High efficiency and stable white OLED using a single emitter

2014 Building Technologies Office Peer Review

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

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Project Summary

Timeline:

Start date: 10/1/2011

Planned end date: 9/30/2014

Key Milestones

1. demonstrating a single-doped white device (CRI> 80) with a PE of 40 lm/W @ 1000 cd/m^2 and an operational lifetime over 100 hrs @ 1000 cd/m^2; 9/30/13
2. blue device using halogen-free Pt-based emitters with an EQE of over 15%; 9/30/14
3. demonstrating a single-doped white device (CRI> 80) with a PE of 50 lm/W @ 1000 cd/m^2 and an operational lifetime over 10000 hrs @ 1000 cd/m^2; 9/30/14

Budget:

Total DOE $ to date: $664,785

Total future DOE $: $0

Target Market/Audience:

OLED based solid state lighting industry/
R&D and manufacturing people

Key Partners:

ASU	

Project Goal:

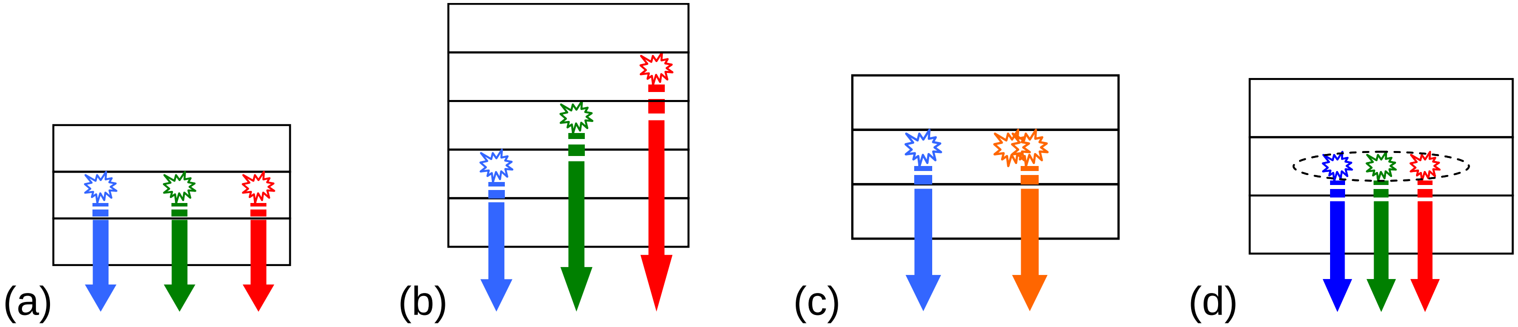
This project is to demonstrate an efficient and stable white OLED using a single emitter on a planar glass substrate.

The successful outcome of this project will provide a solution to lower the fabrication cost of white OLEDs significantly by decreasing the complexity of device fabrication, increasing the robustness of materials and providing more cost-effective alternates to the state-of-the-art Iridium-based phosphorescent emitters.

Purpose and Objectives

Problem Statement: The state-of-the art WOLED technology requires the use of multiple emissive materials, which will generate color instability and color aging issues, affecting the performance and operational lifetime of WOLEDs. Moreover, the manufacturing process of white OLED becomes more complicated with the incorporation of multiple emissive layers or a single emissive layer with multiple dopants. In order to prevent the color aging and enhance the color stability, the device structures will become inevitably more complexed.

The <u>**goal**</u> of this project is to demonstrate an efficient and stable white OLED using a single emitter, which will provide a solution to lower the fabrication cost of white OLEDs significantly by decreasing the complexity of device fabrication.



Schemes for 4 possible WOLED architectures: (a) triple-doped emissive layer; (b) multiple emissive layers; (c) emissive layer with monomer and excimer; (d) emissive layer with a single broadband emitter.

Purpose and Objectives

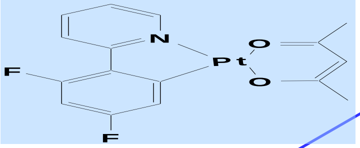
Target Market and Audience: Lighting consumes ~765 trillion Whr of electricity every year in the United States, i.e. 22% of all electricity generated nation-wide. It costs close to $58 billion a year to light the residential, business and manufacture buildings. However, two current widely used lighting devices have their drawbacks and limitations. Incandescent lamp, a one-hundred-year-old technology, has a low power efficiency (average 12-17 lm/W), which still accounts for 42% consumption of electricity. On the other hand, a fluorescent lamp with high power efficiency (> 80 lm/W) could be potentially environmental hazardous due to its use of mercury.

In addition to inorganic white LEDs, the white organic light emitting diodes (WOLEDs) with high power efficiency (>100 lm/W) , are also considered as strong candidates for next generation illumination devices. Especially, WOLEDs use environmentally benign organic materials and their fabrication cost can be significantly reduced with potential roll-to-roll processing technology. Our project focus on developing an efficient and stable WOLED in a simpler device structure, in order to reduce the manufacture cost of WOLEDs.

