LED Technology for Improved Application Efficacy

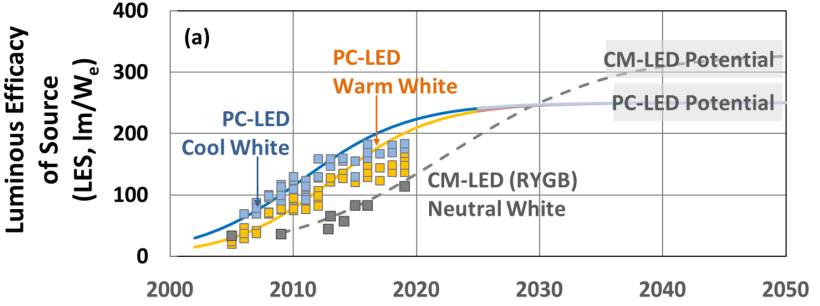
DOE/IES Lighting R&D Workshop | San Diego, CA

Wouter Soer

January 28, 2020

LUMILEDS

Source 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

Tracked pc-LEDs at fixed operating conditions

~140 lm/W to ~180 lm/W

Useful progress metric for LED technology, but…

- Operating conditions vary widely
- Luminous flux is not always the most important metric

State-of-the-art pc-LEDs at actual operating conditions

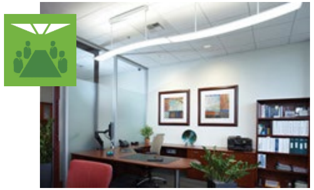
<100 lm/W to >210 lm/W

Each of these LEDs is optimized for system efficacy in their respective application

Breadth of SSL applications requires wide range of LED capabilities

Differentiation in luminance, spectrum, radiation profile, package size

High Efficacy → High Luminance



Indoor Area Lighting
- Mid/Low Power

Outdoor/Stadium
- High Power
- CSP

Spotlights
- HD CoB
- High Power
- CSP

Downlights
- COB
- Mid Power

High Bay & Low Bay
- High Power
- Mid Power

Specialty
- High Power
- CSP

Colors

Architectural
- Color
- High Power

Horticulture
- Color
- Mid Power
- High Power

Application efficacy

Light Source Efficiency ✖ Optical Delivery Efficiency ✖ Spectral Efficiency ✖ Intensity Effectiveness

DOE BTO Lighting R&D Program, "2019 Lighting R&D Opportunities"

Delivery efficiency and intensity effectiveness

- lm (on target) / W
- lm (on target and meeting a desired illuminance distribution) / W
- m^2 (with illuminance above threshold) / W

Spectral efficiency

- Equivalent melanopic efficacy lm / W
- Object-reflected luminous efficacy lm / W
- Photon efficacy (PAR or other range) µmol/s / W = µmol/J

Operational efficiency

- Office: Productive person-hours / kWh
- Vertical farm: Crop fresh weight / kWh
- Retail: Store revenue / kWh

Resource efficiency

- … / lifecycle cost
- … / lifecycle carbon emission

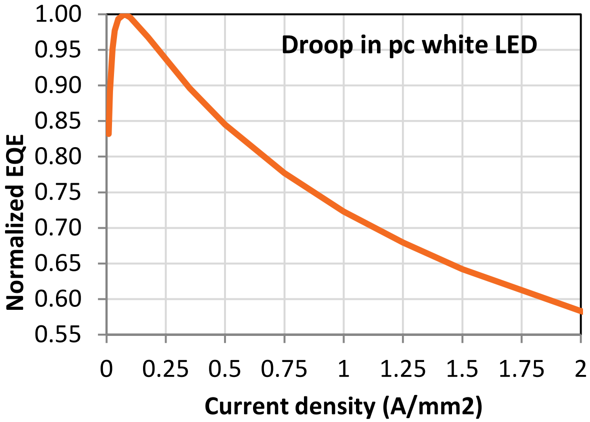
High luminance sources are a key element of directional lighting

Luminance $L_v = d^2\phi / (dS\ d\Omega \cos\theta)$

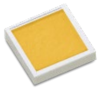
Luminous flux from a given **source area** within a given **solid angle**

