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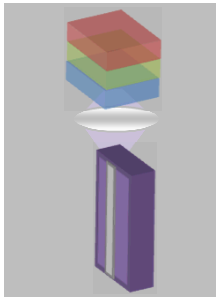

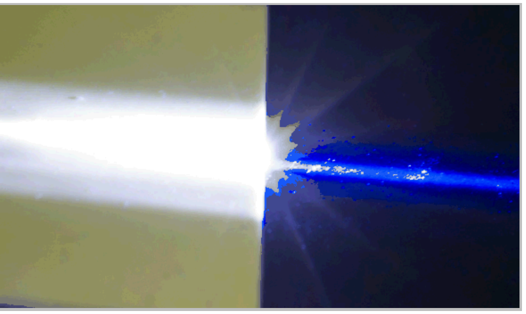

Prospects for laser diodes in solid-state lighting

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Sandia National Laboratories

Exceptional service in the national interest

Meijo University, 21th April 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

SSLS EFRC

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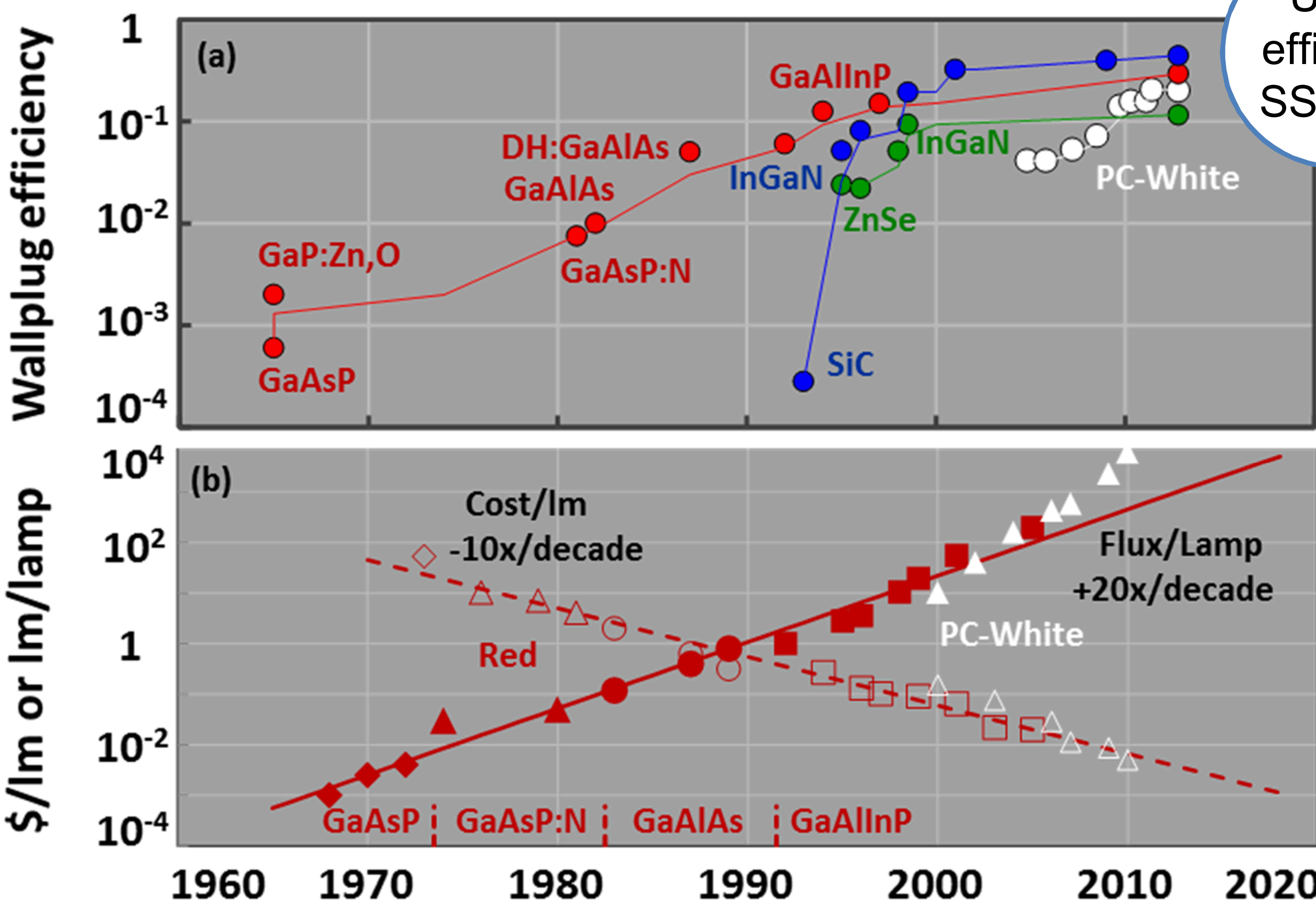
Outline

