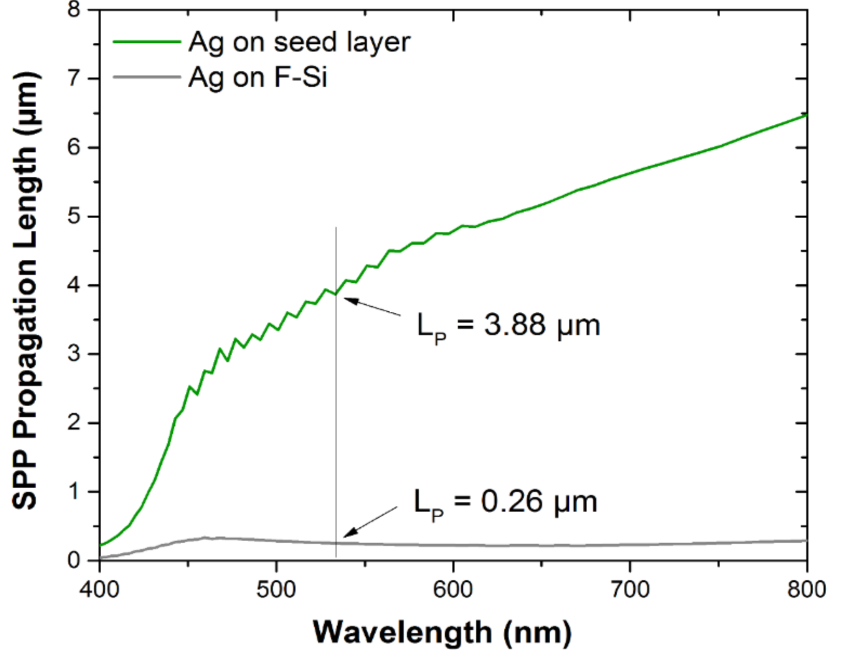
Progress: Materials

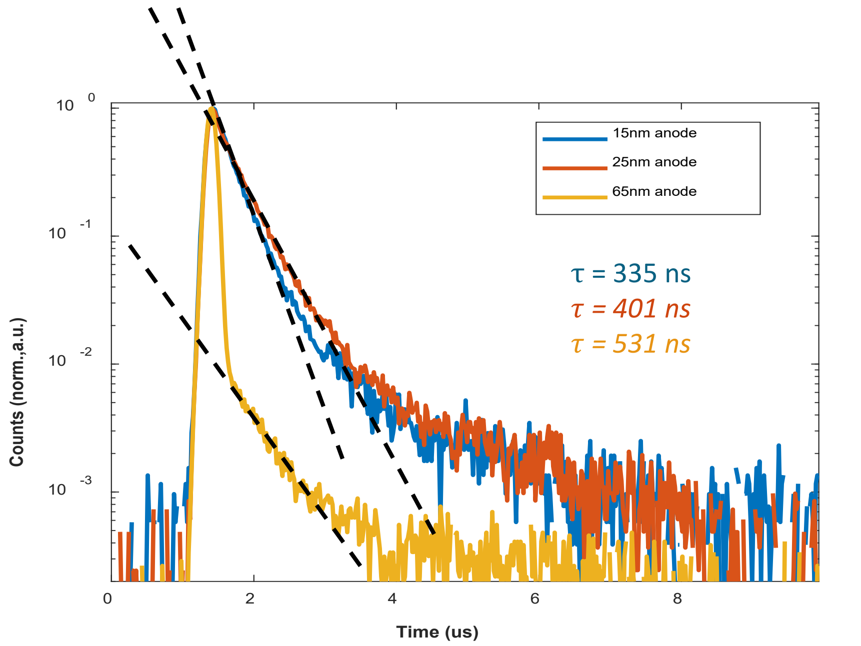
At 15 months (of 36 months)

Material development: need high quality silver anode
(silver cathode desirable but fabrication is challenging)

- Found substantial improvements in stability with Al seed layers.
- Generates flatter silver that has lower optical losses and is less likely to generate filaments.