Lower source efficiency …

due to droop (epi/die/phosphor) and package design



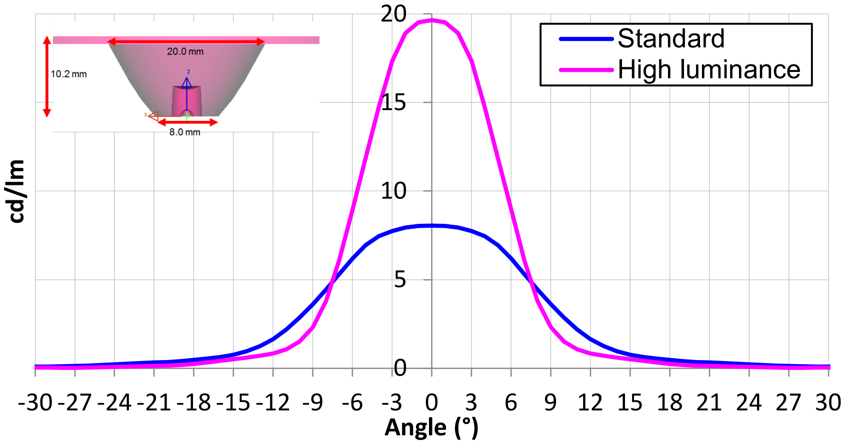
Standard



High luminance

… but higher optical delivery efficiency

through better optical control in secondary optics



Next step in optical delivery efficiency: dynamic directional lighting

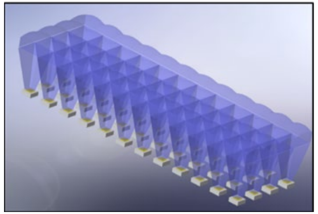
Dynamic light distributions for automotive headlighting

Beam shaping with LED arrays

Currently on the road

Discrete LED module of 3 rows of 84 high-luminance LEDs

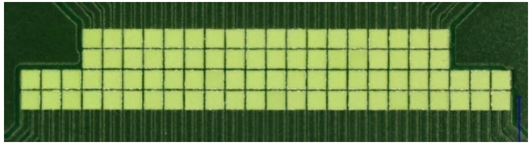
Close coupled precollimation optics to create homogeneous headlighting

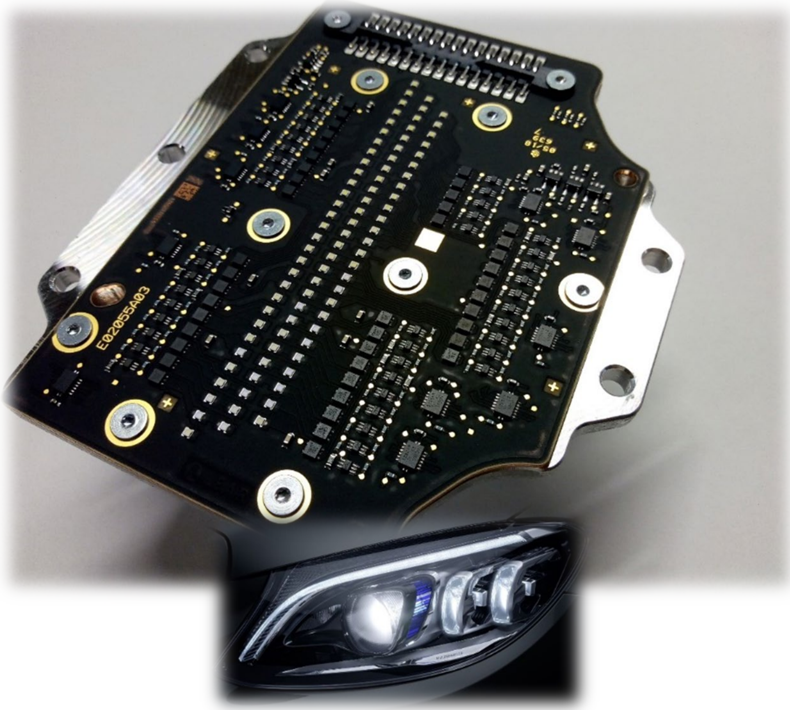


Towards digital headlighting

Densely-packed array eliminating need for precollimation

Enables higher pixel count with more functionality





Dynamic light distributions in general illumination

Configurable spaces
Shop windows and floors
Open plan offices
Exhibition spaces

Scene setting
Hospitality
Human centric lighting
Multi-purpose rooms

Functionality and performance
Adjust to occupants / activity / traffic
Improved uniformity
Reduced glare