- Efficiency comparison and projections for blue LEDs and laser diodes (LDs).
- White light from LDs.
- LD system benefits.

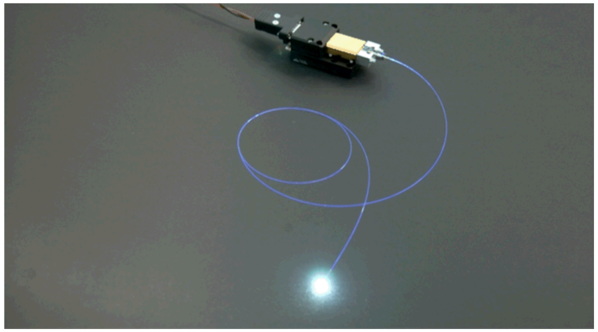
Efficiency comparison and projections of LEDs and LDs

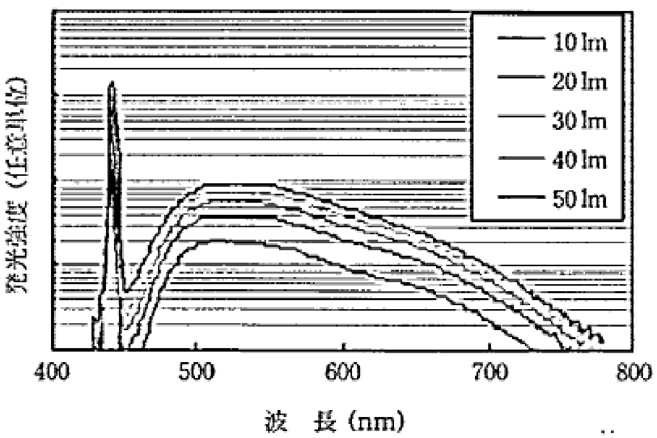
LED efficiency and cost over time



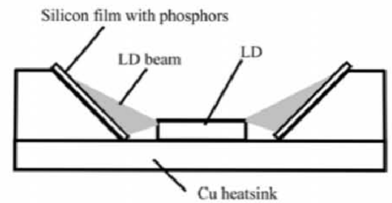
Ultra-efficient SSL ???

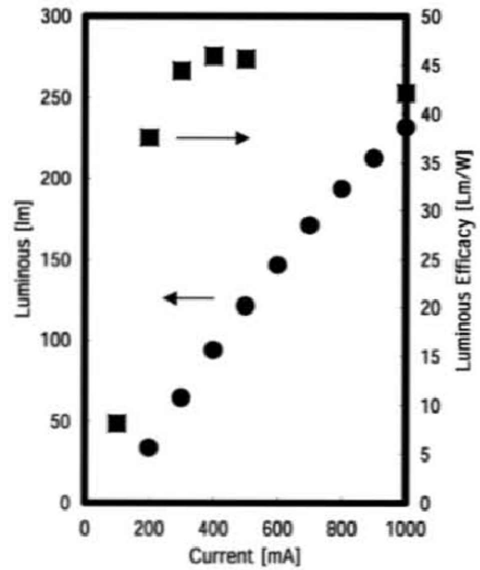
Early work on lasers and white light



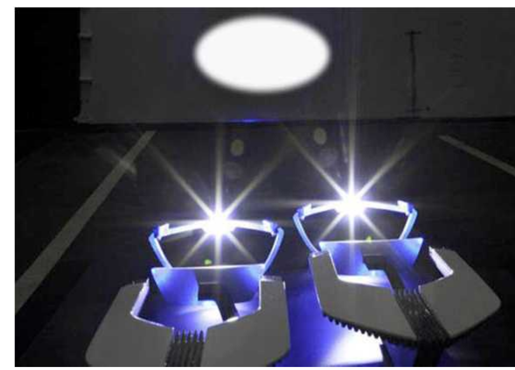


Y. Narukawa, et al., *"Development of high-luminance white light source using GaN-based light emitting devices*", Oyo Butsuri, 74 (2005).





