Hyperfluorescence
Materializing the Future of OLEDs

Kyulux

October 17, 2017

Junji Adachi

Display Innovation CHINA 2017/Beijing Summit
Company

- Founded March 9, 2015
- HQ in Fukuoka, Japan, U.S. Operations in Boston
- 35+ employees, and growing

Investors

- LG Display
- Samsung Display
- JDI Japan Display Inc.
- Kyushu University
- Harvard
- JOLED
- MS&AD MSIVC
- QEB
- Real Tech Venture
- JST
- DBJ
- NVCC
- SMBC VC
- Entrepreneur Aid
1. TADF
2. Hyperfluorescence™
3. Commercialization
Legacy OLED Emission (Gen. 1&2)

Fluorescence (1987~)
- Low Efficiency
- Low Cost
- Unlimited Design
- High color purity
- Enables Deep Blue

Phosphorescence (2000~)
- High Efficiency
- High Cost
- Limited Design
- Low color purity
- No Deep Blue

Conventional fluorescence and phosphorescence processes
- Intersystem crossing (ISC)
- 25% Fluorescence
- 75% Phosphorescence
- 25% Intersystem crossing (ISC)
- 100% Phosphorescence
TADF: Thermally Activated Delayed Fluorescence

- Enables **Deep Blue**
- High Efficiency (via Reverse Intersystem Crossing)
- Low Cost
- Low color purity
- Unlimited Design
- Aromatic Compounds

TADF: 3\textsuperscript{rd} Generation OLED Emission

\begin{align*}
\lambda & \propto \frac{H_{SO}}{E_{ST}} \\
\lambda & : \text{First-order mixing coefficient between singlet and triplet states} \\
H_{SO} & : \text{Spin-orbit coupling} \\
\Delta E_{ST} & : \text{Singlet-triplet energy gap}
\end{align*}

Fluorescence (1987~) \rightarrow \text{Phosphorescence (2000~)} \rightarrow \text{TADF (2012~)}

\text{Nature, 492, 234 (2012)}
1. TADF
2. Hyperfluorescence™
3. Commercialization
Wide emission spectrum is not suitable for display applications.

Narrow emission spectrum is required for display applications.
Hyperfluorescence™: A New Route for Triplet Harvesting

**TADF : Exciton Generation & Fluorescence: Emission**

![Diagram of TADF process]

- **Cathode (Metal)**
- **EIL**
- **ETL**
- **EML**
- **HTL**
- **HIL**
- **Anode (ITO)**
- **Glass Substrate**

**Emission**

**Fluorescence**

**Upconversion TADF**

**Host**

- **S₁**
- **T₁**

**Energy Labels**

- 2.30 eV
- 2.23 eV
- 1.14 eV
- 2.18 eV

**FRET**

Intermolecular exciton transfer from TADF to fluorescence

Hyperfluorescence™ combines the efficiency of TADF with the pure colors of fluorescent emitters.
Fluorescence vs. Hyperfluorescence™

**J – V**

Hyperfluorescence™ vs. Fluorescence

Current density (mA/cm²) vs. Voltage (V)

**J – L**

Hyperfluorescence™ vs. Fluorescence

Luminance (cd/m²) vs. Current density (mA/cm²)
Hyperfluorescence™
- High efficiency: $\text{EQE}_{\text{MAX}} = 20\%$

Fluorescence
- Low efficiency: $\text{EQE}_{\text{MAX}} = 5\%$

Emission
- Fluorescence
- Exciton Generation
  - TADF

Energy Label
- $S_0$ → $T_1$
- $S_1$ → $T_1$

Hyperfluorescence
- TADF: Excitons Generation
- FRET: Inter molecular excitons transfer
- Fluorescence: Emission

Energy Label
- $S_0$ → $T_1$
- $S_1$ → $T_1$

Kyulux
- Lighting up the world of display
Enhancement of Color Purity and Efficiency

Hyperfluorescence™: Improved Color Purity

TADF

Hyperfluorescence
Lighting up the world of display

FWMH = 89nm

FWMH = 32nm
Enhancement of Color Purity and Efficiency

Hyperfluorescence™: Higher Light Intensity

Hyperfluorescence: 519 nm, FWHM 32 nm, @10mA: cd/m² = 134.4, EQE = 18.1%
TADF: 531 nm, FWHM 89 nm, @10mA: cd/m² = 73.8, EQE = 18.6%