Example: area lighting

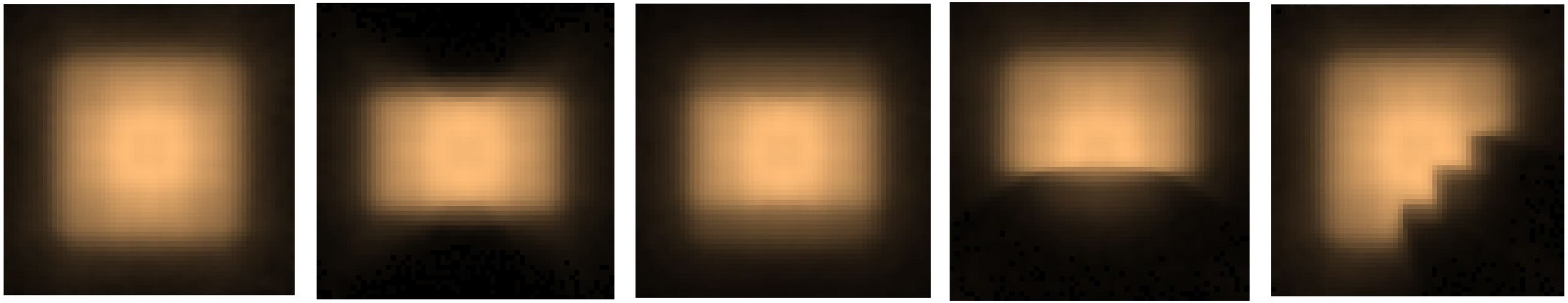
LED technology enables excellent illuminance uniformity

- IES RP-20-98 recommends <15:1-20:1 max/min
- 3:1 max/min is considered very good
- State of the art LED fixtures can achieve <2:1 max/min with optimal positioning

… but results vary in practical applications

- Retrofit with existing poles
- Physical space constraints
- Availability of desired fixture
- Installation difficulties
- Budget

Improved delivery and intensity efficiency with pixelated LED sources



Modeled illuminance on plane receiver using example lens with 5x5 array of LED elements
Lens design can be optimized to achieve desired balance between beam angle, spatial resolution and optical efficiency

Key benefits

- Reduce # optics SKUs
- Flexible commissioning adjusting to local conditions (luminaire spacing, obstacles)
- Create high resolution map for advanced controls

 | February 19, 2020

Digital directional lighting: from automotive to illumination applications

Automotive
Application characteristics

High pixel count

Contrast over efficacy

Color quality:
cool white, color discrimination

Narrow beam

Glare reduction by beam pixelation

Single application

Illumination
Application characteristics

Medium pixel count

Efficacy over contrast

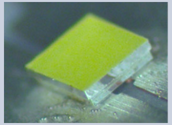
Color quality:
full CCT range, high color fidelity, color tuning