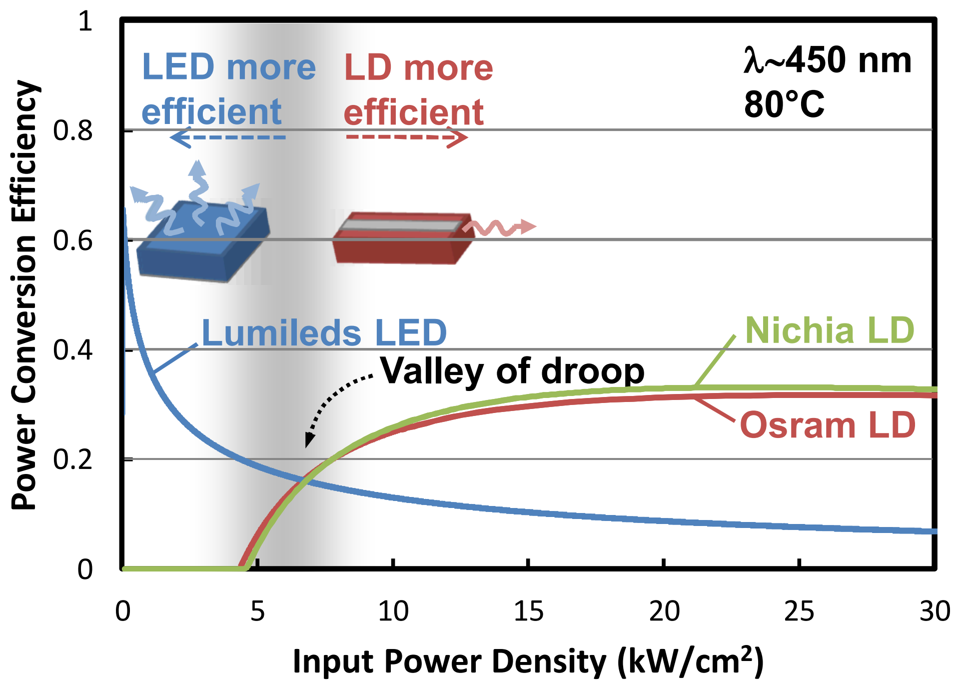
S. Saito, et al., *"High Efficiency GaN Laser Diodes for Solid-State Lighting*", IEEE Inter. Semi. Laser Conf. (2008).



BMW headlight, i8, (2012).

Is there a good reason to use LDs for SSL?