Luminance (cd/m²)/nm @10mA/cm²

Wavelength (nm)

400 500 600 700

0 50 100 150

Hyperfluorescence

TADF
Red Hyperfluorescence

TADF

Hyperfluorescence™: color tunable

Kyulux

Hyperfluorescence
Lighting up the world of display

TADF CIE (0.49 0.51)

HF CIE (0.66 0.34)
Red Hyperfluorescence

TADF

Hyperfluorescence™: color tunable

Kyulux

Hyperfluorescence
Lighting up the world of display

Graph showing intensity vs. wavelength for TADF and Hyperfluorescence with FWHM values.
Sky Blue TADF

TADF: stable sky blue emitter
Top Emission Display
## Optical Simulation of Top Emission Device

### Assumption
- **Emitting Material**
  - Phosphorescence: Ir(ppy)₃
  - TADF: 4CzIPN
  - Hyperfluorescence: TADF + Fluorescence
- **Exciton Generation Efficiency:** 100%

### Device Structure

<table>
<thead>
<tr>
<th>Device</th>
<th>Phosphorescence</th>
<th>TADF</th>
<th>Hyperfluorescence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device_1</td>
<td>150/7.5</td>
<td>10</td>
<td>105</td>
</tr>
<tr>
<td>Device_2</td>
<td>150/7.5</td>
<td>10</td>
<td>106</td>
</tr>
<tr>
<td>Device_3</td>
<td>150/7.5</td>
<td>10</td>
<td>107</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Device</th>
<th>Phosphorescence</th>
<th>TADF</th>
<th>Hyperfluorescence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device_1</td>
<td>150/7.5</td>
<td>10</td>
<td>111</td>
</tr>
<tr>
<td>Device_2</td>
<td>150/7.5</td>
<td>10</td>
<td>112</td>
</tr>
<tr>
<td>Device_3</td>
<td>150/7.5</td>
<td>10</td>
<td>113</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Device</th>
<th>Phosphorescence</th>
<th>TADF</th>
<th>Hyperfluorescence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device_1</td>
<td>150/7.5</td>
<td>10</td>
<td>108</td>
</tr>
<tr>
<td>Device_2</td>
<td>150/7.5</td>
<td>10</td>
<td>109</td>
</tr>
<tr>
<td>Device_3</td>
<td>150/7.5</td>
<td>10</td>
<td>110</td>
</tr>
</tbody>
</table>

Unit: nm
### Optical Simulation of Top Emission Device

#### Results

<table>
<thead>
<tr>
<th>Device</th>
<th>① Phos.</th>
<th>② TADF</th>
<th>③ Hyper.</th>
<th>Peak emission intensity $W/(m^2 \cdot nm \cdot sr)$</th>
<th>Peak Wavelength (nm)</th>
<th>FWHM (nm)</th>
<th>CIE(x,y)*</th>
<th>Current Efficiency (cd/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Device_1</strong></td>
<td>0.286</td>
<td>0.228</td>
<td>0.560</td>
<td>518</td>
<td>45</td>
<td>0.198</td>
<td>0.709</td>
<td>70.0</td>
</tr>
<tr>
<td><strong>Device_2</strong></td>
<td>0.292</td>
<td>0.234</td>
<td>0.569</td>
<td>518</td>
<td>39</td>
<td>0.177</td>
<td>0.723</td>
<td>62.3</td>
</tr>
<tr>
<td><strong>Device_3</strong></td>
<td>0.303</td>
<td>0.242</td>
<td>0.584</td>
<td>518</td>
<td>36</td>
<td>0.165</td>
<td>0.731</td>
<td>58.5</td>
</tr>
</tbody>
</table>

*BT. 2020 CIE $(x_G, y_G) = (0.170, 0.797)$*
Hyperfluorescence shows superior performance

<table>
<thead>
<tr>
<th>Device_3</th>
<th>Peak emission intensity W/(m²·nm·sr)</th>
<th>Peak Wavelength (nm)</th>
<th>FWHM (nm)</th>
<th>CIE(x,y)</th>
<th>Current Efficiency (cd/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>① Phos.</td>
<td>0.303 (1.0)</td>
<td>518</td>
<td>36 (1.0)</td>
<td>0.165</td>
<td>0.731 58.5 (1.0)</td>
</tr>
<tr>
<td>② TADF</td>
<td>0.242 (0.80)</td>
<td>531</td>
<td>42 (1.17)</td>
<td>0.228</td>
<td>0.705 61.8 (1.06)</td>
</tr>
<tr>
<td>③ Hyper.</td>
<td>0.584 (1.93)</td>
<td>523</td>
<td>24 (0.67)</td>
<td>0.164</td>
<td>0.772 85.5 (1.46)</td>
</tr>
</tbody>
</table>