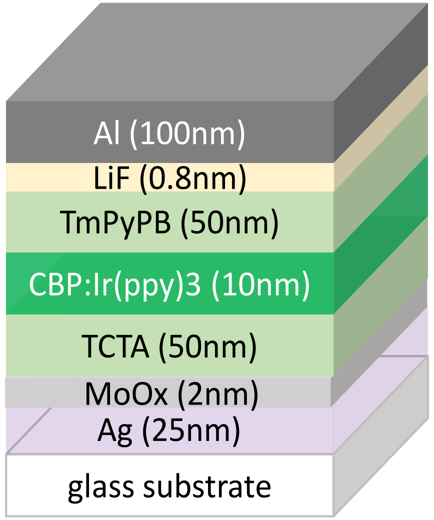






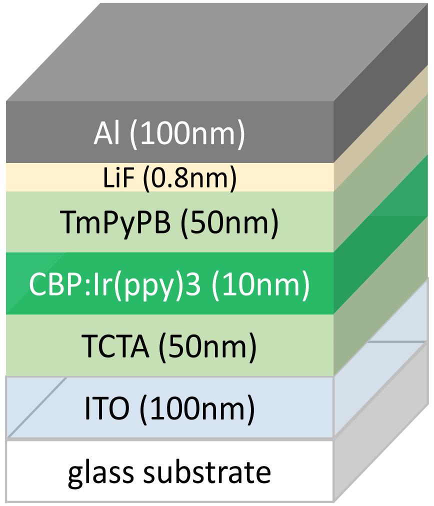
Progress: Fabrication

Initial design, fabrication & characterization of green devices

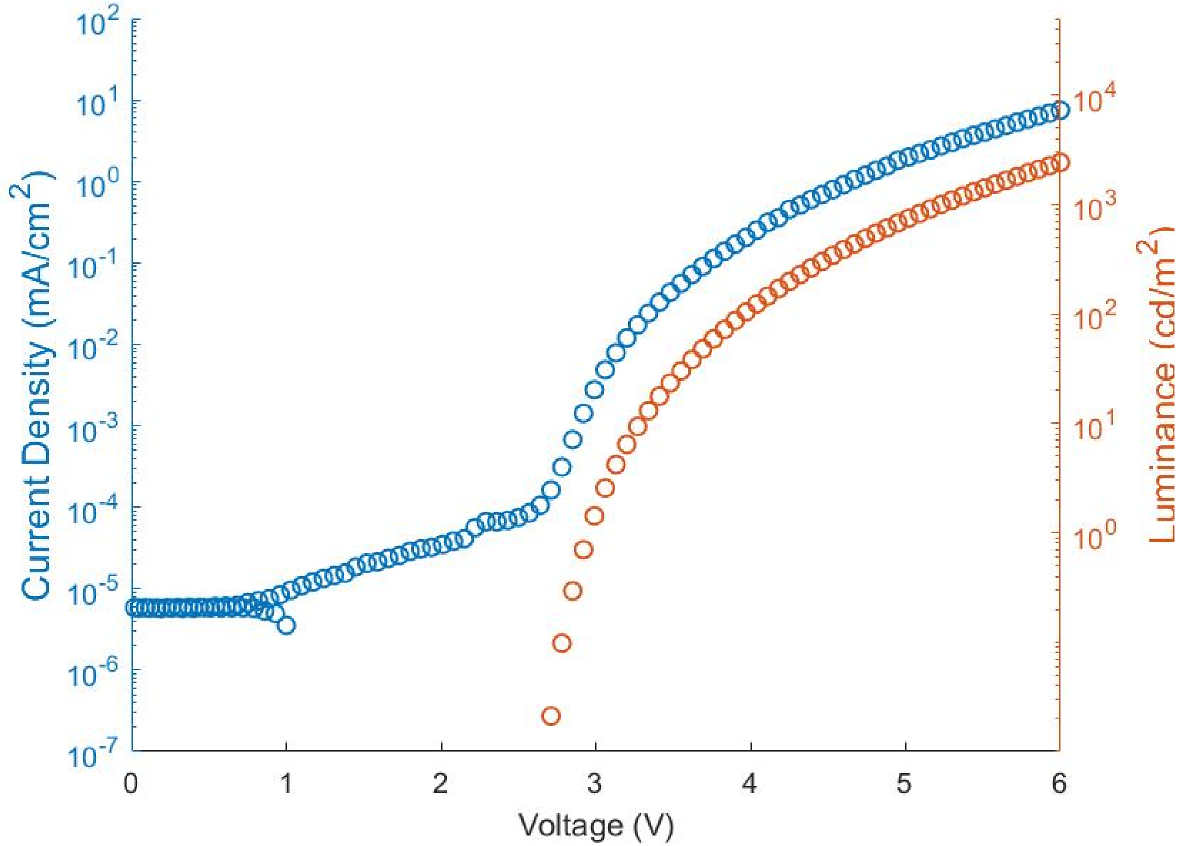


Simulated PF = 1.9
Simulated EQE = 35%

control

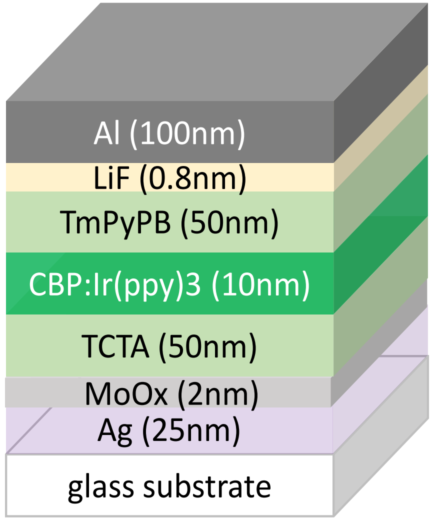


Simulated PF = 1.1
Simulated EQE = 34%



Progress: Fabrication

Initial design, fabrication & characterization of green devices



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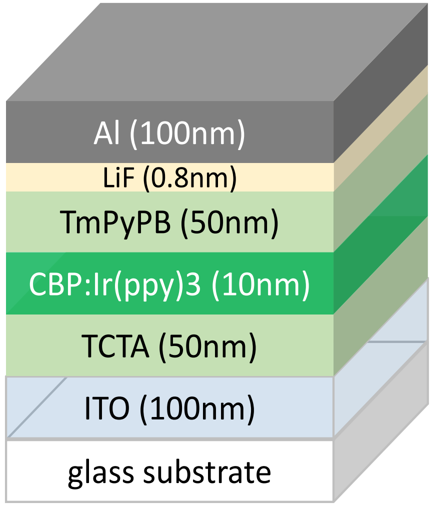

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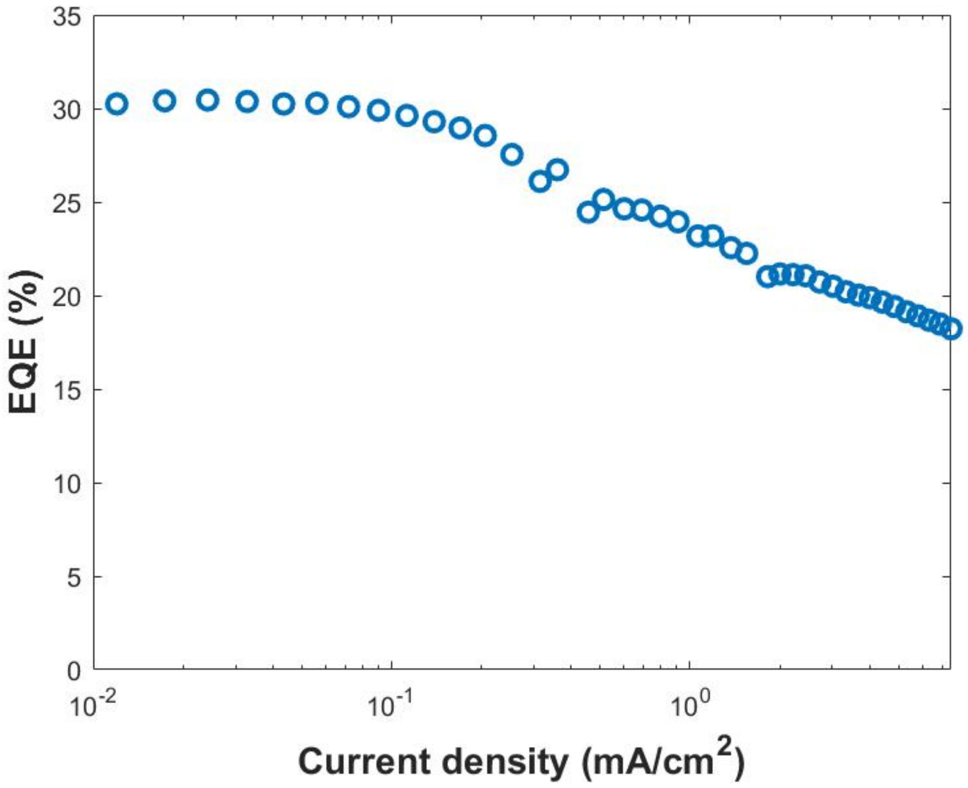


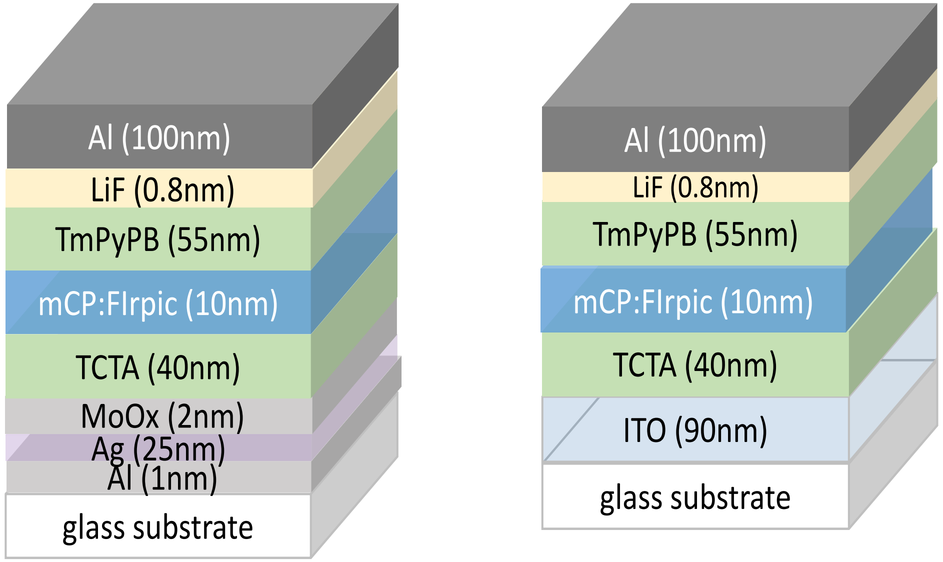
Outcoupling > 30% (target is 25%)

EQE >20% at 1000cd/m^2 (target is 10%)

Progress: Stability

At 15 months (of 36 months)