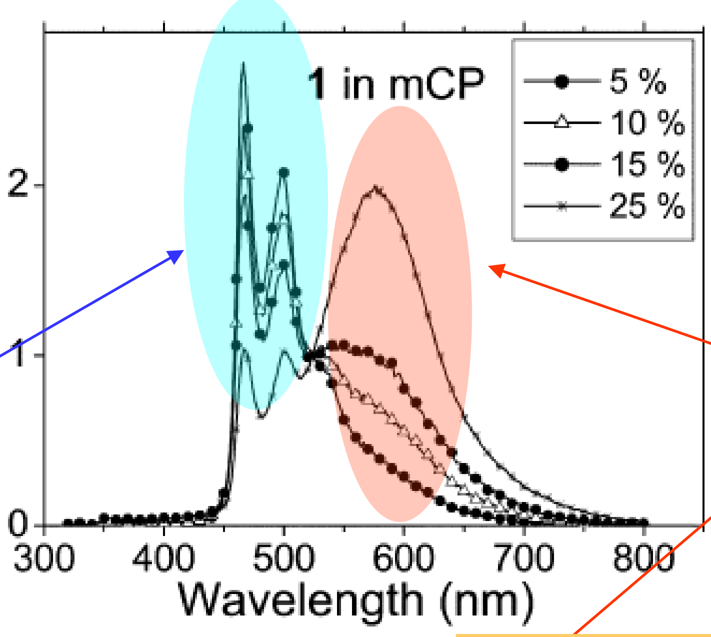
Purpose and Objectives

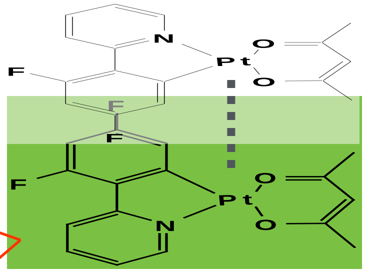
Impact of Project:
The ultimate objective of this project is to demonstrate an efficient and stable white OLED using a single emitter on a planar glass substrate without outcoupling enhancement and a luminous efficiency of at least 50 lm/W and an operational lifetime over 10000 hrs @ 1000 cd/m^2. In a more advanced device structure with enhanced outcoupling effect (2-3x improvement), a stable single-doped white OLED with an efficacy of 100-150 lm/W can be demonstrated using the outcome of this project. The successful outcome of this project will provide a solution to lower the fabrication cost of white OLEDs significantly by decreasing the complexity of device fabrication, increasing the robustness of materials and providing more cost-effective alternates to the state-of-the-art Iridium-based phosphorescent emitters. Moreover, a single-doped white OLED will also provide a greater control of emission color by eliminating color aging. This could help to meet the targeted cost of organic solid state lighting set in the DOE MYPP.

Approach

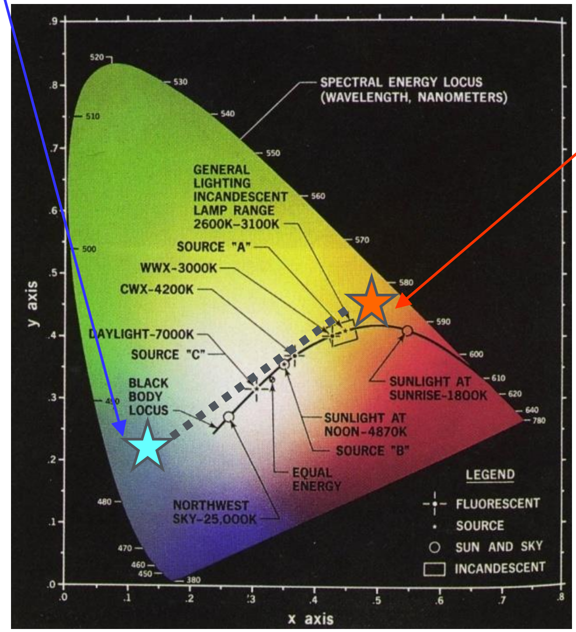


FPt
blue-green like
emission





[FPt-FPt]*
orange like emission



Benefits

(a) No problem of energy transfer from blue to red emitters
(b) No problem of Differential Aging
(c) Spectrum is voltage independent
(d) Simple structure
(e) Easy to manufacture

Plus, Pt complexes will be more cost-effective.

Adamovich et. al., *New J. Chem.* (2002).

Approach

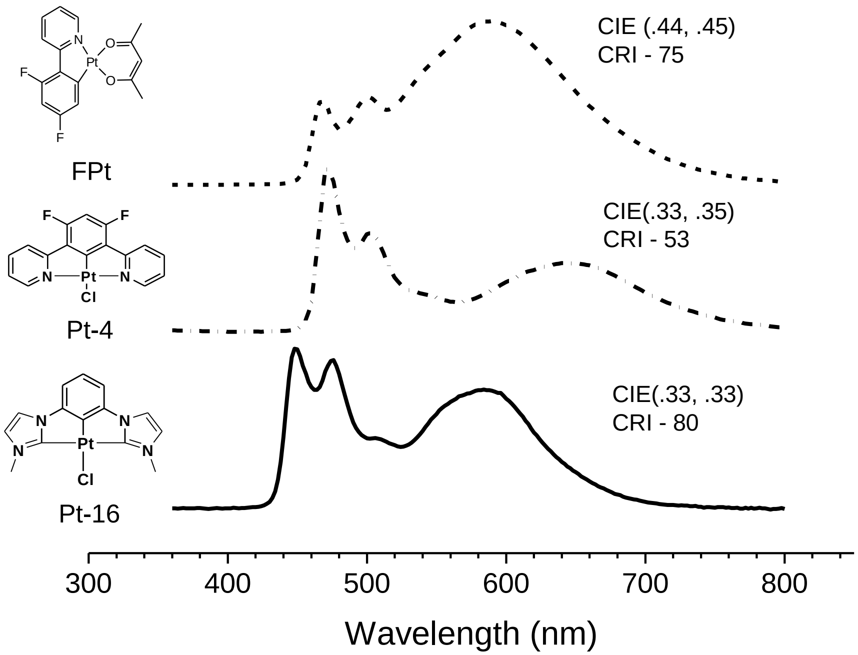
Approach: To deliver this research goal, the project will be focused on two main areas including 1) the development of efficient and stable square planar phosphorescent emitters and ambipolar host materials; and 2) the device optimization using stable injection materials to balance charge in the recombination zone.

