Light source technologies for next-generation lighting applications

2022 DOE/IES Solid-State Lighting Workshop

January 31, 2022

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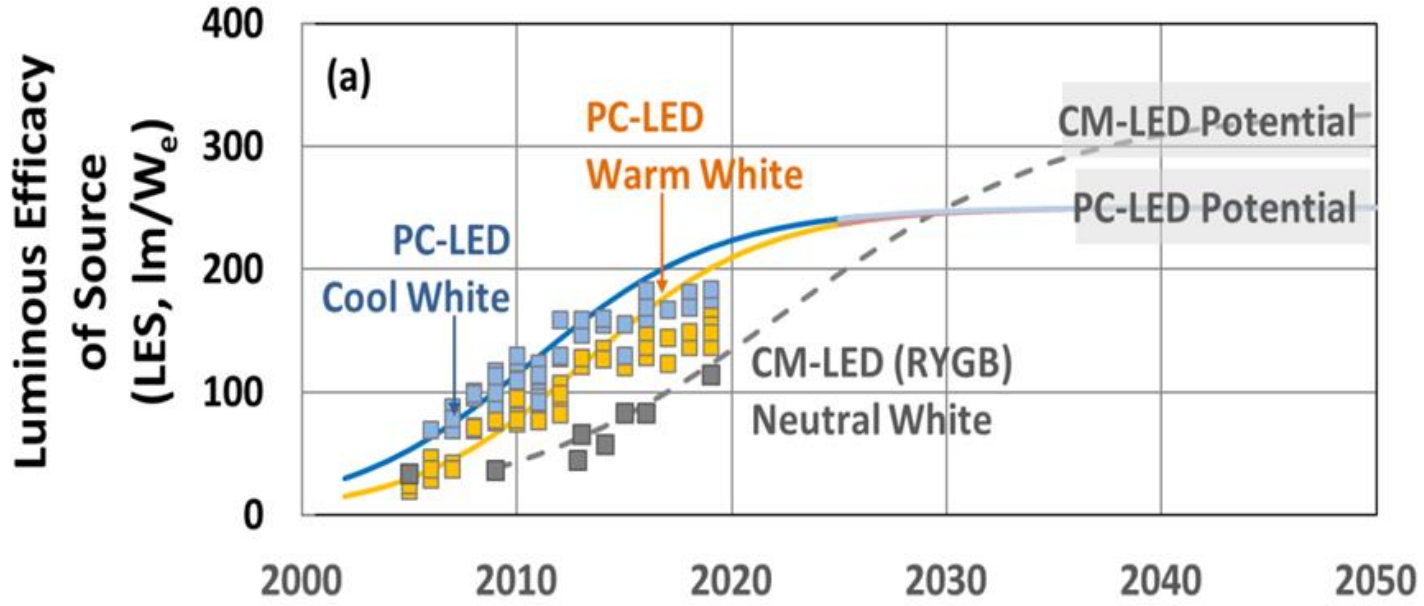
Outline

- Progress in lm/W and investment areas for the future

- Beyond source efficiency: Digital and Human centric lighting
  - Perspectives from Automotive lighting on digital light and enabling technology
  - Concepts for spatially adaptive and spectrally tunable lighting
  - Importance of source efficiency

- micro-LED technology and its potential for illumination

Tremendous progress in Luminous Efficacy

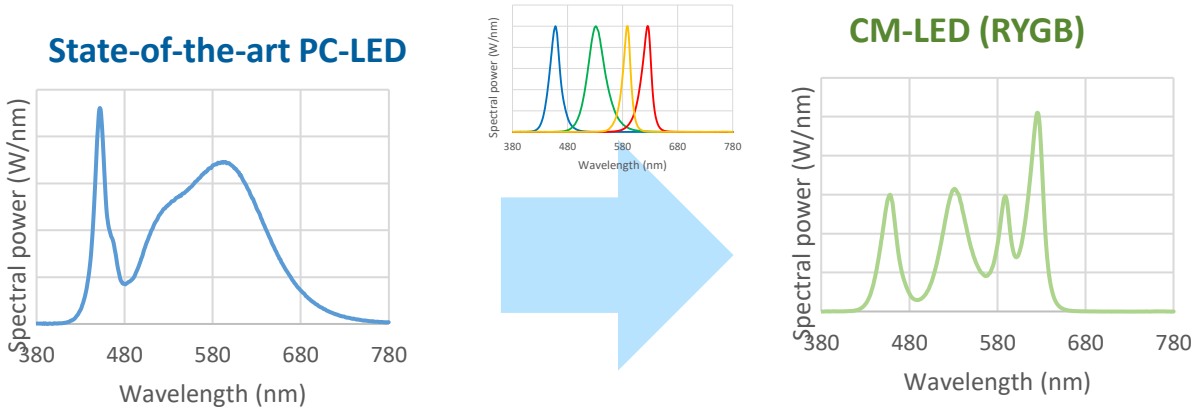


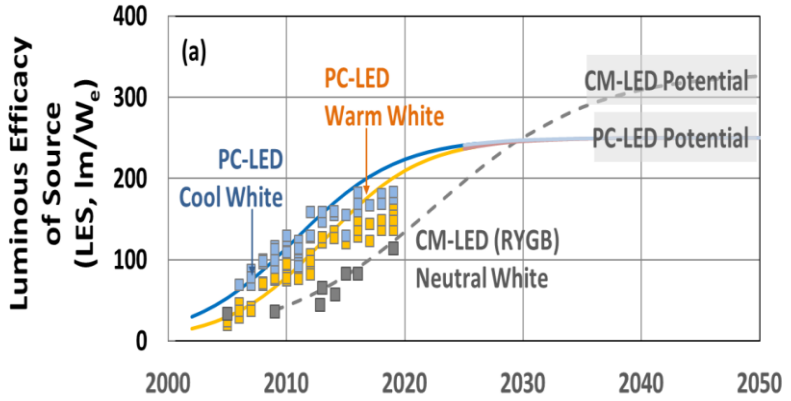
DOE BTO Lighting R&D Program, "2019 Lighting R&D Opportunities"
Operating conditions: 35 A/cm^2, 25 °C, 3000K warm white / 5700K cool white