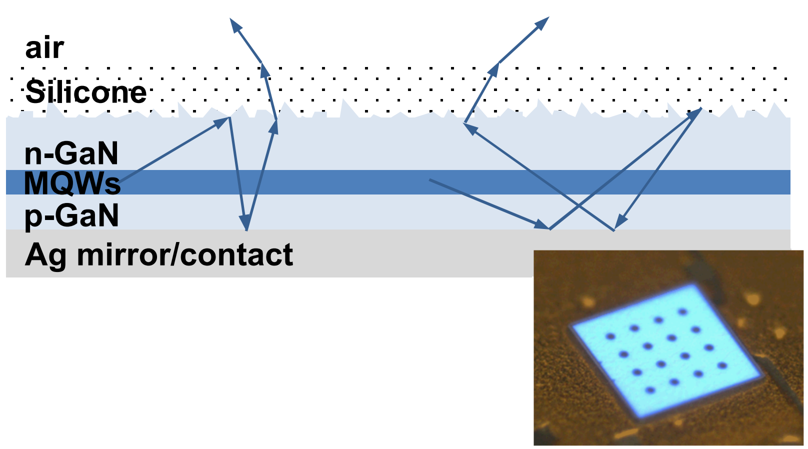
III-nitride blue LEDs vs. LDs



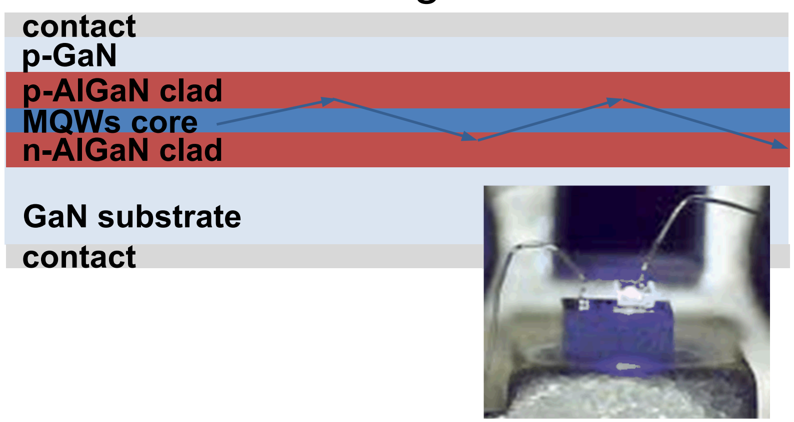
J. J. Wierer, Jr., D. S. Sizov, and J. Y. Tsao, "Comparison between Blue Laser and Light-Emitting Diodes for Future Solid-State Lighting", Laser and Photonics Review (2013).

- After threshold LDs are not affected by efficiency droop.
- LDs are more efficient at higher input power densities.

