Achieving BT. 2020 Color Gamut – Quantum Dots vs. Lasers

March 2016 Bay Area SID Conference
24.03.2016

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Color is a Psychovisual Perception Detected By Our Eyes

1931 CIE xyY

Color matching functions

Cone Response Curves
CIE 1931 – “The Horseshoe Diagram”

Takeaways:

- Represents range of human color perception
- Spectral locus, represents pure, monochromatic light (i.e. saturated colors)
- Conversely, desaturated colors are in the center of the horseshoe with white in the middle
- RGB display primaries form vertices of color gamut triangle

Anatomy of a CIE Chromaticity Diagram

Source: Nanosys
Full HD
(Rec. 709)

33.5%
Increasing Resolution - Diminishing Returns

Trends in Smartphone Display Performance

Resolution reaching limits of HVS = Diminishing returns

Color gamut remains largely untapped (< 50%)

Source: Nanosys
Rec. 2020 is Happening Now: Creation, Delivery, Displays
What is Rec. 2020?

ITU-R Recommendation BT. 2020 ("Rec. 2020"):  
- Approved in 2012 by ITU-R  
- Standard for broadcast “UHD-TV”  
- Picture format/container for program interchange (same as Rec. 709)  
- Includes system colorimetry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opto-electronic transfer characteristics before non-linear pre-correction</td>
<td>Assumed linear$^{(1)}$</td>
</tr>
<tr>
<td>Chromaticity coordinates (CIE, 1931)</td>
<td>x</td>
</tr>
<tr>
<td>Red primary (R)</td>
<td>0.708</td>
</tr>
<tr>
<td>Green primary (G)</td>
<td>0.170</td>
</tr>
<tr>
<td>Blue primary (B)</td>
<td>0.131</td>
</tr>
<tr>
<td>Reference white (D65)</td>
<td>0.3127</td>
</tr>
</tbody>
</table>

$^{(1)}$ Picture information can be linearly indicated by the tristimulus values of RGB in the range of 0-1.  
$^{(2)}$ The colorimetric values of the picture information can be determined based on the reference RGB primaries and the reference white.
What is Rec. 2020 color?

Rec. 2020 RGB primaries:

- Based on NHK’s Super Hi-Vision
  - Preserves hue of primaries with smaller gamuts
  - Intended for RGB lasers
  - Covers ~100% of Pointer’s Gamut

- The widest TV color gamut standard with physical primaries
  - RGB primaries equivalent to monochromatic light (467nm, 532nm, 630nm)
  - No imaginary or negative RGB colors

Source: Masaoka et. al., IEEE Transactions on Broadcasting, Vol. 56, No. 4, 2010
How to Achieve Maximum Overlap of Rec. 2020?

• Full gamut can only be achieved in theory
  – What does BT. 2020 compliance mean?

• Primaries originally developed by NHK:
  – Covers all existing gamut standards and real object colors
  – Compatible with potential laser wavelengths
  – Located on loci of constant hue
Lasers provide best performance, but are not practical

- Full gamut nearly achieved

- Speckle and observer metamerism remain key technical challenges

- Prohibitive cost/complexity
How to Achieve Maximum Overlap of Rec. 2020?

- Assumes Ideal Color Filters and 25 nm FWHM QDs

- In practice, only ~93% gamut coverage achieved due to blue and green color filter leakage

- Getting to visually indistinguishable coverage of BT. 2020 requires covering ~97% of gamut
### Rec. 2020 Implementations in Common Display Technology