- New technology like narrow-FWHM phosphors and high efficiency direct colors are needed for next significant steps in lm/W for illumination

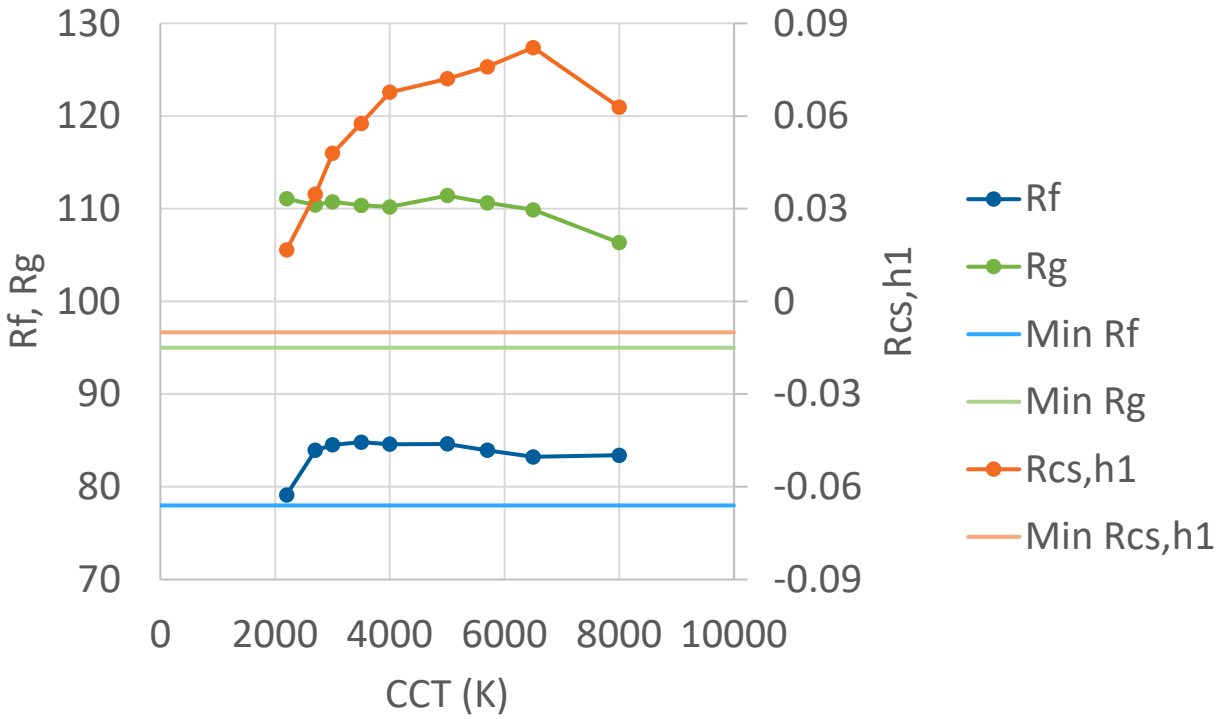
Color Mixed LED – CM LED

- CM-LED – **using four direct colors (Red, Amber, Green, Blue)** to create white light
- Next level in luminous efficacy
- No longer trade-off between full gamut and efficiency
- Excellent color quality for vast majority of lighting applications





CM-LED meets TM-30 Annex E Preference Level 1



Design Intent
(The desired effect of color rendition on the illuminated environment)

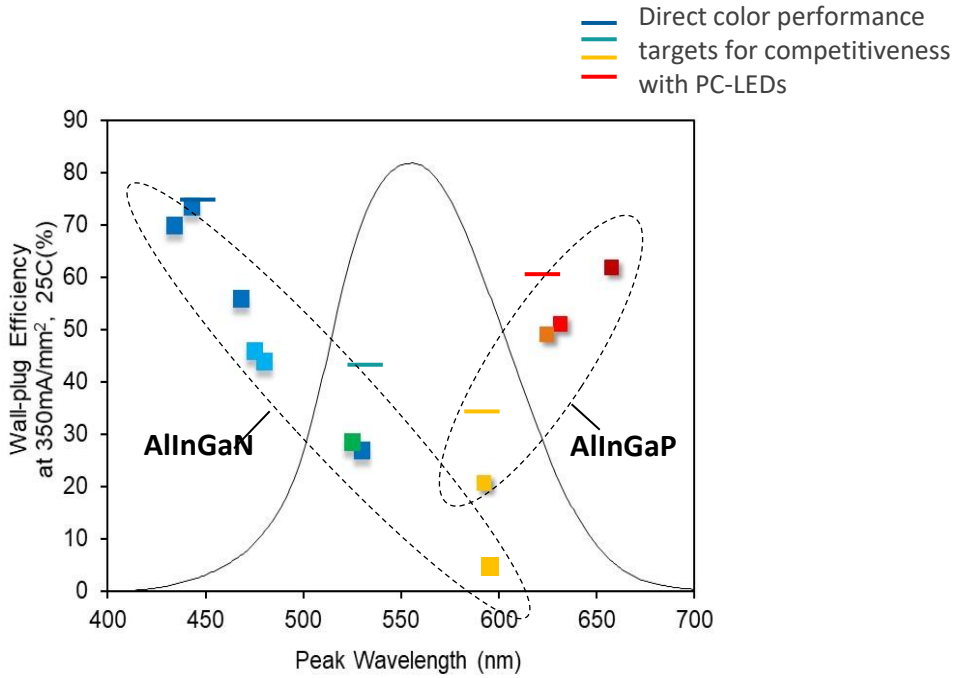
Priority Level (The balance between allowing for tradeoffs and increasing the likelihood of meeting the design intent)		Preference (P)	Vividness (V)	Fidelity (F)
	1	P1: $R_f \geq 78$, $R_g \geq 95$, $-1\% \leq R_{cs,h1} \leq 15\%$	V1: $R_g \geq 118$, $R_{cs,h1} \geq 15\%$	F1: $R_f \geq 95$
	2	P2: $R_f \geq 75$, $R_g \geq 92$, $-7\% \leq R_{cs,h1} \leq 19\%$	V2: $R_g \geq 110$, $R_{cs,h1} \geq 6\%$	F2: $R_f \geq 90$, $R_{f,h1} \geq 90$
	3	P3: $R_f \geq 70$, $R_g \geq 89$, $-12\% \leq R_{cs,h1} \leq 23\%$	V3: $R_g \geq 100$, $R_{cs,h1} \geq 0\%$	F3: $R_f \geq 85$, $R_{f,h1} \geq 85$