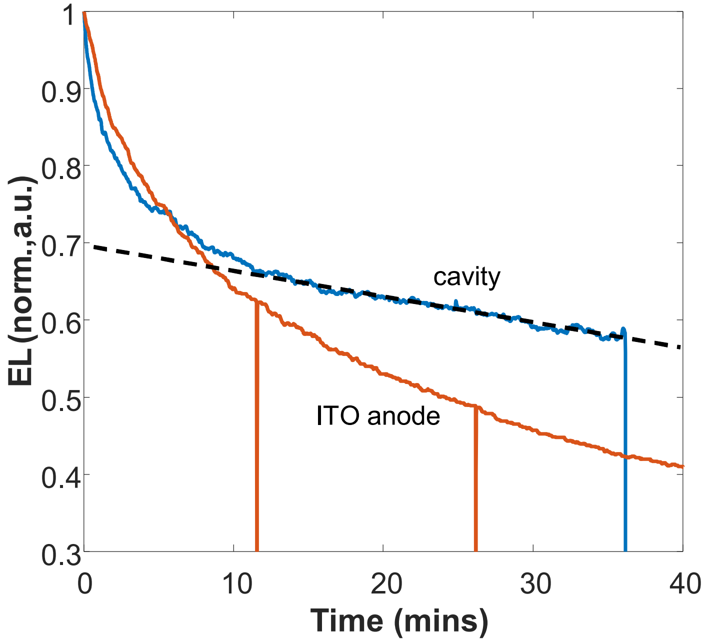
Blue Device Fabrication



Cavity Design

Control

Initial Stability Measurements



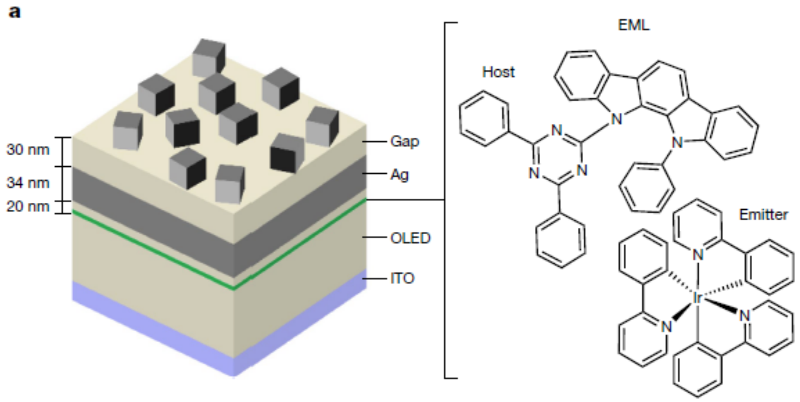
Blue OLEDs showing significant stability improvements at constant brightness

Stakeholder Engagement

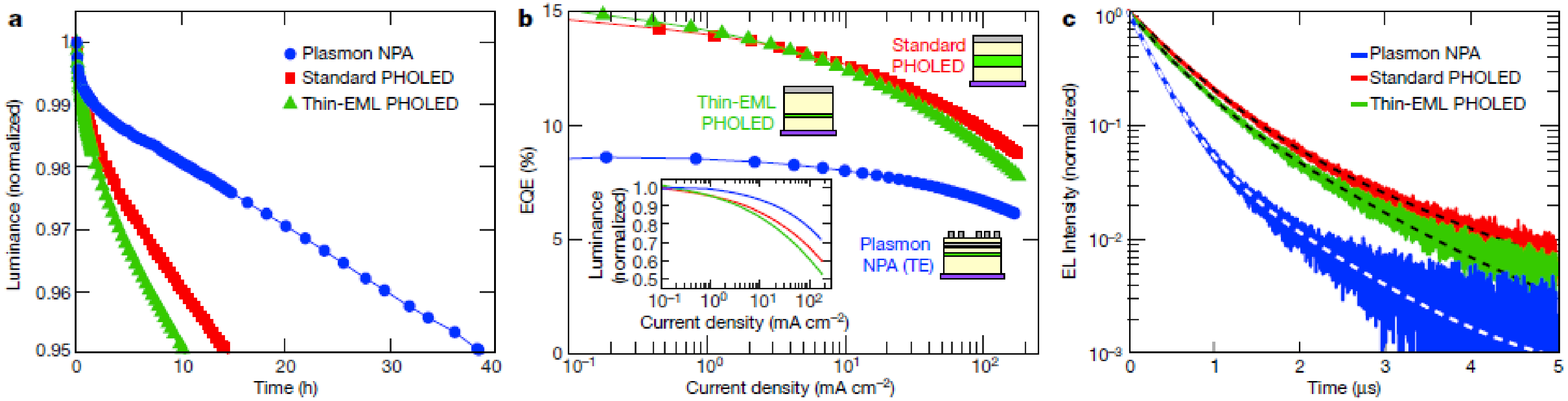
UDC was collaborator, now pursuing this approach independently.

- UDC's comparison at constant brightness is missing & device is not blue
- OLED structure is complex and hard to manufacture.

Next steps:
Develop our own IP portfolio and re-engage with UDC and/or other industry.



Structure same as our optical study but with silver cubes above top silver electrode to scatter energy out of surface plasmon modes.



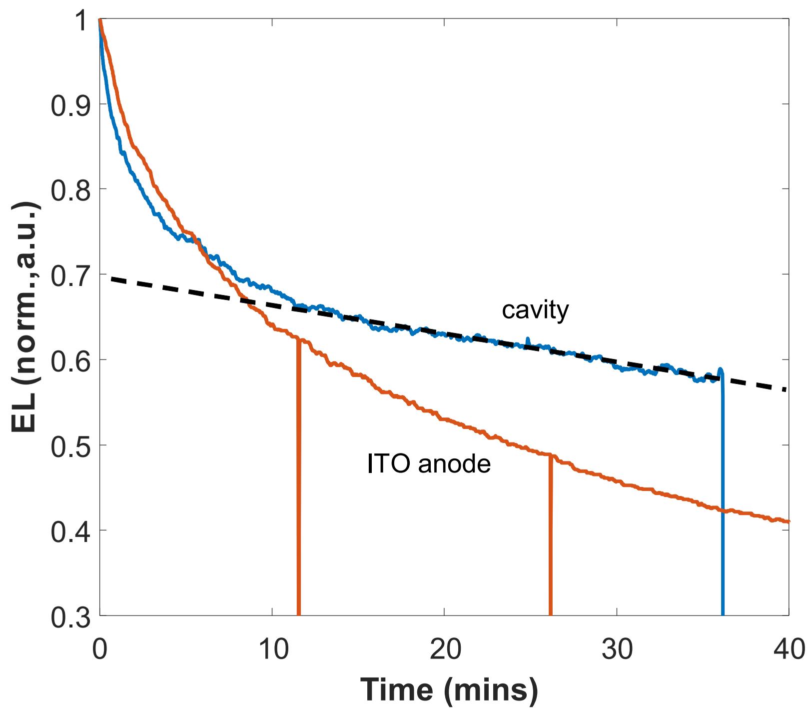
Fusella, et al. Nature 2020

Comparison at constant current (80mA/cm^2) not constant brightness.

Remaining Project Work

Present status: (at 15 of 36 months) We have substantially completed Yr 2 Go/No Go of demonstrating stability enhancement in high efficiency blue OLEDs.

- Have good sky-blue OLEDs with >30% EQE and sub 1μs transient lifetime.
- Show enhanced stability vs ITO controls.



Remaining challenge is to improve absolute stability in both cavity and control devices.

Also, need to measure the scaling factor relating emission speed to improved lifetime.

Overall program goal (Yr 3) is to demonstrate better whites.

Design complete. Fabrication expected in Yr 3. Aim is for blue + downconversion.