>90% Rec. 2020 requires either laser or CdSe backlight technology

<table>
<thead>
<tr>
<th>Display Technology</th>
<th>Category</th>
<th>Model</th>
<th>xy area</th>
<th>xy overlap</th>
<th>u'v' area</th>
<th>u'v' overlap</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdSe QD</td>
<td>Product</td>
<td>TCL 65H9700</td>
<td>81%</td>
<td>81%</td>
<td>84%</td>
<td>84%</td>
</tr>
<tr>
<td>InP QD</td>
<td>Product</td>
<td>Samsung SUHD UN55JS9000</td>
<td>68%</td>
<td>68%</td>
<td>76%</td>
<td>76%</td>
</tr>
<tr>
<td>RGph</td>
<td>Product</td>
<td>Auo RS65-B2</td>
<td>65%</td>
<td>65%</td>
<td>72%</td>
<td>72%</td>
</tr>
<tr>
<td>RGph + notch filter</td>
<td>Product</td>
<td>Samsung SUHD UN55JS7000FXZA</td>
<td>69%</td>
<td>69%</td>
<td>75%</td>
<td>76%</td>
</tr>
<tr>
<td>WLED</td>
<td>Product</td>
<td>Samsung UN55HU6950</td>
<td>54%</td>
<td>54%</td>
<td>58%</td>
<td>58%</td>
</tr>
<tr>
<td>BG-Rph</td>
<td>Product</td>
<td>Dell U2713HB MNT</td>
<td>78%</td>
<td>78%</td>
<td>81%</td>
<td>82%</td>
</tr>
<tr>
<td>WOLED</td>
<td>Product</td>
<td>LG 55EC9300</td>
<td>62%</td>
<td>62%</td>
<td>66%</td>
<td>66%</td>
</tr>
<tr>
<td>R laser, Cyan LED</td>
<td>Product</td>
<td>Philips 8900 series</td>
<td>87%</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>CdSe QD</td>
<td>Demo</td>
<td>LG 31MU97-B MNT (modified)</td>
<td>92%</td>
<td>93%</td>
<td>94%</td>
<td>94%</td>
</tr>
<tr>
<td>RGB Laser Backlight</td>
<td>Demo</td>
<td>Mitsubishi 50&quot; TV</td>
<td>98%</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Reduced green and blue color filter leakage is necessary for high-spec Rec. 2020 displays
**QDs and Rec. 2020**

**Benefits**
- Most efficient down conversion material
- Spectrally narrow primaries (FWHM ~25 nm)
- Leverages existing LCD supply chain
- Cost effective
- Tunable primaries

**Challenges**
- Potential for Observer Metameric Failure (OMF)
- Regulatory barrier (Cadmium)
- Color filter materials
- Customer awareness
- Good enough color

![Image of Quantum Dots and their applications](image-url)
**Available Laser Primary Options**

<table>
<thead>
<tr>
<th>Color</th>
<th>Wavelength (nm – FWHM)</th>
<th>Device Type</th>
<th>Watts per Device</th>
<th>Lumens Per watt</th>
<th>Lumens per Device</th>
<th>étendue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>650 - 1</td>
<td>Diode</td>
<td>~1</td>
<td>73</td>
<td>73</td>
<td>med</td>
</tr>
<tr>
<td>Red</td>
<td>638 - 1</td>
<td>Diode; Bar</td>
<td>≤ 8</td>
<td>131</td>
<td>1,048</td>
<td>high</td>
</tr>
<tr>
<td>Red</td>
<td>615 - 8</td>
<td>DPSS + OPO</td>
<td>10</td>
<td>301</td>
<td>3010</td>
<td>low</td>
</tr>
<tr>
<td>Green</td>
<td>550 – 0.1</td>
<td>VCSEL SHG</td>
<td>2</td>
<td>679</td>
<td>1358</td>
<td>med</td>
</tr>
<tr>
<td>Green</td>
<td>546 - 12</td>
<td>DPSS wide spectrum</td>
<td>20-40</td>
<td>671</td>
<td>&gt;20K</td>
<td>low</td>
</tr>
<tr>
<td>Green</td>
<td>532 – 0.1</td>
<td>DPSS; VCSEL; FL SHG</td>
<td>2-100</td>
<td>603</td>
<td>&gt;60K</td>
<td>range</td>
</tr>
<tr>
<td>Blue</td>
<td>525 - 2</td>
<td>Diode</td>
<td>1</td>
<td>542</td>
<td>542</td>
<td>med</td>
</tr>
<tr>
<td>Blue</td>
<td>462 - 2</td>
<td>Diode</td>
<td>1</td>
<td>50</td>
<td>50</td>
<td>med</td>
</tr>
<tr>
<td>Blue</td>
<td>445 - 2</td>
<td>Diode</td>
<td>3</td>
<td>20</td>
<td>60</td>
<td>med</td>
</tr>
</tbody>
</table>

**Benefits**
- Efficient, high powered light sources
- Near-monochromatic primaries (FWHM < 1 nm)
- Can be used in backlight or projection mode

**Challenges**
- Potential for Observer Metameric Failure (OMF)
- Speckle
- Étendue (i.e. beam quality)
- Available wavelengths
- Regulatory barrier (laser safety)
- Prohibitive cost
- Differential aging

**Source:** Bill Beck
Do You See What I See?

- Observer Metamerism: When two observers experience the same light source as different hues
- Potential for OMF increases with narrow RGB primary sources
  - Careful selection of peak wavelengths necessary to minimize this effect
How Does Observer Metamerism Occur?