Key Issues: 1) controlling emission color of emitters and their excimers, 2) improving optical and electrical stability of emissive dopants, 3) incorporating the state-of-the-art of transporting and blocking materials to maximize the power efficiency and operational lifetime of WOLEDs at the same time.

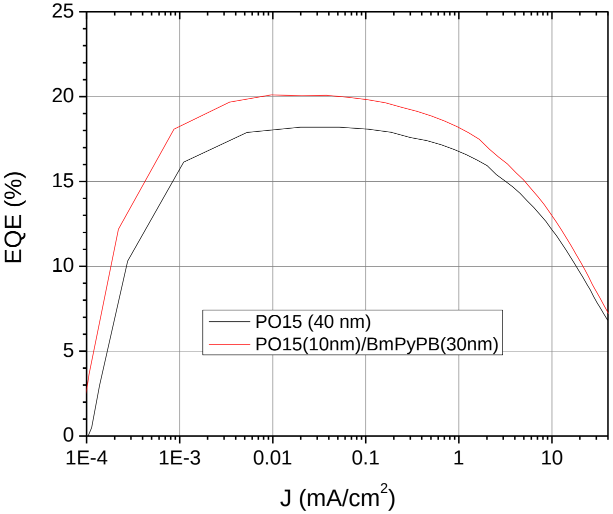
Approach

Distinctive Characteristics: Compared with the stat-of-the-art white OLEDs using Ir complexes with different emission colors, the proposed research has several advantages. First of all, because an excimer does not have a bound ground state, the cascade of energy from the host or the “blue” (higher energy) emitter to the excimer can be prevented, leading to a stable emission color independent of the driving voltage. Secondly, the problem of “color aging” can be resolved due to the use of a single emitter. Thirdly, the Pt-based emitters will be more preferable over Ir-analogue for displays and lighting with equal performance, which can be justified by potentially large cost difference between Ir (natural abundance: $3x10^{-6}$ ppm) and Pt complexes (natural abundance: $>1x10^{-3}$ ppm). On the other hand, single-doped white OLED has not demonstrated to be efficient and stable enough compared with the current best white OLEDs due to insufficient research effort from the community.

Progress and Accomplishments



device structure:ITO/PEDOT:PSS/NPD(30nm)/TAPC(10nm)/10%Pt-16:TAPC:PO15(25nm)/ ETL/LiF/Al.



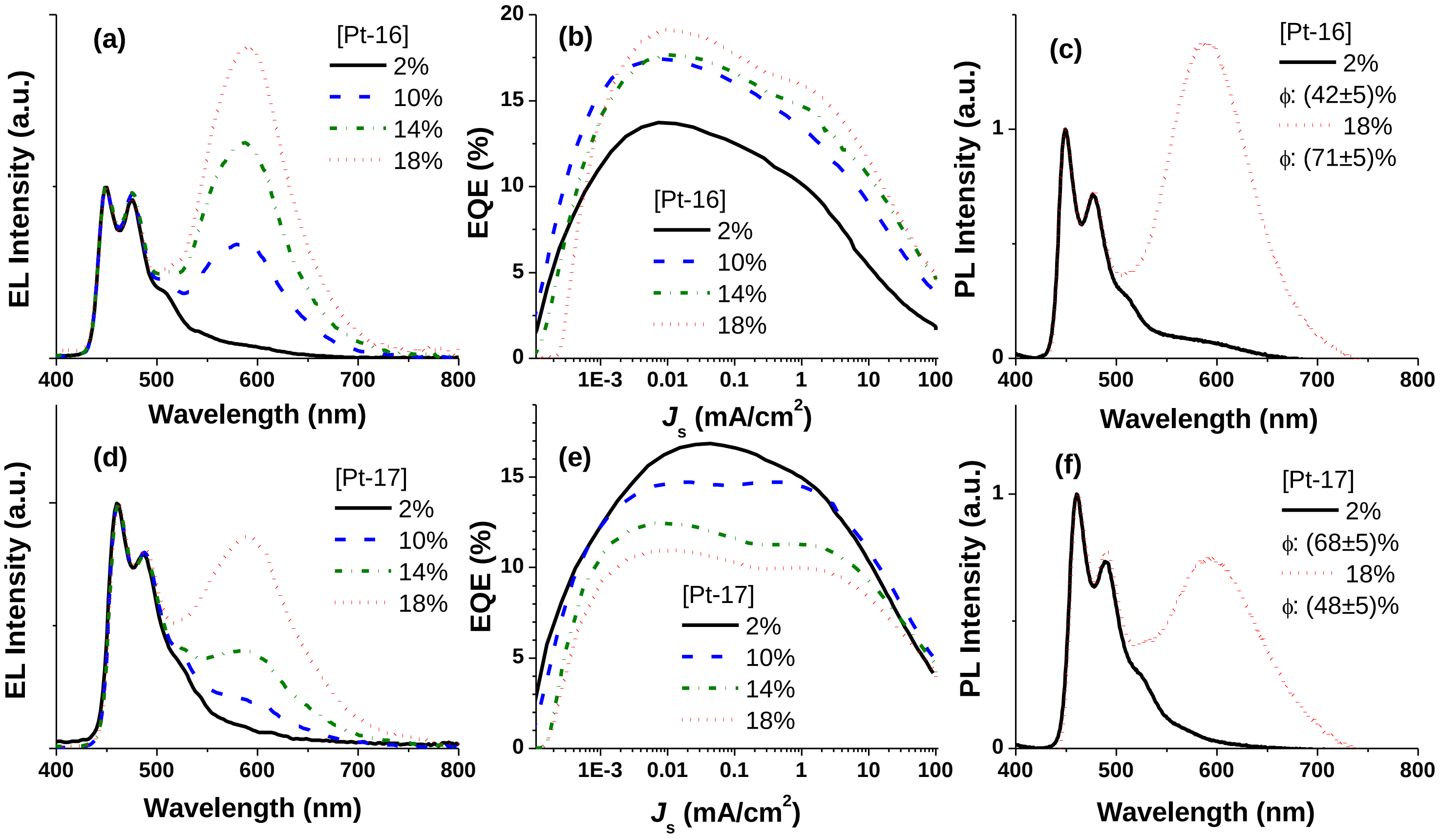
For Pt-16 WOLED, power efficiency exceeds 50 lm/W (no n/p-doping and enhanced outcoupling), CIE (0.33, 0.32), CRI >=80, showing promise for lighting applications.