Thank You

Massachusetts Institute of Technology
Prof. Marc Baldo, Prof. Troy Van Voorhis
baldo@mit.edu, tvan@mit.edu

REFERENCE SLIDES

Project Budget

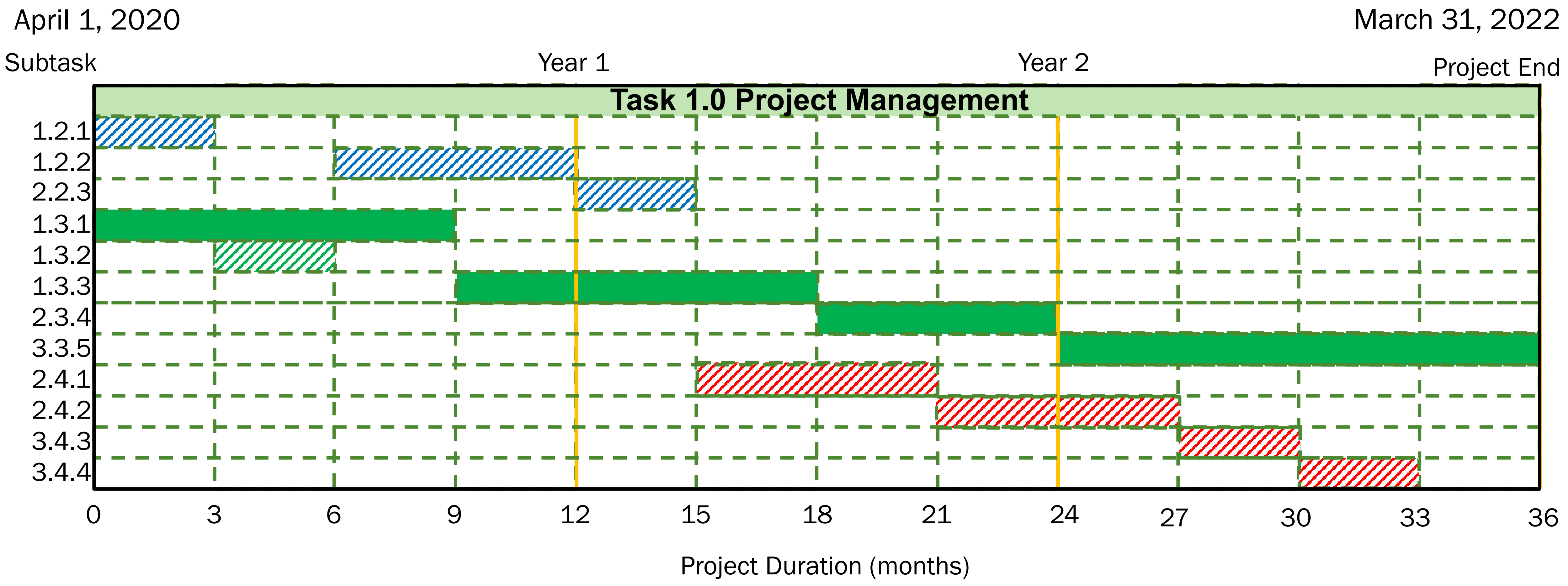
Project Budget: Personnel: $610,860; Fringe: $37,988; RA Tuition: $339,146; Travel: $15,005; Other Direct Costs: $138,106

Variances: Major equipment approved by DOE. Equipment costing $17,099.93; rebudgeted from travel and M&S.

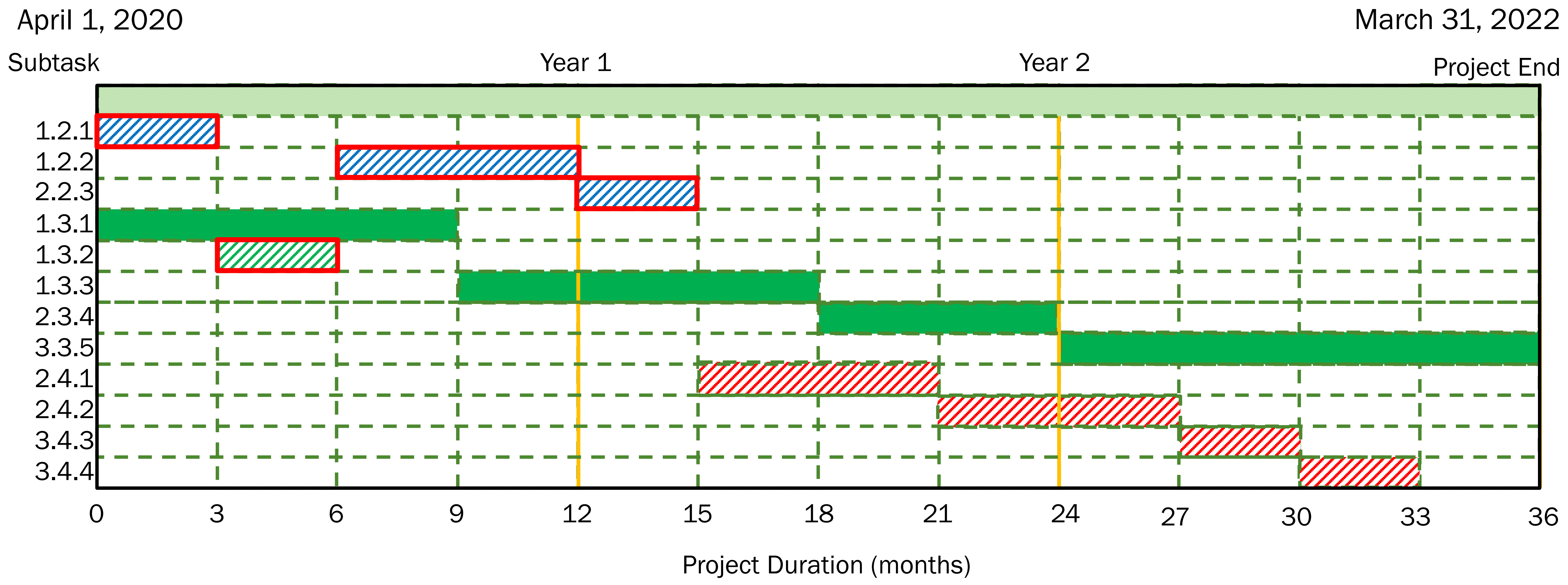
Cost to Date: $567,476.01. **Additional Funding**: N/A.

Budget History					
04/01/2020– FY 2020 (past)		FY 2021 (current)		FY 2022 – 3/31/2022 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$500,000	$125,000	$500,000	$125,000	$500,000	$125,000