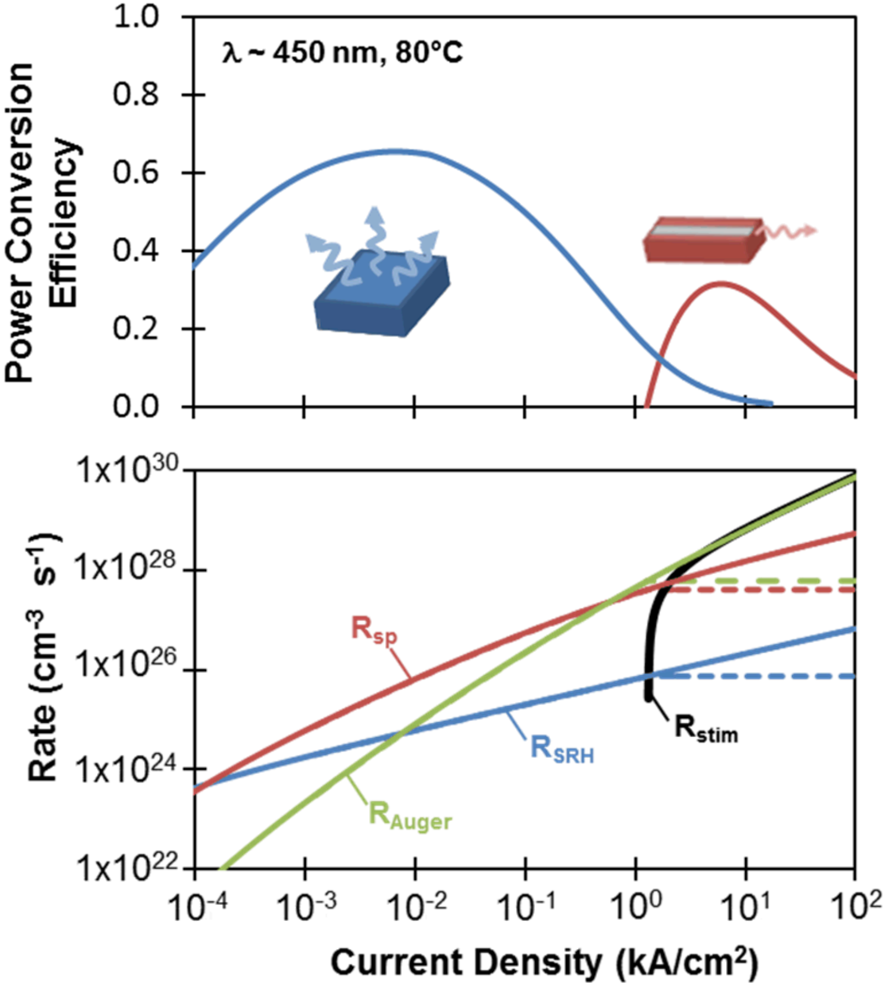
Blue LED: thin-film



Blue LD: edge-emitter



Stimulated vs spontaneous emission



- Recombination processes determine efficiency.
- $R_{total}= R_{SHR}+R_{Sp}+R_{Auger}+R_{stim}$
- *LED:*
  - $\eta_{rad}=R_{sp}/(R_{SRH}+R_{sp}+R_{Auger})$
  - $R_{stim}=0$
- LD:
  - $R_{SHR}+R_{Sp}+R_{auger}$ *are fixed, and* R_{stim} *grows after threshold.*
- Method to circumvent efficiency droop, and achieve ultra-high efficiency!

LED Efficiencies

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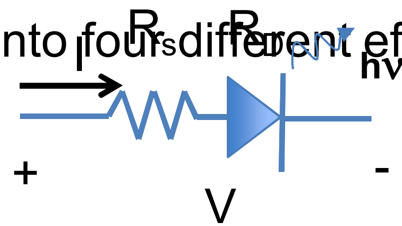
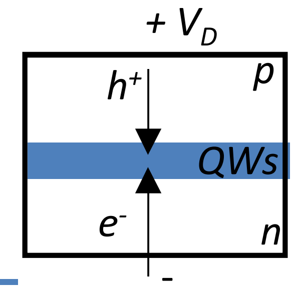
Power conversion efficiency = $\eta_J \, \eta_{inj} \, \eta_{rad} \, \eta_{ext}$

- Power conversion efficiency can be separated into four different efficiencies:
  1) Joule efficiency: η_J
  2) Injection efficiency: η_{inj}
  3) Radiative efficiency: η_{rad}
  4) Extraction efficiency: η_{ext}

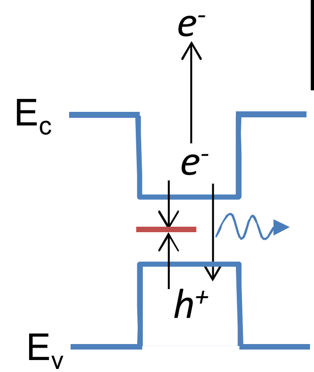
- Joule Efficiency, η_J:
  - Fraction of photon energy ($h\nu$) to input energy (VI).



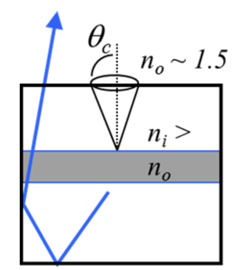
- Injection Efficiency, η_{inj}:
  - Fraction of electrons and holes that arrive at the QWs.



- Radiative Efficiency, η_{rad}:
  - Fraction of electrons and holes that participate in light emission



- Extraction Efficiency, η_{ext}:
  - Fraction of produced light that exits the semiconductor



SSLS EFRC

State-of-the-art blue LED

- Joule Efficiency: η_J
  - $\eta_J = h\nu/qV$
  - $V = V_D + IR_s$.
  - $V_D = n_f \frac{kT}{q} ln\left(\frac{I}{I_o}\right)$

R_s	0.26 (ohms)
I_o	9×10^{-26} (A)
n_f	1.62

- Injection efficiency: η_{inj}
  - Function of the bandstruture, carrier lifetimes, and internal and external fields.