Power efficiency is 29 lm/W at 1000 cd/m^2

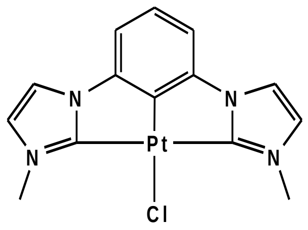
Fleetham et al. *Adv. Mater.* (2013)

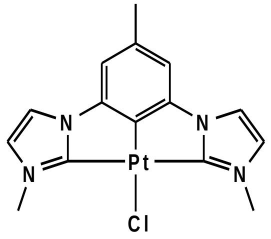
Progress and Accomplishments

device structure:ITO/PEDOT:PSS/NPD(30nm)/ TAPC(10nm)/x%dopant:26mCPy25nm)/ PO15(40nm)/LiF/Al.



Pt-16



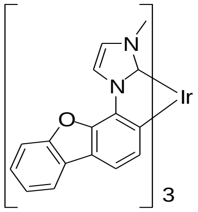


Pt-17

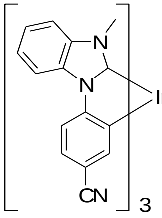
It is very interesting to find out that the behavior of excimers could be so different with similar monomer structures.

Fleetham et al. *Adv. Mater.* (2013)

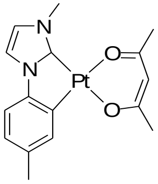
Progress and Accomplishments



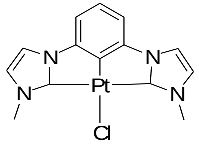
Ir(dpfmi)



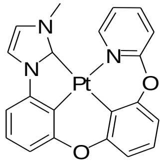
Ir(cnpmic)



Pt(Mepmi)

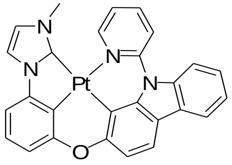


Pt-16



Pt[*pmi*-O-POPy]

PtOO7

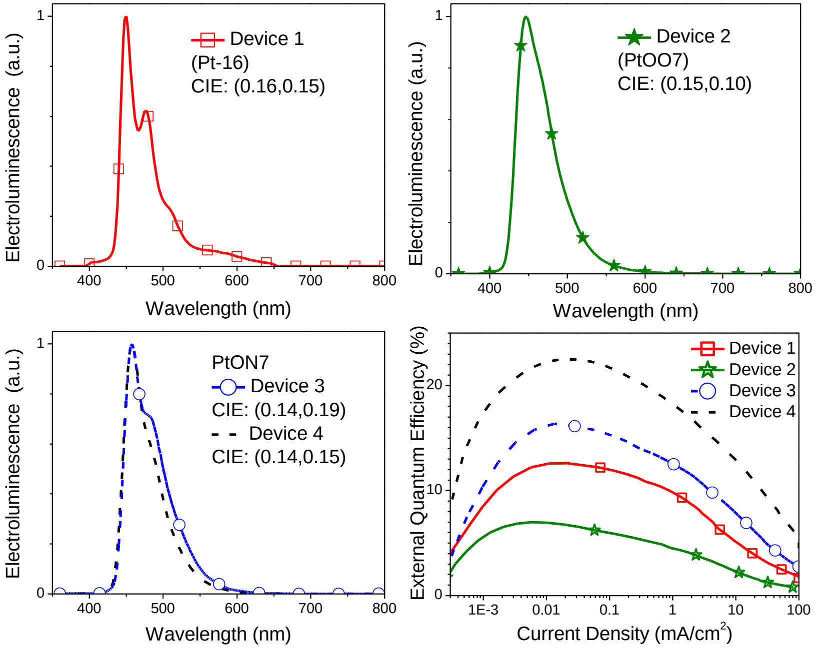


Pt[*pmi*-O-CbPy]

PtON7

Complex	λ_{max} (nm)	Φ(%)	τ (μs)	k_r ($x10^4 s^{-1}$)	k_{nr} ($x10^4 s^{-1}$)
PtON7	452	89	4.1	21	2.6
PtOO7	442	58	2.5	23	17
Pt-16[9b]	450	32	5.1	6.3	13.3
Pt(Mepmic)[9a]	419	20	25	0.8	3.2
Ir(cnpmic)$_3$[7b]	425(sh), 450	78	19.5	4	1.1
Ir(dbfmi)[7a]	445	70[a]	19.6	3.6	1.5
PtON1	449	85	4.5	19	3.3

ITO/PEDOT:PSS/NPD(30 nm)/TAPC(10 nm)/2% emitter:26mCPy(25 nm)/PO15(40 nm)/LiF/Al.