Project Plan and Schedule



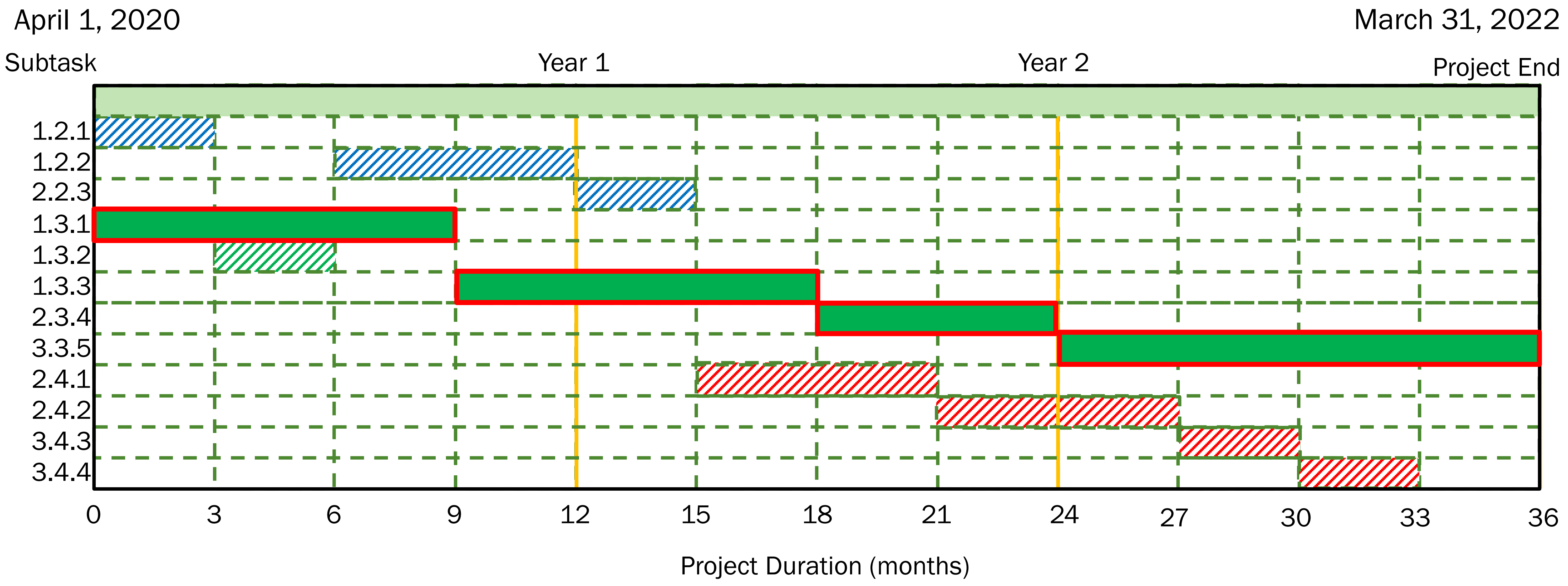
Project Plan and Schedule



Task 2.0 – [Nanophotonic and Nanoplasmonic Designs]: 1 person

- The recipient will design multifunctional optical outcouplers. (complete)

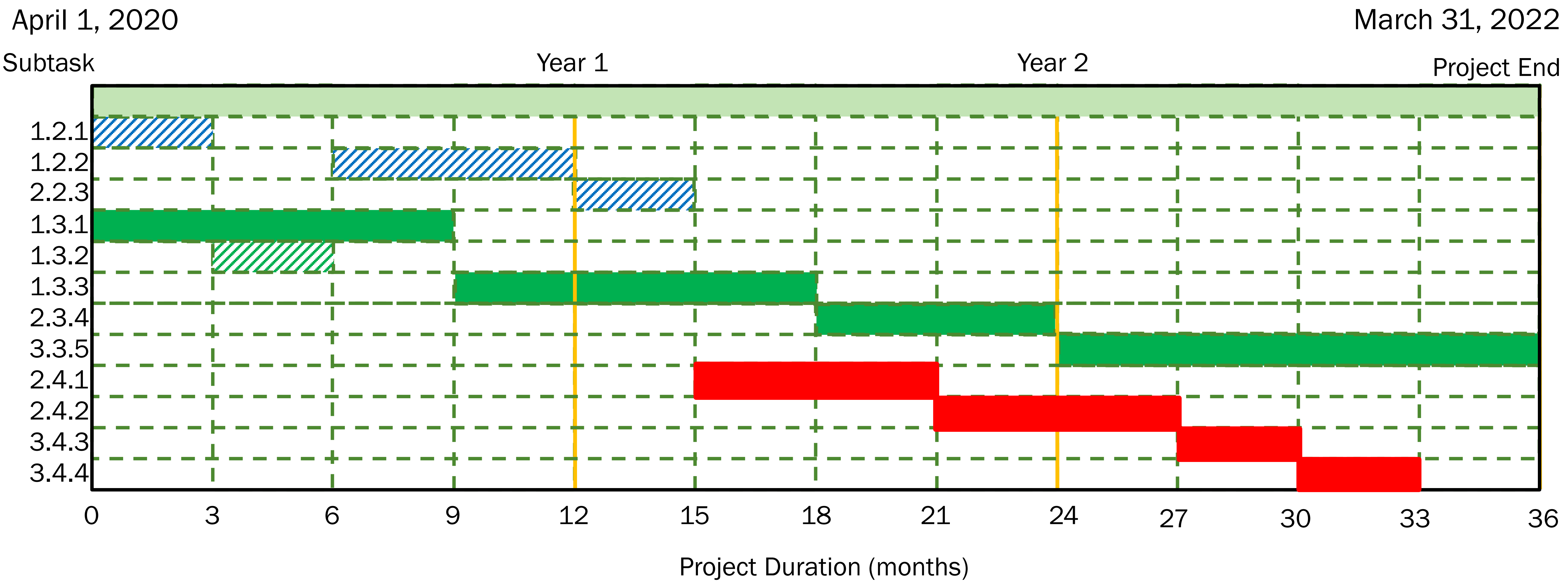
Project Plan and Schedule



Task 3.0 – [OLED Fabrication and Characterization]: 2 people

The recipient will build and characterize the OLEDs designed in Tasks 2 and 4

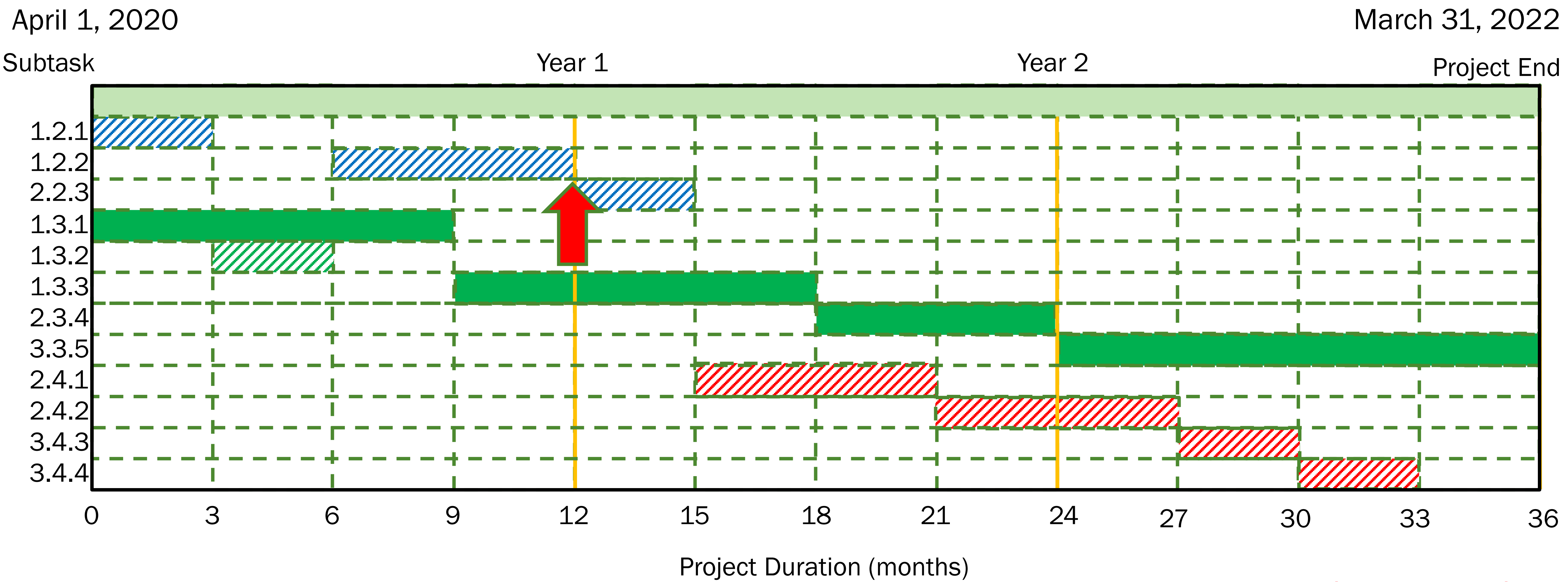
Project Plan and Schedule



Task 4.0 – [Efficiency droop]: 1 person

The recipient will design and test devices for improved droop.