Wide beam

Glare reduction by luminance uniformity

Scalable in area and flux

Illumination
Required technology elements



High luminance mini-LED device architecture optimized for efficacy

Phosphor integration technology

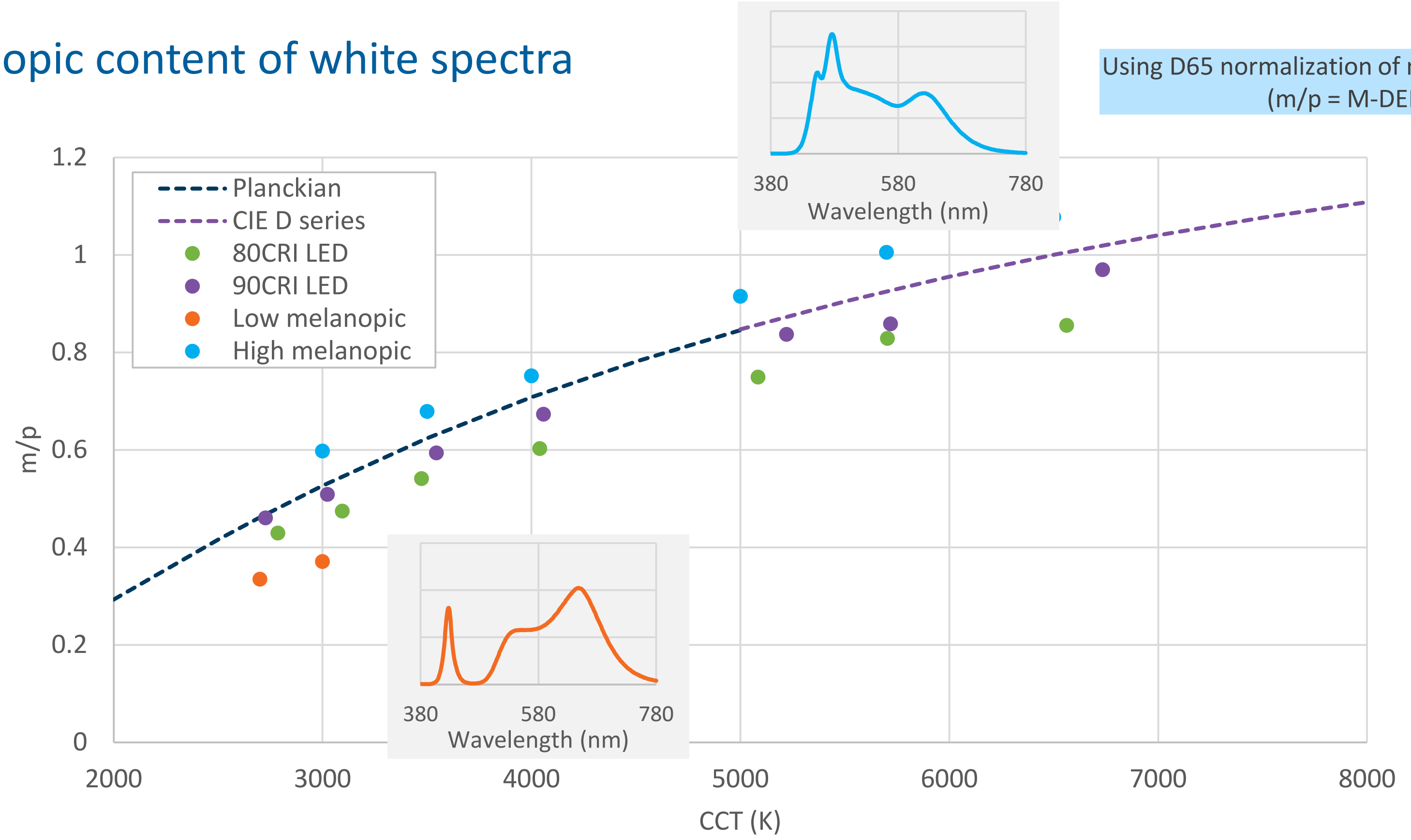
Scalable optical designs:

Refractive and lightguide optics

Sparse clusters of densely packed mini-LEDs

Melanopic content of white spectra

Using D65 normalization of m/p per CIE S026
(m/p = M-DER)



Spectrum-engineered LEDs can increase or reduce melanopic spectral content vs. broadband reference spectra

Efficacy of high melanopic lighting solutions

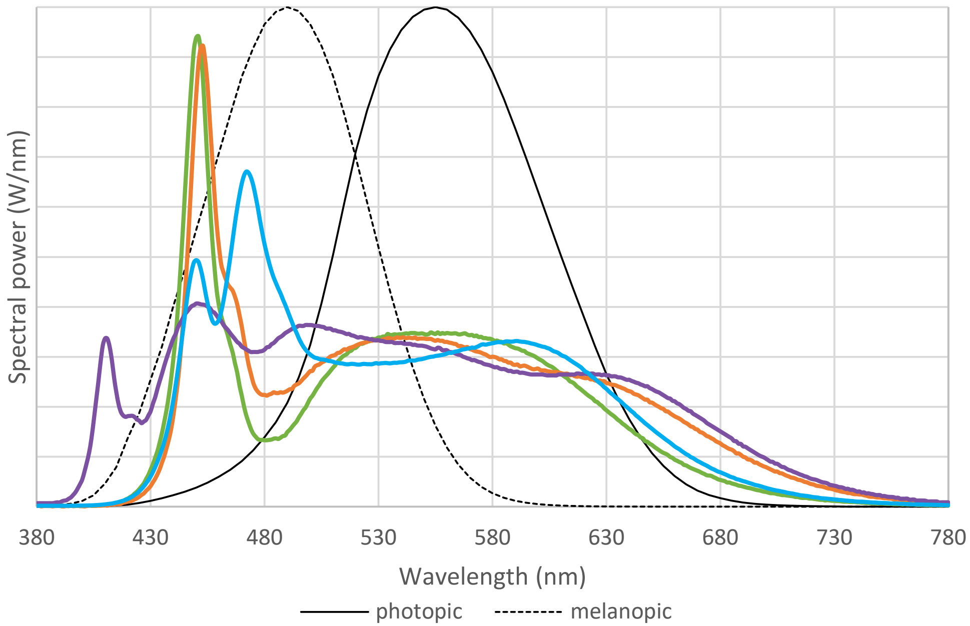
Higher m/p ratio does not equal higher melanopic efficacy