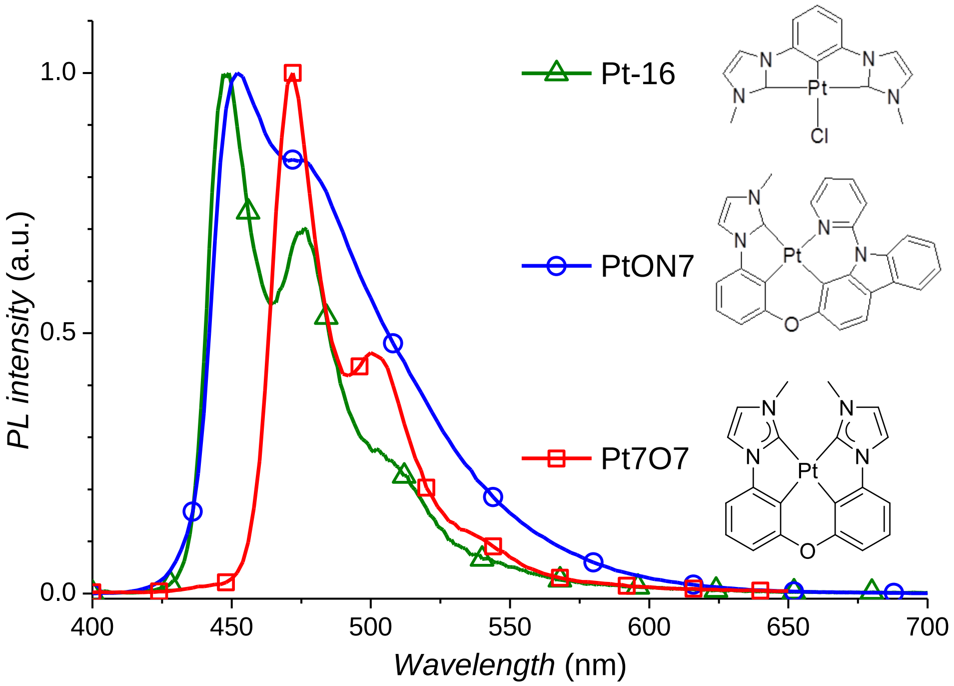


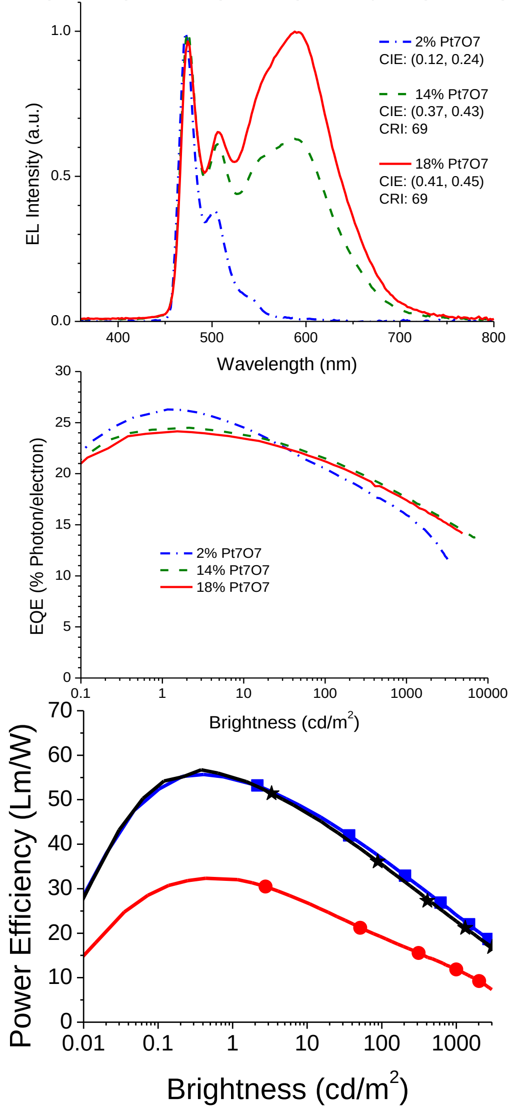
- With such molecular design principle, PtON7 shows a better photophysical properties than its Pt analogs and Ir analogs;
- A deep blue OLED with a maximum EQE of 22% and CIE coordinates of (0.14, 0.15) was fabricated using PtON7.