Project Plan and Schedule

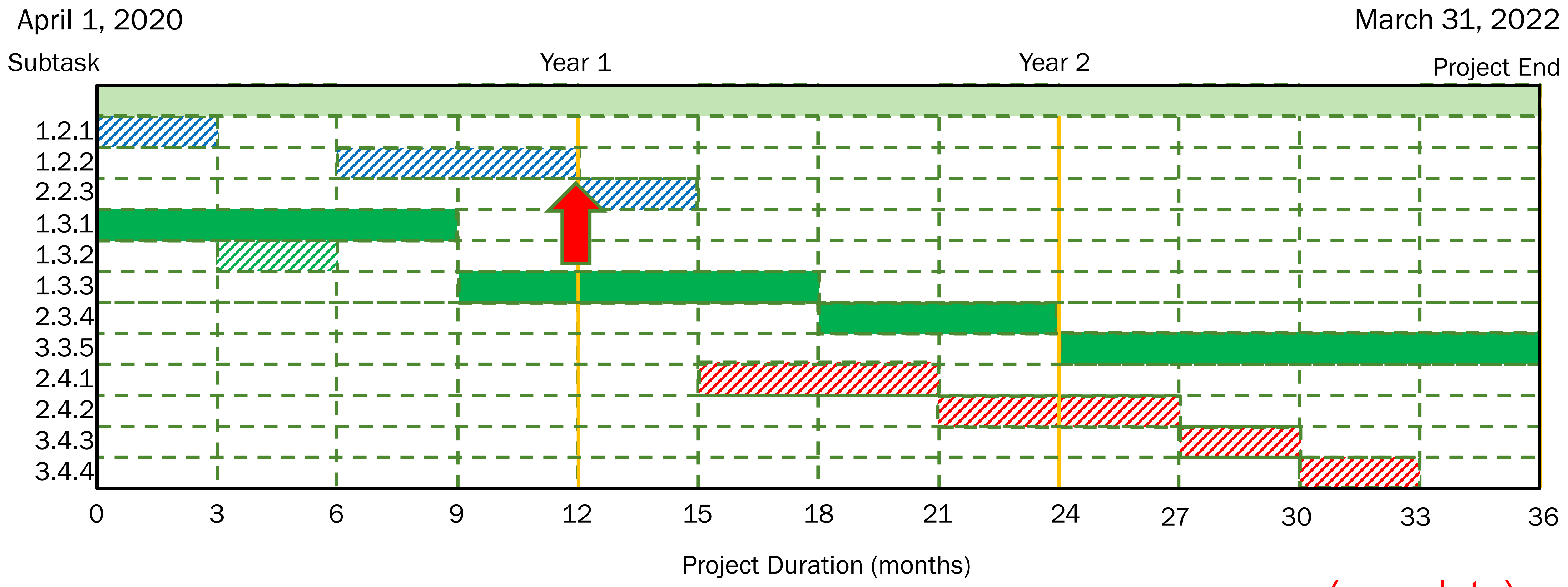


(complete)

<u>Go/No Go: Subtask 1.2.2</u> – Design for Blue Employing Optimized Layer (M6-12)

- The recipient will design a blue phosphorescent OLED with CIE color coordinates $x < 0.25$, $y < 0.30$, a 3× exciton speed up, equivalent to a transient phosphorescent lifetime < 2μs, > 50% outcoupling efficiency, and an external quantum efficiency > 20% at 1000 cd/m^2.

Project Plan and Schedule



(complete)

<u>Go/No Go: Subtask 1.2.2</u> – **Design for Blue Employing Optimized Layer (M6-12)**

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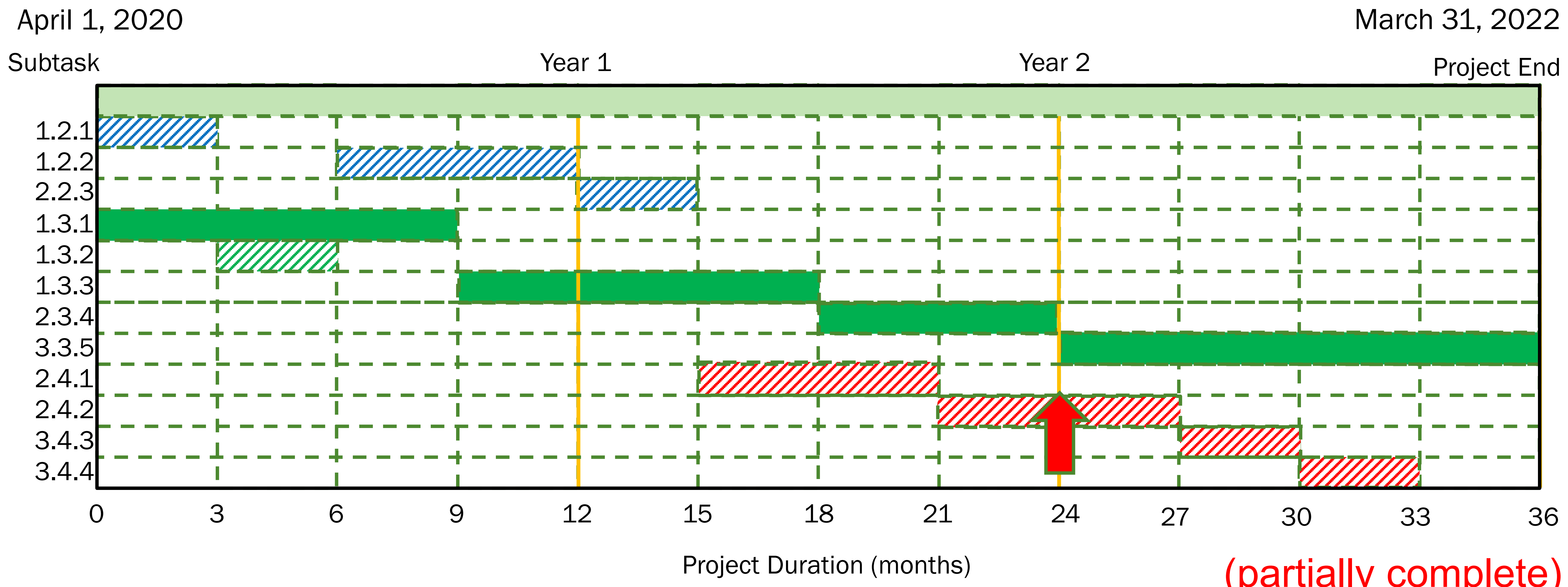
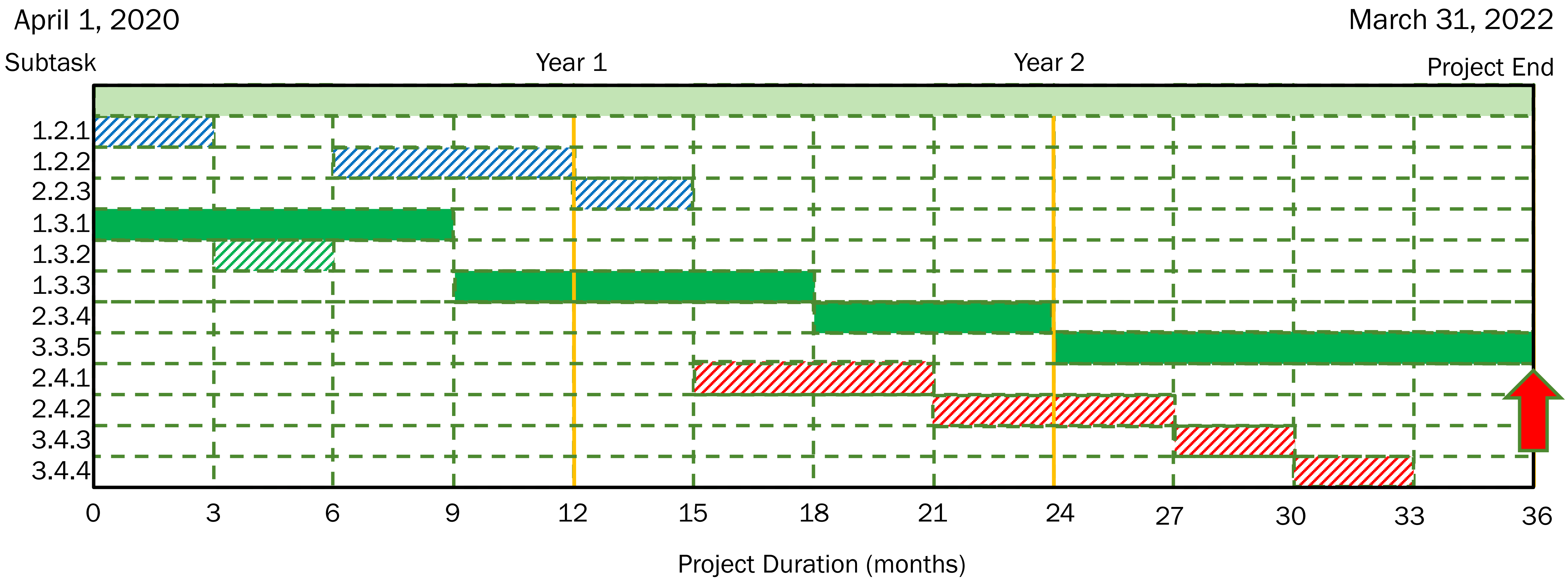
Project Plan and Schedule