**Spectrum**

1. **① Phos.**
   - Blue line: Top emission
   - Red line: PL

2. **② TADF**
   - Green line: Top emission
   - Black line: PL

3. **③ Hyper.**
   - Blue line: Top emission
   - Black line: PL
Hyperfluorescence: Far Superior to Phosphorescence

EL intensity W/(m²·nm·sr)

- Phos.
- TADF
- Hyper.

UHD TV

Wavelength (nm)
Hyperfluorescence shows superior performance

◆ Hyperfluorescence vs Phosphorescence

- Two times higher light intensity at the peak wavelength

- 2/3 tighter color spectrum

- Achieving the next generation UHDTV color space

- 1.5 times higher Current Efficiency
### Hyperfluorescence™ Summary

The Optimum Solution for OLED Displays

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost</th>
<th>Efficiency</th>
<th>Color Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescence</td>
<td>$</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Phosphorescence</td>
<td>$$$</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>TADF</td>
<td>$</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Hyperfluorescence™</td>
<td>$</td>
<td>Highest</td>
<td>High</td>
</tr>
</tbody>
</table>
1. TADF
2. Hyperfluorescence™
3. Commercialization
Virtual discovery of molecules by using AI
Software is already matching (or beating) humans

Driverless cars, AlphaGo, IBM’s Watson, speech & image recognition and generation, …

Is it time for molecular discovery?

- Predictive: Accurate Computational Chemistry (+ ML + heuristics).
- Fast and parallel
- Cheaper: Lower capital and operation costs.
- First Principles: Ideas out of the box.
- Automated: Frees operator to do more elevated tasks.
Device performance data feeds back to every level of development.
Library Generation

Millions of molecules

Quantum Simulation

Hundreds of top candidates

Machine Learning

Synthesis

AI based Material Screening

Material Design & Synthesis

Device Physics & Durability

Testing

Device fabrication

Feedback to focus and improve computational screening

Scaling

Manufacture

Workflow to accelerate material development
AI and machine learning permeate our R&D

**AI**
Deep neural networks, genetic algorithms, Bayesian optimization

**Molecules**
Design, synthesis characterization

**Proprietary data management toolset**

**Modeling**
DFT, MM

**EL Devices**
Design, fabrication, JV & LT testing

**Intellectual property**
More patents faster

**Products to market**
Better products faster

**Kyulux**
We set out in 2017 to be the first company with a commercial TADF OLED in any color and we are on track to achieve that.

<table>
<thead>
<tr>
<th>Yellow Hyperfluorescence™</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LT50</td>
<td>47,000 hours</td>
</tr>
<tr>
<td>EQE</td>
<td>14.0%</td>
</tr>
<tr>
<td>Color</td>
<td>CIE(x,y)</td>
</tr>
<tr>
<td>-------</td>
<td>--------------</td>
</tr>
<tr>
<td>Red</td>
<td>(0.64, 0.36)</td>
</tr>
<tr>
<td>Yellow</td>
<td>(0.46, 0.52)</td>
</tr>
<tr>
<td>Green</td>
<td>(0.28, 0.65)</td>
</tr>
</tbody>
</table>
and more
The world first product will be launched by the end of 2017

More than two times higher performance achieved

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Fluorescence</th>
<th>Hyperfluorescence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>128 x 64</td>
<td>128 x 64</td>
</tr>
<tr>
<td>Size (inches)</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>CIE</td>
<td>0.48, 0.49</td>
<td>0.47, 0.52</td>
</tr>
<tr>
<td>Lum. (cd/m²)</td>
<td>252</td>
<td>516</td>
</tr>
<tr>
<td>C.E. (cd/A)</td>
<td>21.5</td>
<td>41.1</td>
</tr>
<tr>
<td>E.Q.E. (%)</td>
<td>7.4</td>
<td>13.4</td>
</tr>
<tr>
<td>Power* (mW)</td>
<td>62</td>
<td>62</td>
</tr>
</tbody>
</table>

* All pixel on, Vcc @9V
Thank you

Materializing the Future of OLEDs