Hang et al. *Angew Chem. Int. Ed.* (2013)

Progress and Accomplishments

ITO/HATCN(10 nm)/NPD(30 nm)/TAPC(10 nm)/x% Pt7O7: mCBP (25 nm)/DPPS(10 nm)/BmPyPB(30 nm)/LiF/Al



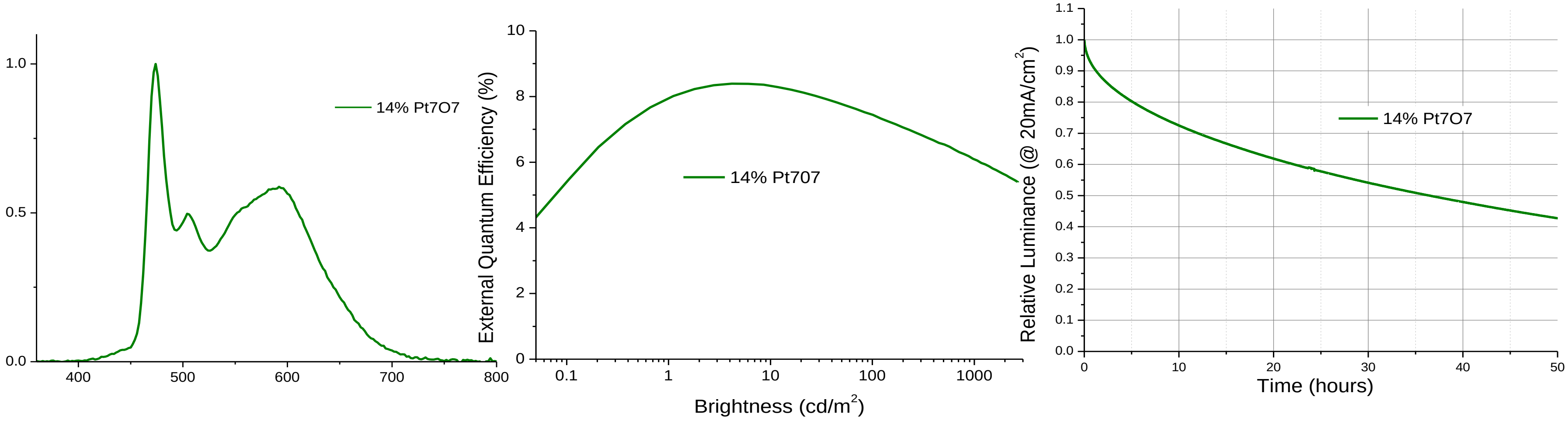


Following the materials design principle from tetradentate Pt complexes, Pt7O7 was synthesized and fabricated in the device settings. We were very thrilled to report that the monomer and excimer can both be efficient at the same time with peak EQE close to 25% and peak power efficiency close to 60 lm/W.

Li et al. *Adv. Mater.* In Press.

Progress and Accomplishments

ITO/HATCN(10 nm)/NPD(30 nm)/ 14% Pt7O7:mCBP (25 nm)/BAlq(10 nm)/Alq3(30 nm)/LiF/Al.

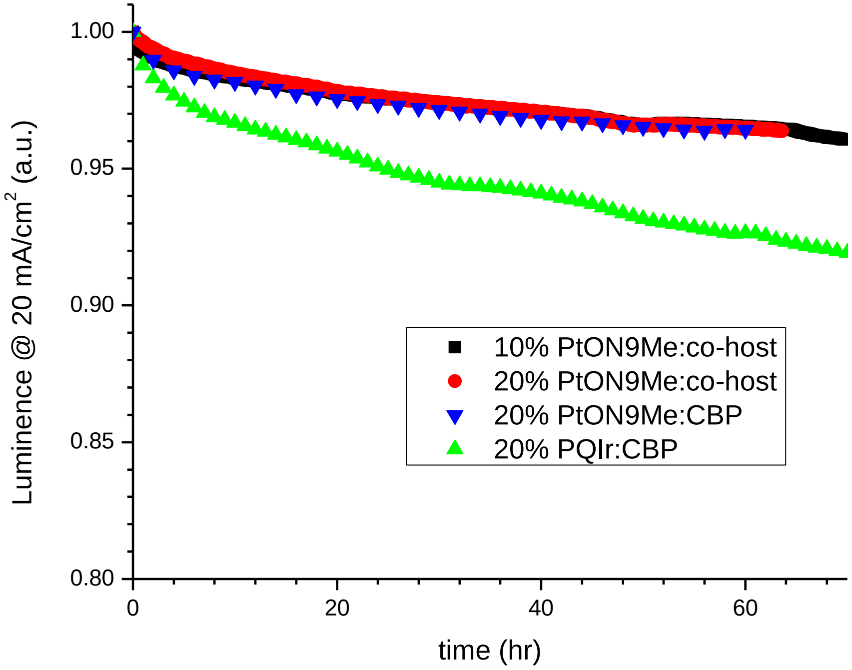


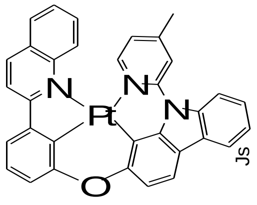
14% doped Pt7O7 device have demonstrated a reasonable device operational lifetime with Lt_{50} over 35 hrs at constant current of 20 mA/cm^2 with initial luminance of around 3000 cd/m^2, which can be translated to a LT50 over 300 hrs at initial luminance of 1000 cd/m^2 citing the formula: $Lt_{50} = Lt_{50}'(L_0'/L_0)^{1.8}$. The use of state-of-the-art of transporting and blocking materials will further improve the power efficiency, which is also expected to significantly improve the operational lifetime of Pt7O7 device @1000 cd/m^2.

Li et al. *Adv. Mater.* In Press.