<u>Go/No Go: Subtask 2.3.4</u> – **Fabricate and characterize the optimized blue design (M18-24)** The recipient will translate the stability improvements to blue phosphorescent OLEDs. Specifically, the milestone is a blue phosphorescent OLED with 3× exciton speed up, and improved stability relative to the control - with absolute stability LT70 > 1 hour at 1000 cd/m^2.

Project Plan and Schedule

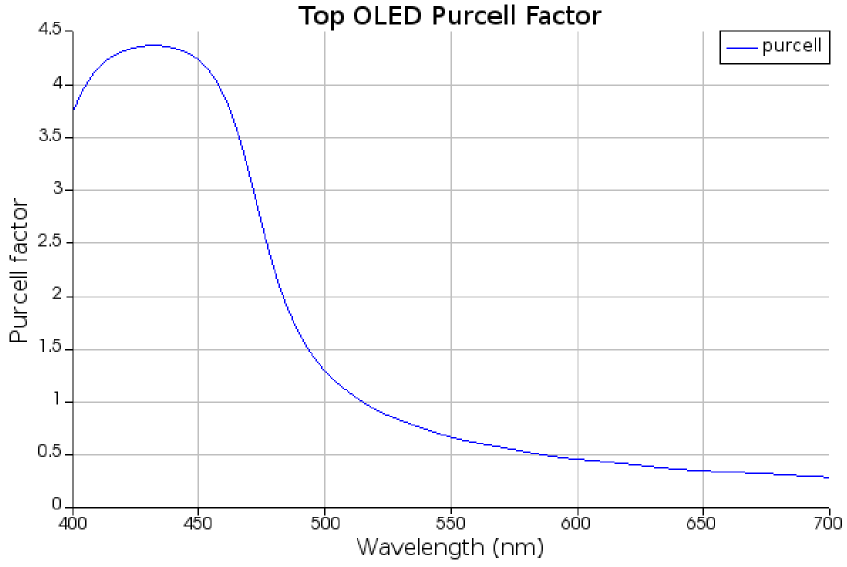


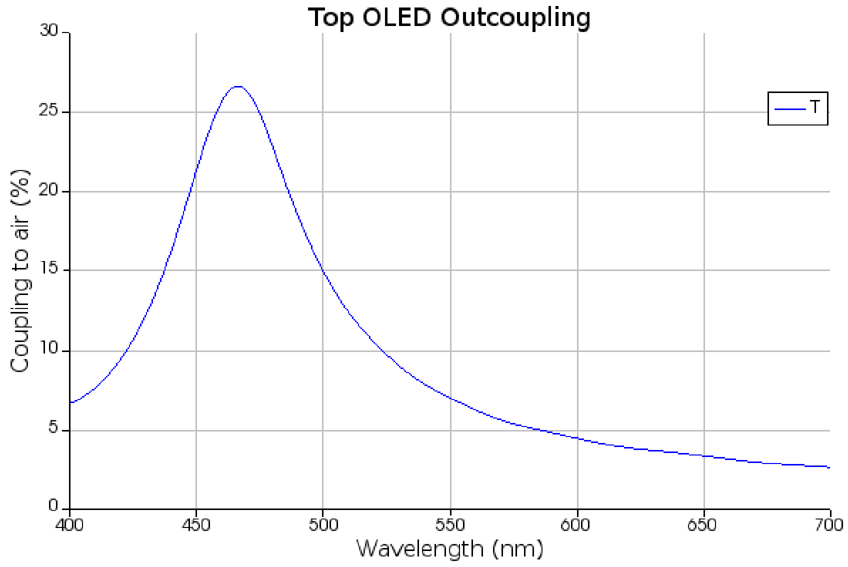
<u>Final: Subtask 3.3.5</u> – Fabricate and characterize the white OLED designed in 2.2.3 and 3.4.3 (M27-36)