CM-LEDs are approaching PC-LEDs in efficacy

… and can go much further

3000K/90CRI efficacy with state-of-the-art LED performance

J (A/cm²)	Tj (°C)	PC-LED efficacy (lm/W)	CM-LED efficacy (lm/W)
10	25 °C	167	145
20	55 °C	134	109
35	85 °C	124	79
70	85 °C	83	48

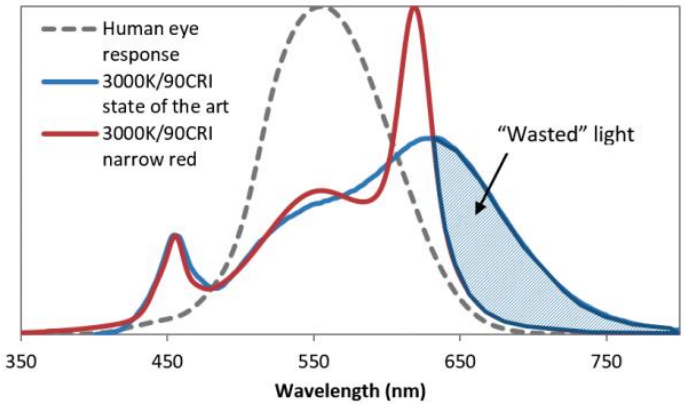


Need **technology research and development** for CM-LEDs

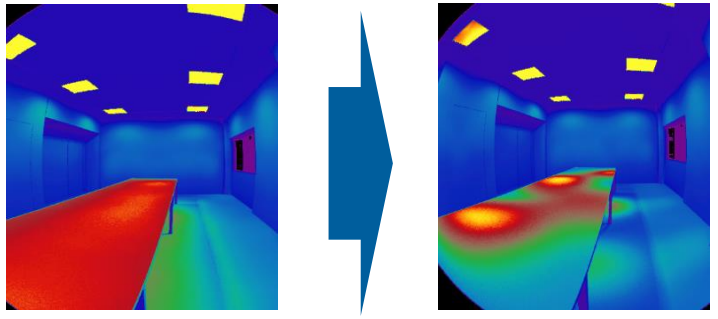
- Green / yellow / amber emitter materials
  - AlInGaP is the choice for red, amber
  - InGaN for blue, green
- Package and system integration for CM-LED illumination

Phosphor downconversion

- Phosphor Converted (PC) LEDs is the dominant technology in SSL
- PC-LEDs are expected to be a key SSL technology even as CM-LED approach surpasses in lm/W
- Despite significant developments, there is not a sufficient set of phosphor materials to maximize lm/W for most applications and color rendering requirements and minimize the trade-off between efficacy and color rendering
- Development of “narrow red” and “narrow green” phosphors needs to continue



Opportunities Beyond Source Luminous Efficacy

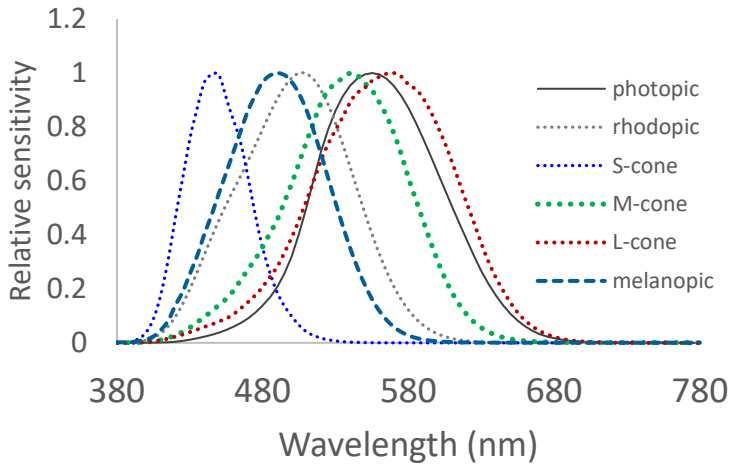


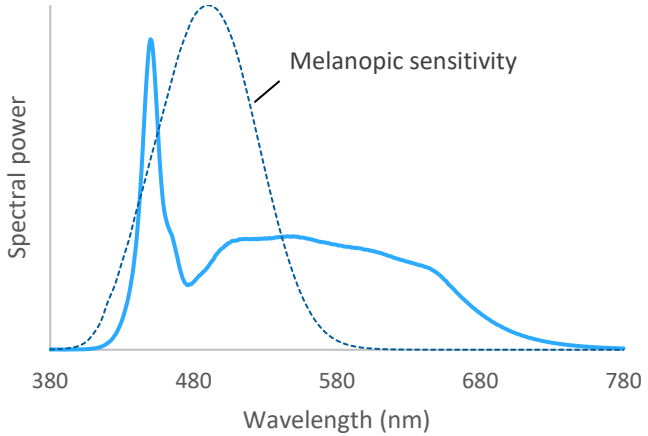
- Use light where it is needed
  - Leverage digital light source technology emerging in automotive and display fields
  - Custom, dynamic light distributions, indoors and outdoors

- Human health and wellbeing
  - Circadian lighting
    - CCT, melanopic content tuning with time of day
    - Challenge: maximizing source efficiency through the tuning range

  - Healthy daytime indoor lighting requires higher light levels
    - Indoor light levels are fraction of recommended
    - Challenge: reduce power consumption at higher lighting levels
    - Light source concepts to avoid overlighting