A Representative Population of 1,000 Human Observers

- Genetic Differences
- Yellowing of lens with age
- Macular pigment spectral density

=> No standard observer!

Blue or purple?

## Assessment of Rec. 2020 Implementations

<table>
<thead>
<tr>
<th>Technology6</th>
<th>Model</th>
<th>Rec. 2020 xy Coverage [%]</th>
<th>Rec. 2020 u’v’ Coverage [%]</th>
<th>Relative Efficiency [%]</th>
<th>Mean DeltaE</th>
<th>Mean DeltaE + 3Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rec.2020 Primaries</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100%</td>
<td>5</td>
<td>24</td>
</tr>
<tr>
<td>Laser*</td>
<td>Avail. Tech.</td>
<td>98.0</td>
<td>97.2</td>
<td>93%</td>
<td>4.6</td>
<td>24</td>
</tr>
<tr>
<td>QD</td>
<td>TCL 55H9700 (modified)</td>
<td>88.8</td>
<td>90.0</td>
<td>85%</td>
<td>4.4</td>
<td>24</td>
</tr>
<tr>
<td>CFL</td>
<td>Apple LCD</td>
<td>55.9</td>
<td>55.3</td>
<td>113%</td>
<td>4.3</td>
<td>24</td>
</tr>
<tr>
<td>CRT</td>
<td>NTSC</td>
<td>46.0</td>
<td>47.7</td>
<td>101%</td>
<td>3.8</td>
<td>22</td>
</tr>
<tr>
<td>WOLED</td>
<td>LG 55EC9300</td>
<td>59.6</td>
<td>60.8</td>
<td>93%</td>
<td>3.8</td>
<td>22</td>
</tr>
<tr>
<td>RGB LED</td>
<td>HP DreamColor</td>
<td>83.6</td>
<td>87.9</td>
<td>102%</td>
<td>3.7</td>
<td>19</td>
</tr>
<tr>
<td>Y Phosphor LED</td>
<td>Samsung 55” UHD TV</td>
<td>52.0</td>
<td>54.7</td>
<td>112%</td>
<td>3.5</td>
<td>20</td>
</tr>
<tr>
<td>RG Phosphor LED</td>
<td>AUO 65”</td>
<td>58.5</td>
<td>62.6</td>
<td>83%</td>
<td>3.4</td>
<td>17</td>
</tr>
<tr>
<td>Optimal Monochromatic Primaries**</td>
<td>Simulation</td>
<td>95.1</td>
<td>91.6</td>
<td>120%</td>
<td>2.5</td>
<td>15</td>
</tr>
<tr>
<td>Optimal 30nm FWHM QD Primaries</td>
<td>Simulation</td>
<td>87.8</td>
<td>89.0</td>
<td>108%</td>
<td>2.8</td>
<td>15</td>
</tr>
</tbody>
</table>

*Available laser technology (462 nm, 532 nm, 638 nm) and FWHM=0.1nm
**Simulated monochromatic primaries (450 nm, 530 nm, and 620 nm) and FWHM=0.1 nm
RGB Primary Tunability Is A Key Advantage

Optimal Color Accuracy

Mean $\Delta E + 3\sigma$ (99.7% of pop.)

% Rec. 2020 xy coverage

% Relative system efficiency
Summary

• Rec. 2020 colorimetry establishes the widest TV color gamut, requiring monochromatic RGB primaries
• Rec. 2020 adoption is widespread and continues to grow
• 100% Rec. 2020 is not physically achievable => need to define compliance
• QDs and lasers can achieve >95% Rec. 2020 coverage
• Potential for OMF increases with narrower primaries => location matters
• Only QDs offer tunable primaries to optimize for gamut, OMF, and system efficiency

Thanks!