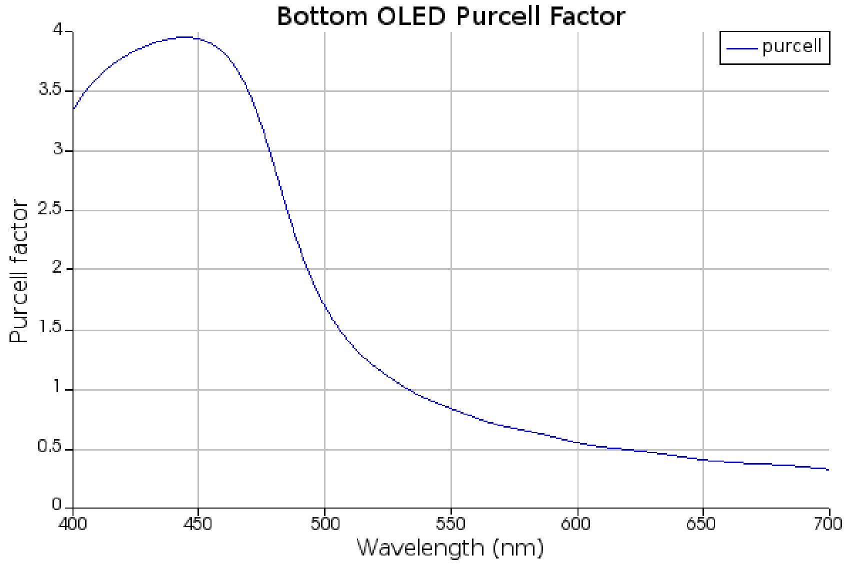
Impact calculations

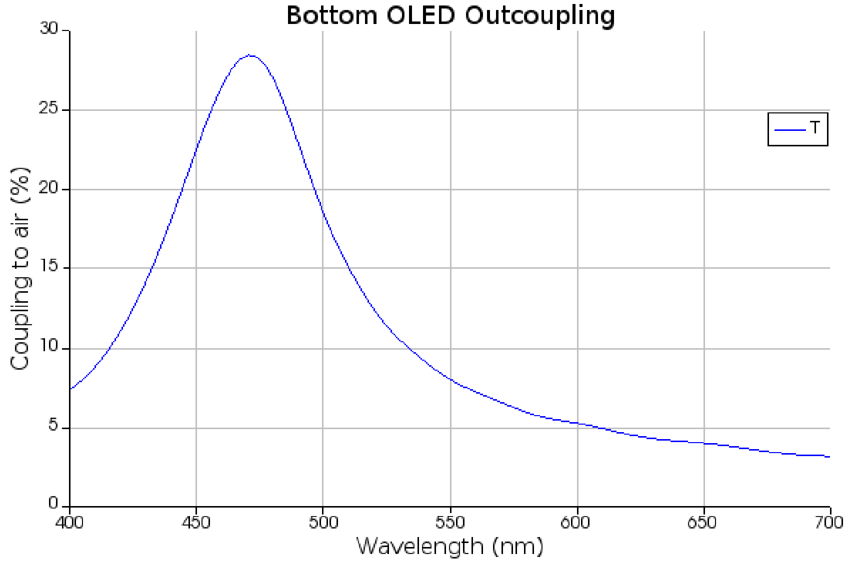
- Consider a relatively uniform white spectrum with high CRI and ideal CIE that is composed of blue, green, and red in a 1:4:2 ratio.
- Assuming that green and red exhibit 100% IQE, while blue operates at 25%, this model is consistent with the present white OLED internal quantum efficiency (IQE) of 60-70%.
- If we quadruple the efficiency of the blue, as might be expected from upgrading to phosphorescence from a fluorescent dye, the overall quantum efficiency increases by approximately 50%.
- The overall goal is to accelerate the 2025 DOE efficiency target of >80% IQE by three years, and save energy consumption of 276 TBtu per annum, with a simple payback period of approximately 3 years.
- The key challenge is achieving LT70 of 50,000 hrs for high efficiency sky blue phosphors at 10,000 lm/m^2.

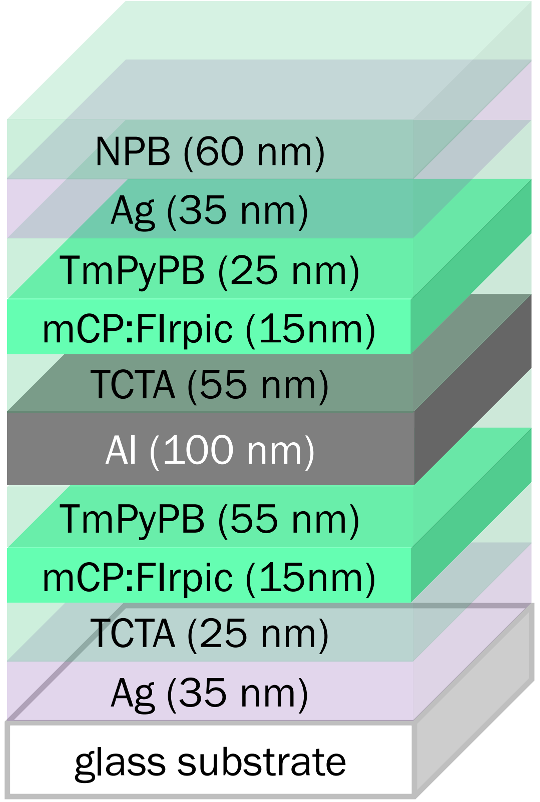
Top and Bottom Emitting Stacked Cavity OLEDs











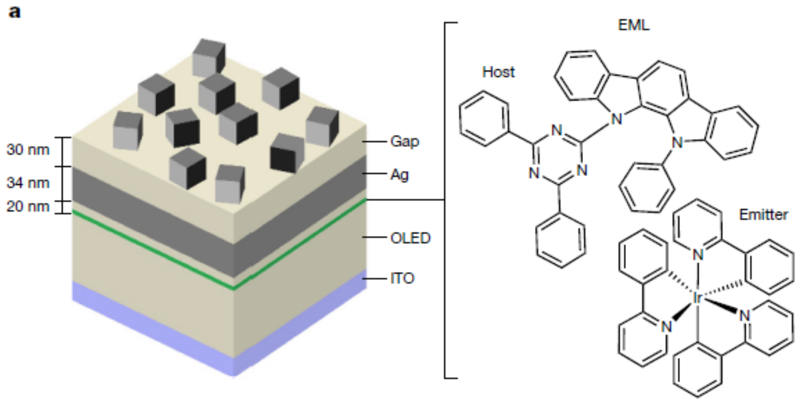
- Both OLEDs behave like single top-emitting or bottom-emitting cavity OLEDs since no fields pass through the thick Al layer
- Advantage of lower current density for same brightness

Analysis of prior work

- UDC's comparison at constant brightness is missing & device is not blue
  - (EQE ratio is ~ 8/15. Stability benefit ~(8/15)^1.5 = 0.39 - >15hrs? Same as standard PHOLED?)

- Stability benefit from faster lifetime is a lot smaller than predicted from our previous joint work.

- OLED structure is complex and hard to manufacture.



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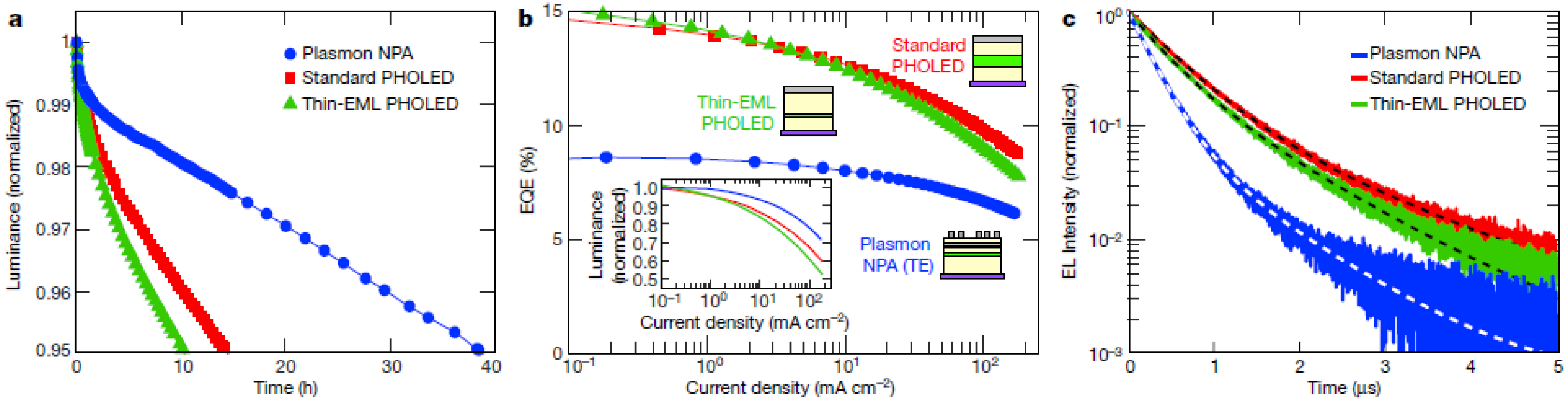

Fusella, et al. Nature 2020

Comparison at constant current (80mA/cm^2) not constant brightness.