Melanopic light exposure during the day





- **Recommended MEDI levels from IWCNP 2**
- > 250 lx daytime
- < 10 lx evening
- < 1 lx nighttime (sleep)

- Exposure depends on light spectrum and intensity at ocular level

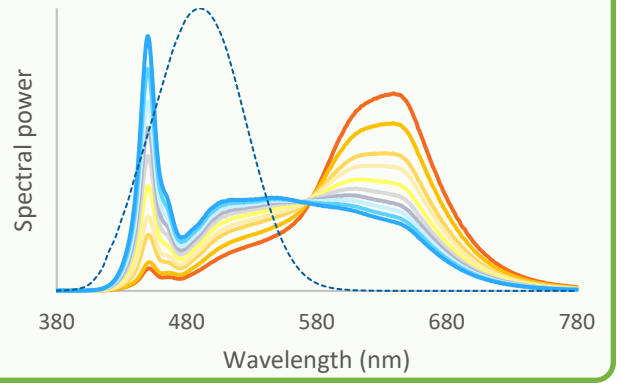
- Significant variations in lux levels indoors, ranging by an order of magnitude
- Most of us do not get enough exposure to light indoors

- Controlling spectrum and light levels can deliver needed EDI

Spectrum

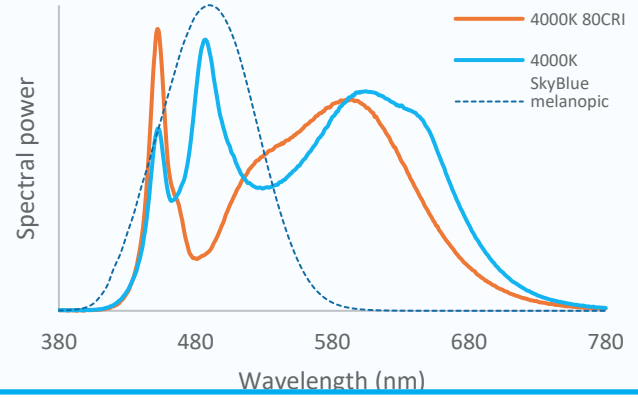
Tunable white LED modules enable up to ~3x dynamic range in melanopic EDI over practical CCT range

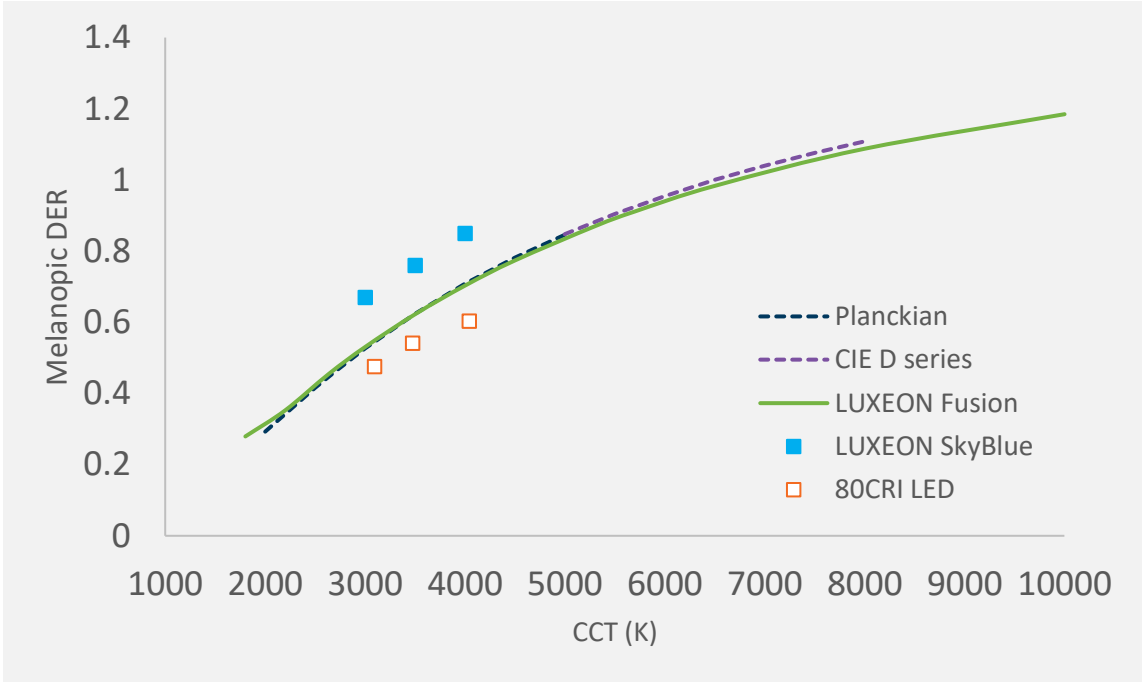
LUXEON Fusion



Engineered spectrum LEDs offer an additional ~1.5x dynamic range in melanopic EDI at constant CCT