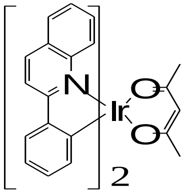
Progress and Accomplishments

ITO/HATCN(10 nm)/NPD(40 nm)/EML(25 nm)/
BAlq(10 nm)/Alq3(30 nm)LiF/Al.

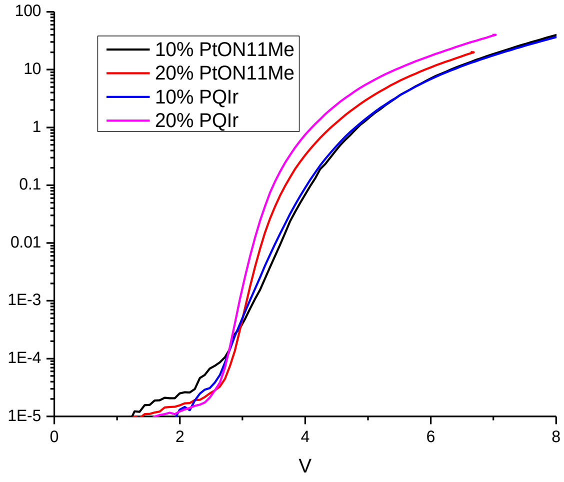


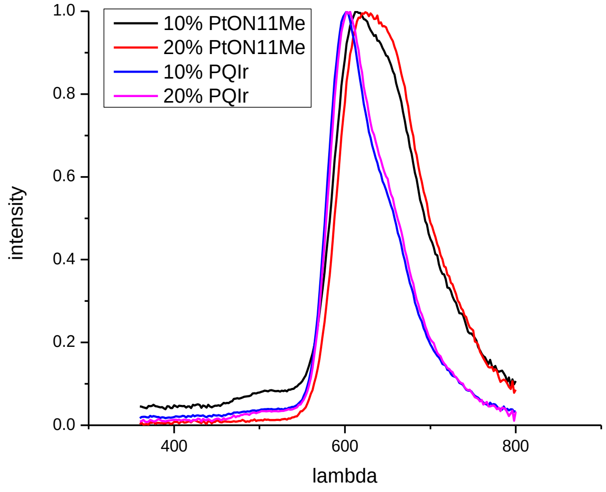


PtON11Me



PQIr





PtON11-Me, a analog to PtON1 and PtON7, have demonstrated a remarkable operational stability in OLEDs. The LT$_{97}$ is more than 70 hrs at a very high current density of 20 mA/cm^2, indicating the potential of such class of emitters as emitters for the stable and efficient blue and white phosphorescent OLEDs.

Li et al. in preparation

Progress and Accomplishments

Lessons Learned: Excimer-based WOLEDs can be as efficient as the state-of-the-art WOLEDs employing multiple emissive materials.

Accomplishments: 1) demonstrating the most efficient excimer-based WOLEDs; 2) demonstrating the most efficient Pt-based deep blue phosphorescent OLEDs; 3) demonstrating great operational stability of Pt-based OLEDs, which is comparable to the state-of-the-art Ir-based OLEDs.

Market Impact: we are still on track to achieve the ultimate goal of project. The research progress has been reported in multiple high-profile publications and also presented in various research conferences.

Awards/Recognition: N/A

Project Integration and Collaboration

Project Integration: PI and one postdoc, two graduate students and one hourly undergraduate student are working on this project.

Partners, Subcontractors, and Collaborators: N/A

Communications: The research progress has been presented in various research conferences, including DOE solid state lighting R&D workshop, ACS and MRS national meetings, and international research conferences or workshops.

Next Steps and Future Plans

Next Steps and Future Plans: we will optimize the efficacy and performance of the excimer-based WOLEDs by employing the state-of-the-art transporting and blocking materials through collaboration with industrial partners.

REFERENCE

1) T.B. Fleetham, J. Ecton, Z. Wang, N. Bakkan, and J. Li*, “Single-Doped White Organic Light-Emitting Device with an External Quantum Efficiency Over 20%”, Adv. Mater., 25, 2573-2576 (2013).
2) X.C. Hang, T.B. Fleetham, E. Turner, J. Brooks and J. Li*, “Highly Efficient Blue-Emitting Cyclometalated Platinum(II) Complexes by Judicious Molecular Design”, Angew. Chem. Inter. Ed., 52, 6753-6756 (2013).
3) G. Li, T.B. Fleetham and J. Li*, “Stable and Efficient White OLEDs Employing a Single Emitter”, Adv. Mater., In Press.
4) E. Turner, N. Bakkan and J. Li*, “Cyclometalated Platinum Complexes with Luminescent Quantum Yields Approaching 100%,” Inorg. Chem., 52, 7344-7351 (2013).
5) N. Bakkan, Z. Wang and J. Li*, “High efficiency excimer-based white organic light emitting device using platinum complex,” J. Photon. for Energy, 2, 021203 (2012).