Application efficacy metric

Melanopic equivalent daylight luminous efficacy

= Luminous efficacy * m/p

At 6500K	m/p	η_v (lm/W)	$\eta^{D65}_{v,m}$ (lm/W)
CRI80	0.86	175	150
CRI90	0.97	152	147
Full spectrum CRI95	1.00	~120	~120
Cyan-enhanced CRI80	1.09	~130	~142



M-EDI targets are more efficiently realized with royal-blue pumped pc-LEDs (fixed or tunable CCT)

Efficacy of low melanopic lighting solutions

Optimizing for 3 quantities: luminous flux (↑), melanopic flux (↓), input power (↓)

Application efficacy metric / figure of merit

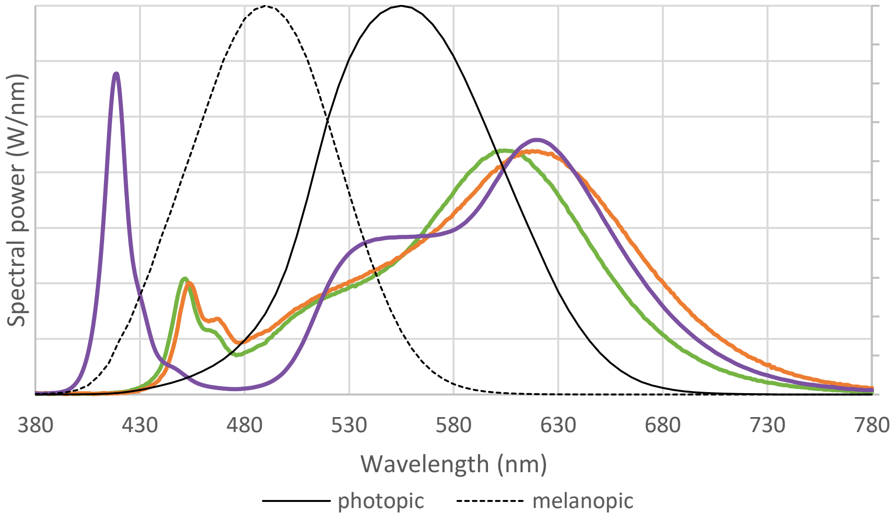
Power conversion efficiency * (photopic spectral weighting)^a / (melanopic spectral weighting)^b

= PCE * p^a / m^b

a=1, b=1: equal weighting

a=2, b=1: luminous efficacy * p/m

At 2700K	m/p	η_v (lm/W)	FOM a=1	FOM a=2
CRI80	0.43	161	1.12	374
CRI90	0.46	135	1.00	292
Low melanopic	0.32	123	1.33	383



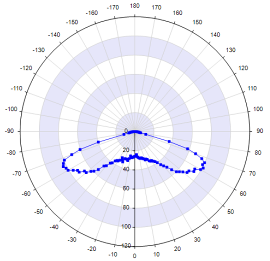
Violet-pumped low melanopic LEDs can be an efficient solution depending on prioritization of key parameters

Integral lighting design for maximum application efficacy

Combining multiple light distributions and spectra

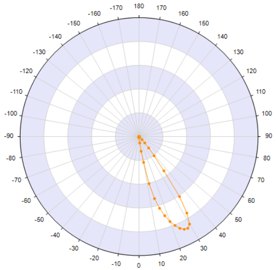
Example design targets

- Vertical melanopic equivalent daylight illuminance of 500 lx early in the day
- Horizontal illuminance of 1000 lx on task surfaces



Diffuse blue-rich light

- High CCT (10,000K) diffuse low luminance source with batwing distribution
- Limit peak intensity setting to time window with maximum circadian efficacy



Directional white light

- Neutral CCT (4000K) directional source
- Tailor light distribution to space layout (task surfaces, corridors)
- Dynamically adapt light distribution to occupancy and daylight

Ultimate freedom in lighting design

Vision: light any surface from **any angle** with **any intensity** and **any spectrum**

Paradigm change in lighting design

From: selecting and positioning fixed building blocks to create a single lighting distribution

To: developing algorithms to create an infinite number of lighting distributions depending on application needs – no energy wasted!

Digitally controlled pixelated LED sources can help realize this vision

Requires collaborative effort in LED device development, electronics integration, optics, control development and lighting design

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