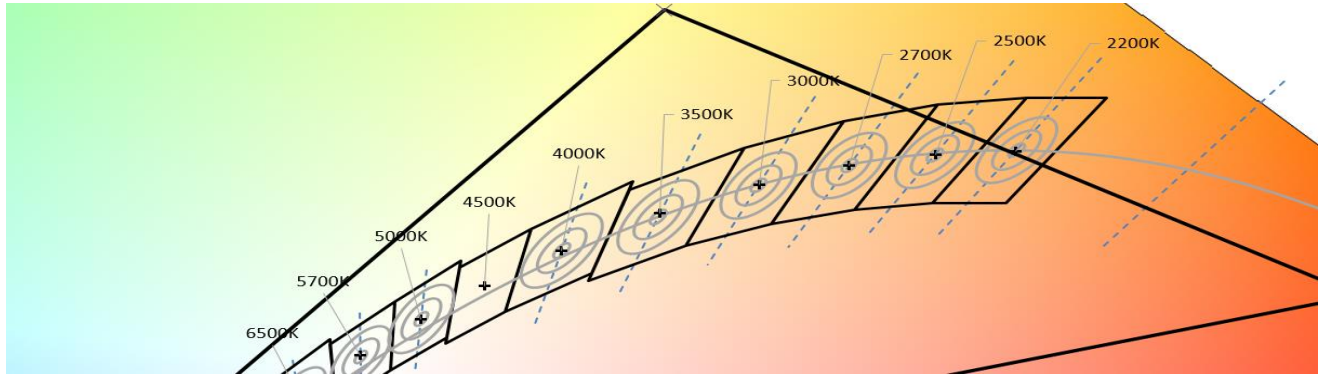
LUXEON SkyBlue





Dynamic White Light: LUXEON Fusion

Improved color quality and human centric lighting performance



	6500K	5000K	4000K	3500K	3000K	2700K	2400K	2100K	1800K
CRI	>90	>90	>90	>90	>90	>90	>80	>80	>80
Light Output	100%	100%	100%	100%	100%	94%		Dim to Warm	
lm/W	100%	100%	100%	100%	100%	94%			

PERFORMANCE

- Constant light output between 2,700K and > 6,500K with virtually no impact on efficacy
- Track Planckian or off Planckian within 0.001 Du'v'
- >90 CRI, typical 94CRI above 3000K, R9>50
- Allow dim to warm to 1800K
- Color consistency: 3McA, <2McA possible

Digital light sources for dynamic indoor spaces

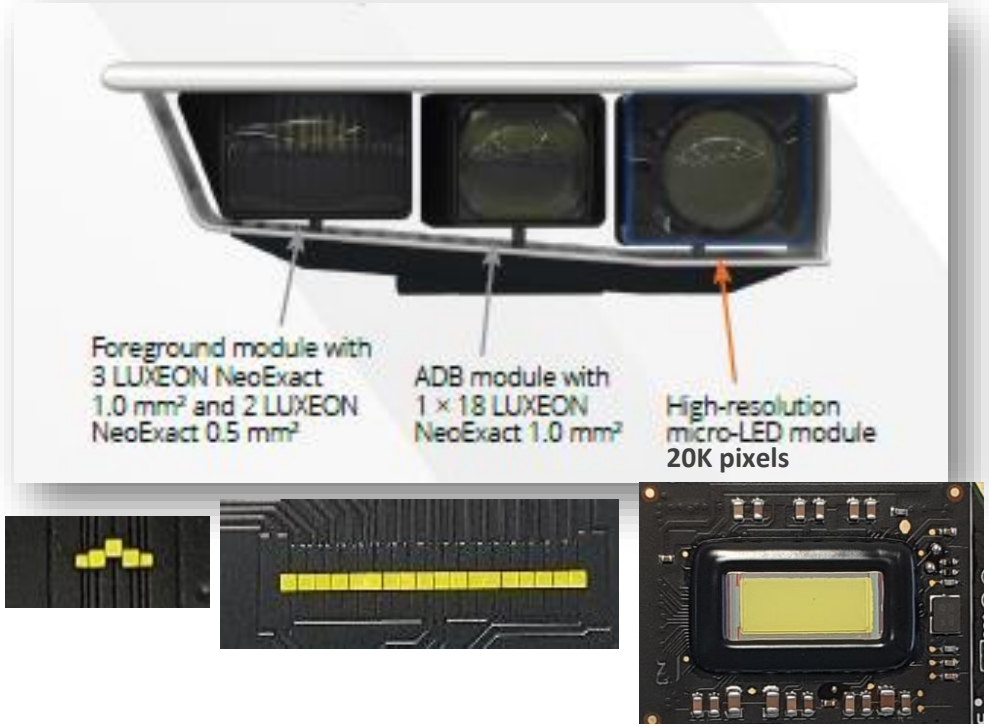
Many variables

- People (# and position)
- Activities
- Space layout
- Time of day

Benefits of digital light source

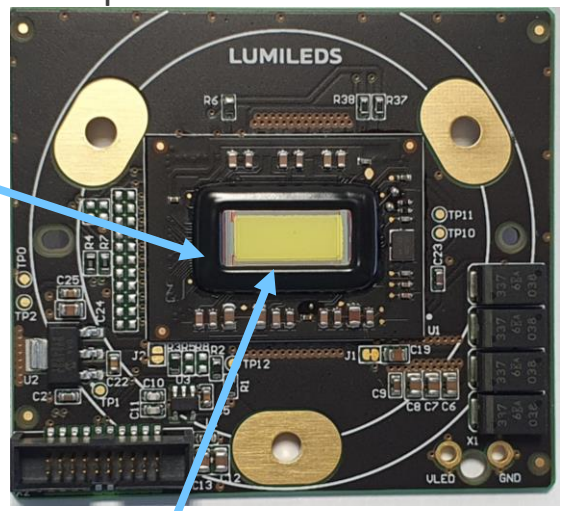
- Optimized visual performance for every situation
- Optimized melanopic light dosage throughout the day
- Energy savings