Project Budget

Project Budget: DOE share - $664,785, ASU share - $170,547

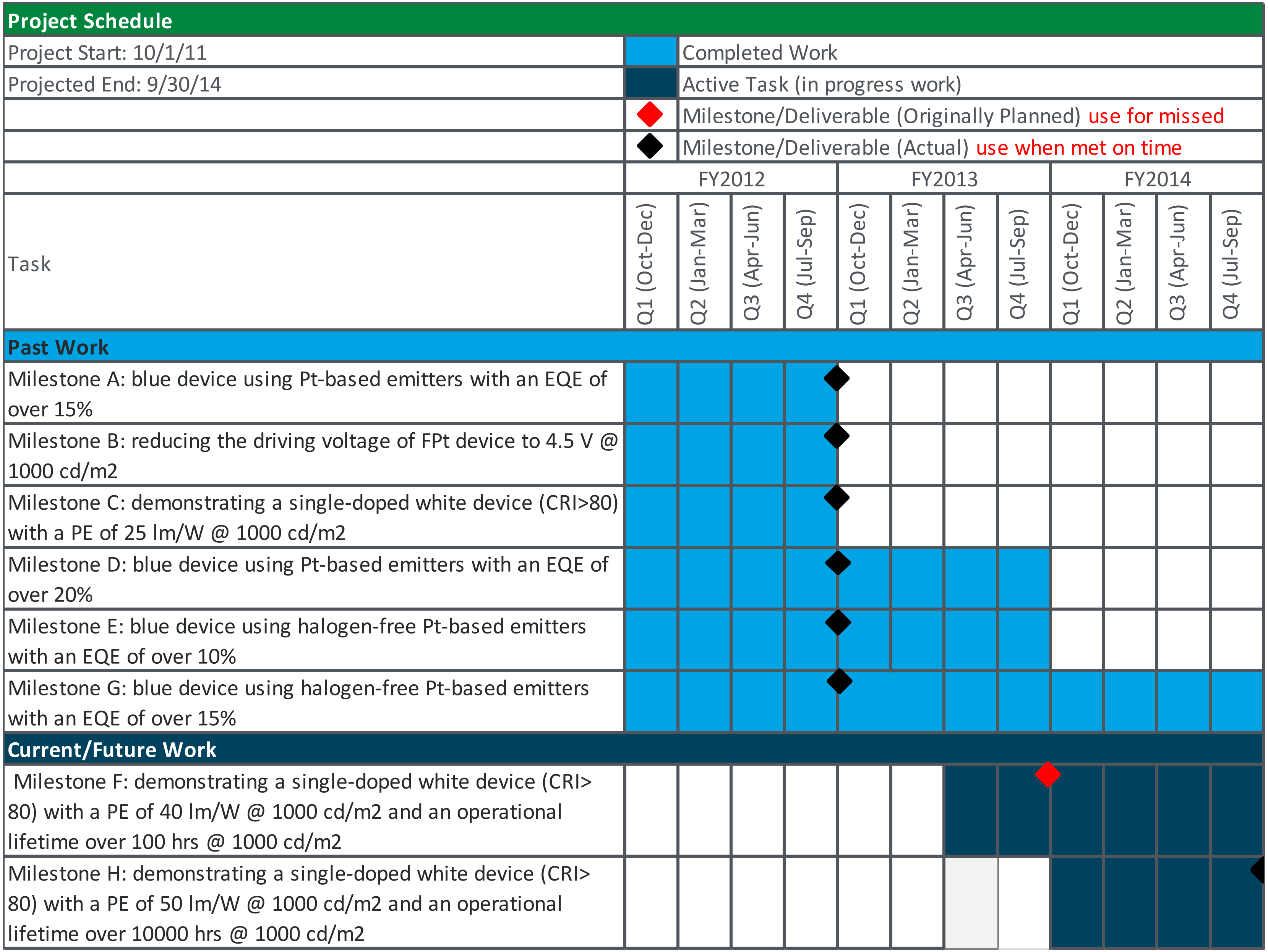
Variances: N/A

Cost to Date: over 95% budget has spent at the end of FY2013.

Additional Funding: N/A

Budget History					
FY2012– FY2013 (past)		FY2014 (current)		FY2015 – N/A (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$443k	$111k	$221k	$59k	$0	$0

Project Plan and Schedule



Project Schedule

Project Start: 10/1/11	🟦	Completed Work
Projected End: 9/30/14	⬛	Active Task (in progress work)
	♦	Milestone/Deliverable (Originally Planned) use for missed
	◆	Milestone/Deliverable (Actual) use when met on time

	FY2012				FY2013				FY2014			
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												
Milestone A: blue device using Pt-based emitters with an EQE of over 15%	🟦	🟦	🟦	🟦 ◆								
Milestone B: reducing the driving voltage of FPt device to 4.5 V @ 1000 cd/m2	🟦	🟦	🟦	🟦 ◆								
Milestone C: demonstrating a single-doped white device (CRI>80) with a PE of 25 lm/W @ 1000 cd/m2	🟦	🟦	🟦	🟦 ◆								
Milestone D: blue device using Pt-based emitters with an EQE of over 20%	🟦	🟦	🟦	🟦 ◆	🟦	🟦	🟦	🟦				
Milestone E: blue device using halogen-free Pt-based emitters with an EQE of over 10%	🟦	🟦	🟦	🟦 ◆	🟦	🟦	🟦	🟦				
Milestone G: blue device using halogen-free Pt-based emitters with an EQE of over 15%	🟦	🟦	🟦	🟦 ◆	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Current/Future Work												
Milestone F: demonstrating a single-doped white device (CRI> 80) with a PE of 40 lm/W @ 1000 cd/m2 and an operational lifetime over 100 hrs @ 1000 cd/m2							⬛	⬛ ♦	⬛	⬛	⬛	⬛
Milestone H: demonstrating a single-doped white device (CRI> 80) with a PE of 50 lm/W @ 1000 cd/m2 and an operational lifetime over 10000 hrs @ 1000 cd/m2									⬛	⬛	⬛	⬛ ◆