Digital light sources are transforming automotive headlighting…

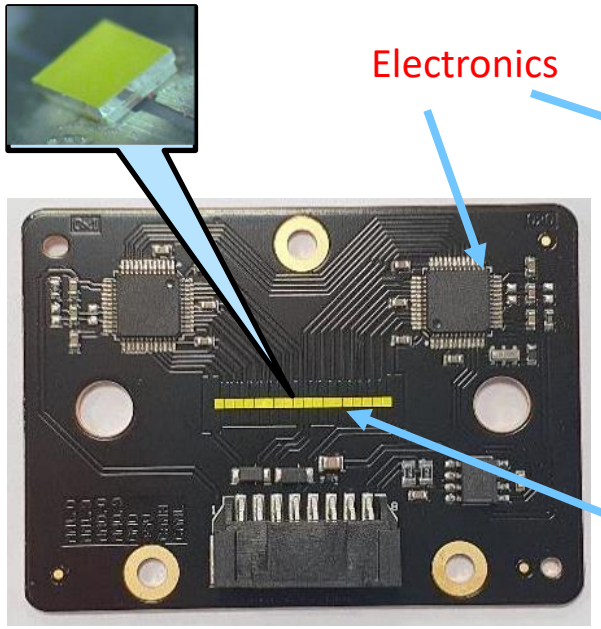


Digital light sources are transforming automotive headlighting…

2. LED/CMOS Hybrid
on L2 board
20K pixels



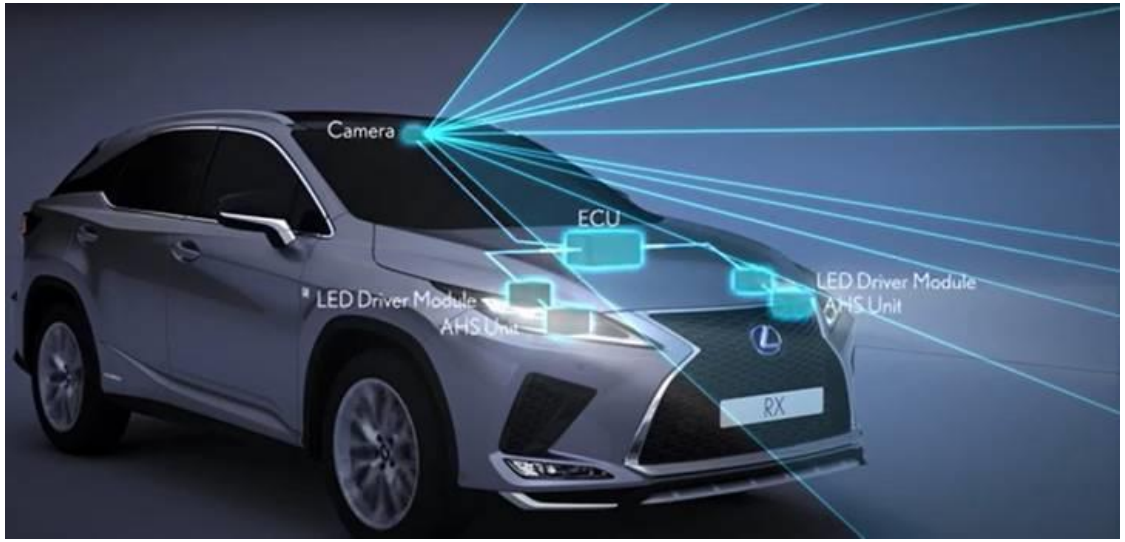
Electronics



Segmented individually addressable light sources discrete or monolithic

1. Pixelated sources, discrete emitters
Integrated on L2 boards with driver electronics

Sensor (camera) information processing and light source control is done via an ECU



…what benefits can they bring to general lighting applications?

Digital light source technology: from automotive to illumination applications

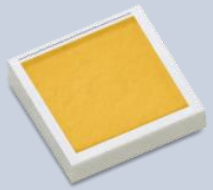
Automotive
Application characteristics

- Contrast over efficacy
- Color quality: cool white, color discrimination
- Complex lens system OK
- Image quality over efficiency
- Single application
- High pixel count, CMOS hybridization

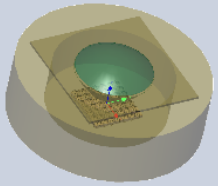
Illumination
Application characteristics

- Efficacy over contrast
- Color quality: full CCT range, high color fidelity, color tuning
- Single lens preferred
- Efficiency over image quality
- Scalable in area and flux
- Modular driver ICs, deep dimming and color control

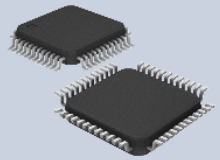
Illumination
Required technology elements



- High luminance LEDs optimized for efficacy with illumination-grade phosphors



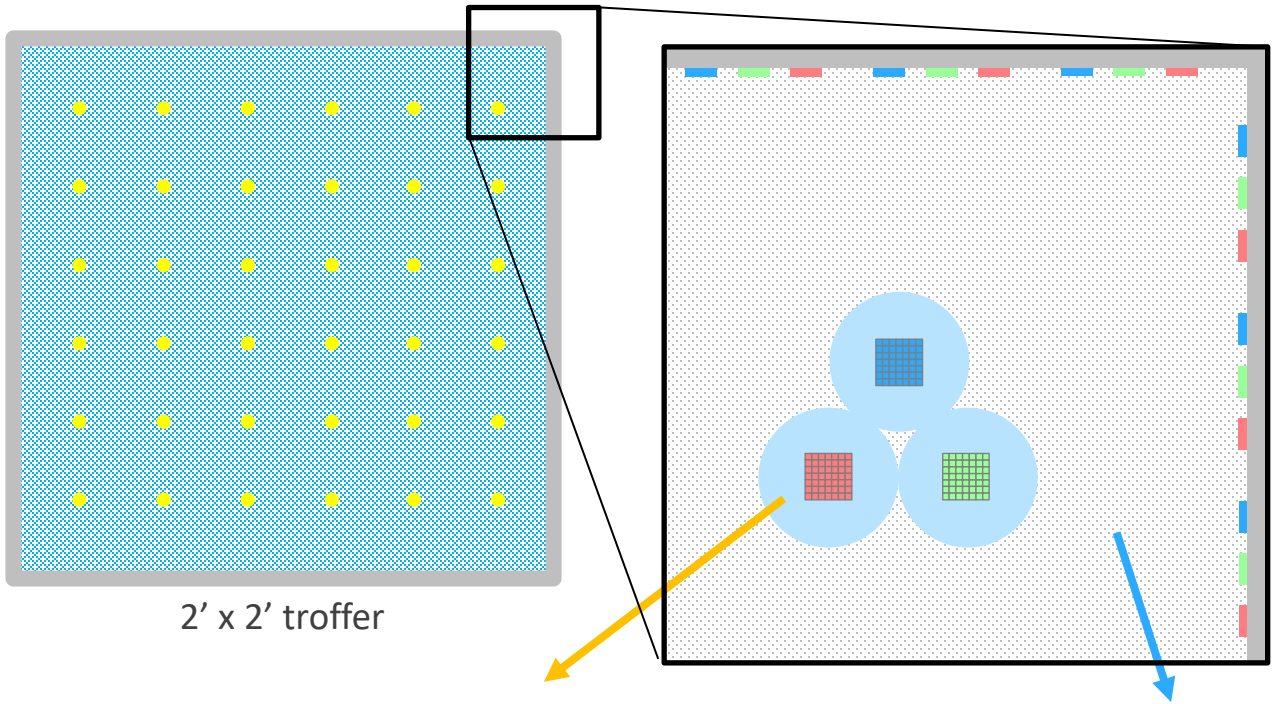
- Scalable optical designs with illumination projection optics



- Driver and PCB technology for routing and addressing of individual pixels

Full-function dynamic light source

Tuning over wide range of beam angles and spectra



2’ x 2’ troffer

“Spatially Adaptive Tunable Lighting Control System with Expanded Wellness and Energy Saving Benefits”

DE-EE0009167

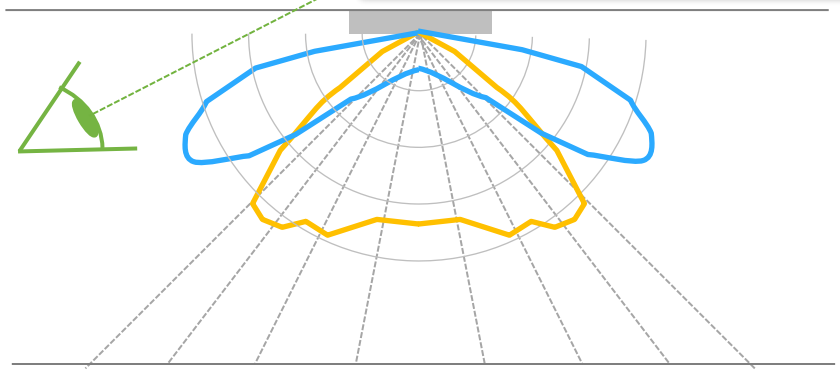
Rensselaer Polytechnic Institute, Lumileds, HKS

Recommended MEDI levels from IWCNP 2

> 250 lx daytime

< 10 lx evening

< 1 lx nighttime (sleep)



Projection optics for low/medium angles

- Precise beam control with pixelated source
- Stitch light engines for full coverage of horizontal surface (desk/floor)

Light guide optics for high angles

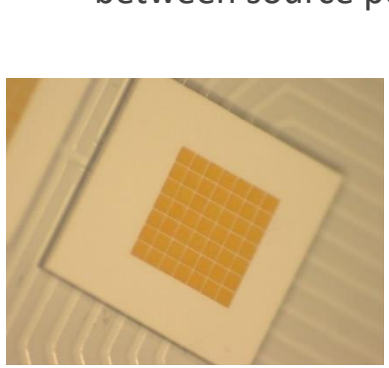
- Complement to cover full beam angle range
- Enable vertical illuminance
- Mitigate glare from projection optics

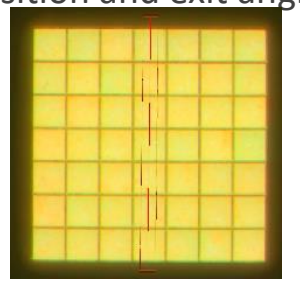
Both sections fully CCT tunable

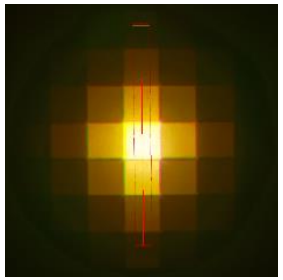
A digital source for special and spectral tuning

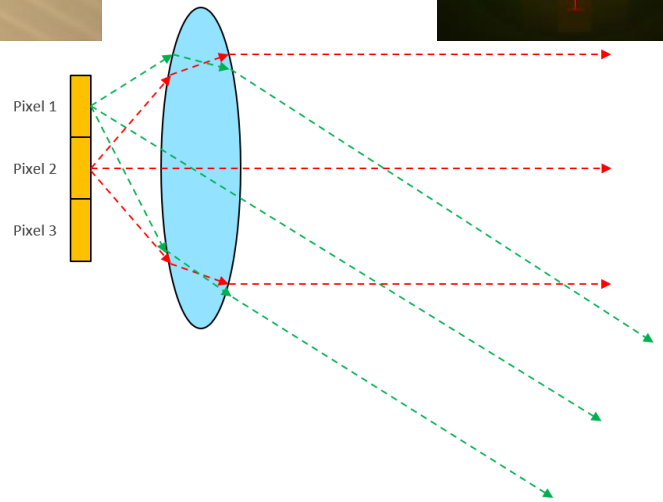
Digital source

- LED source consisting of multiple pixels or segments that can be individually and digitally addressed
- Projection lens or other optic with defined correlation between source position and exit angle



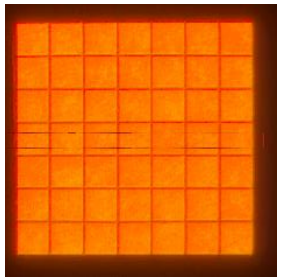


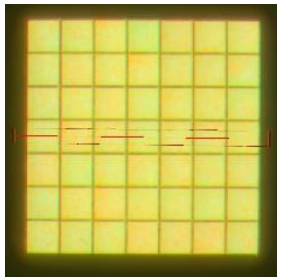


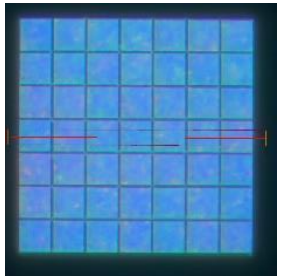


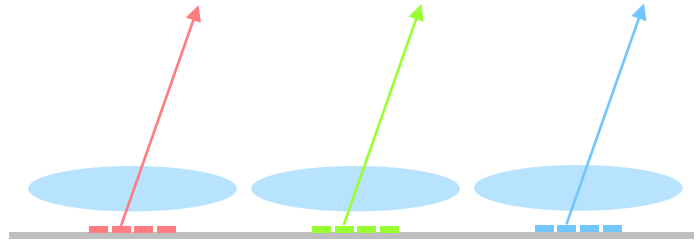
Color / spectral tuning

- Color mixing at source level not practical with projection optics
- Mix colors in the far field, but beware of artefacts

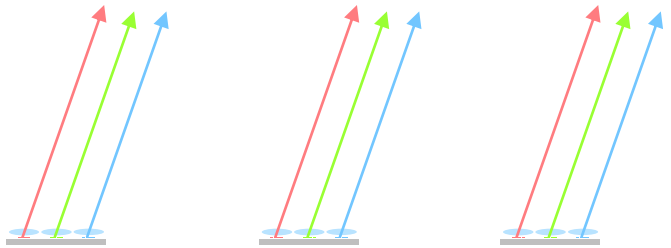








Place primaries close together to minimize visible color separation

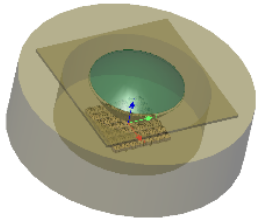
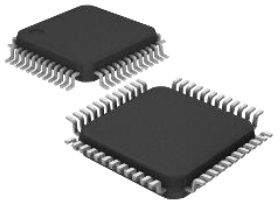


Use multiple primary clusters to soften shadows

Digital light source application extend to all areas of lighting

Digital light source technology

Essential technology building blocks are available now and will further improve over time

Digital light source applications

Initial applications based on conventional lighting performance criteria

- Energy consumption
- Beam definition
- Illuminance uniformity
- Glare control




Advanced applications with value beyond traditional scope of lighting

- Human health and wellbeing
- Building space flexibility
- Aesthetics / artistic design
- Streamlined supply chain
- Accelerated building construction

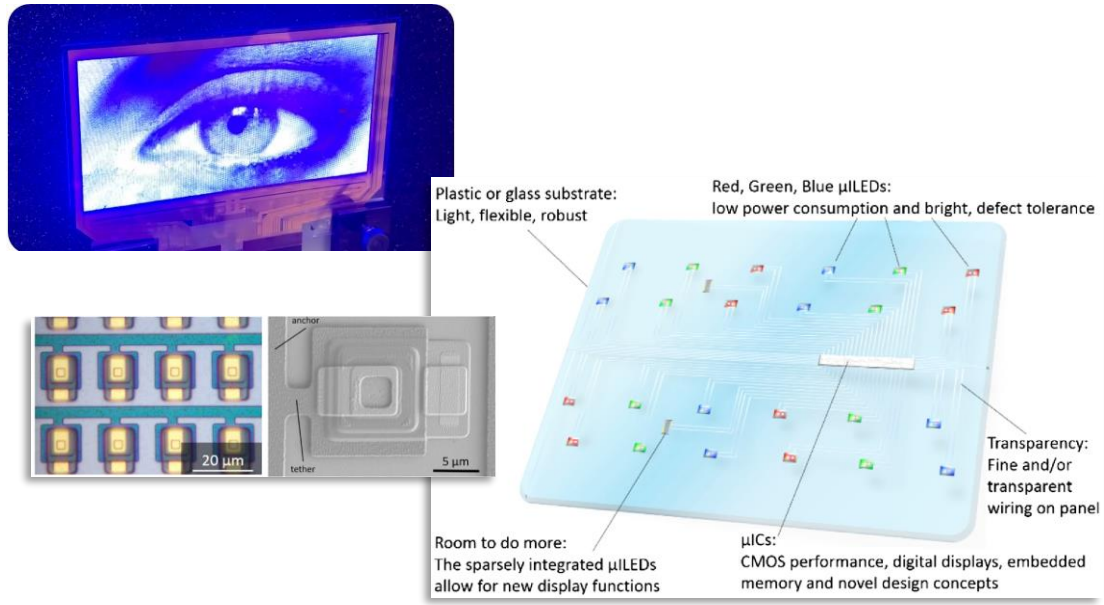
How will you use digital light sources in your next product or lighting design?

Micro-LED Displays:

- Micro-LEDs will bring significant benefits over incumbent display technologies:
  - reduction in energy consumption
  - greater brightness and high dynamic range
  - customization
  - integration of sensors and other electronic and optical functions into the display and many others

Micro-LED Display technology:

- Micro-LED size varies from single to tens of microns. The small size significantly lowers LED efficiency compared to that of mm-size LEDs.
- EQE targets are in 10-40% range depending on color/ application: not directly beneficial for meeting SSL lm/W roadmap
- Architectural elements of panel-level assembly's with driver ICs and CMOS hybrids for HMD leverage packaging/hybridization technologies from silicon industries
- The adaption of micro-LED displays will result in significant shifts in LED technology, manufacturing and will require considerable investment
- Realizing indirect benefits from micro-LED display adoption for general lighting (digital light, focus on direct color emission) will require dedicated effort and investment



Christopher A. Bower, et al, "Emissive displays with transfer-printed assemblies of 8 µm × 15 µm inorganic light-emitting diodes," Photon. Res. 5, A23-A29 (2017)

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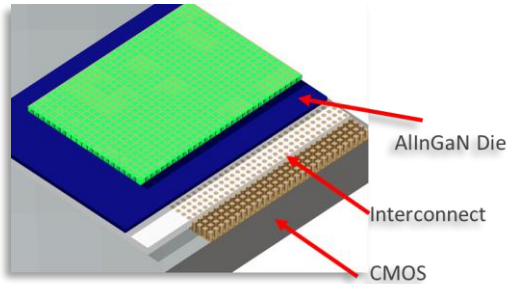

Conclusion

- Investment in LED technology needs to continue to reach next level in source luminous efficacy
- Digital lighting will bring the benefits
  - Optimized visual performance for every situation
  - Optimized melanopic light dosage throughout the day
  - Energy savings
- Digital light is feasible: adoption is happening in automotive applications
- Micro-LED displays is a significant area of investment and development. Realizing indirect benefits for general lighting from micro-LED display adoption will require dedicated effort and investment