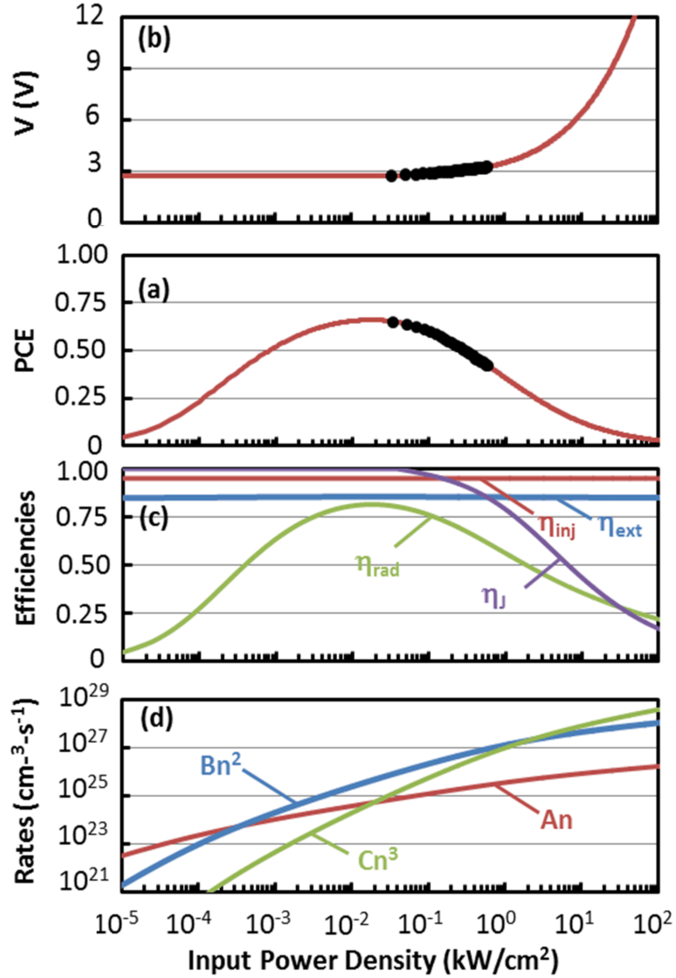
η_{inj}	0.97

- Radiative efficiency: η_r
  - $\eta_r = \frac{Bn^2}{An+Bn^2+Cn^3}$
  - $B = B_0/\left(1+\frac{n}{n^*}\right)$
  - $\frac{n_{inj}I}{qdA_{LED}} = An + Bn^2 + Cn^3$

A	2×10^6 (1/s)
B_o	7.88×10^{-12} (cm^3/s)
C_o	3.15×10^{-31} (cm^6/s)
n*	2.2×10^{19} (1/cm^3)
d	3 x 2.5 nm

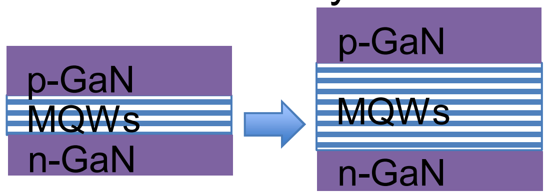
- Extraction efficiency: η_{ext}
  - $\eta_{ext} \cong \sum_{b=1}^{\infty}\frac{1}{2}(1-T)^{b-1}T[R_m^{b-1}+R_m^b]$

η_{ext}	0.81
T	0.27
R_m	0.93

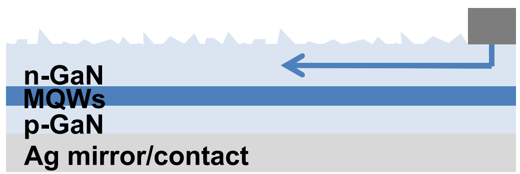


Projection of LED improvements

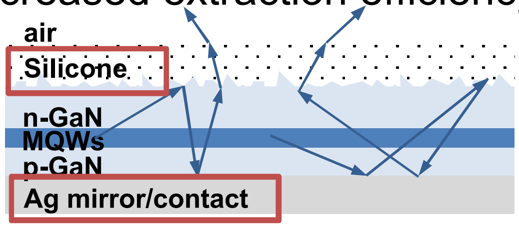
Increased active layer thickness:



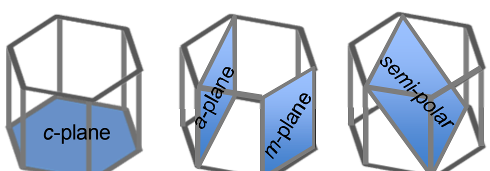
Reduced series resistance:

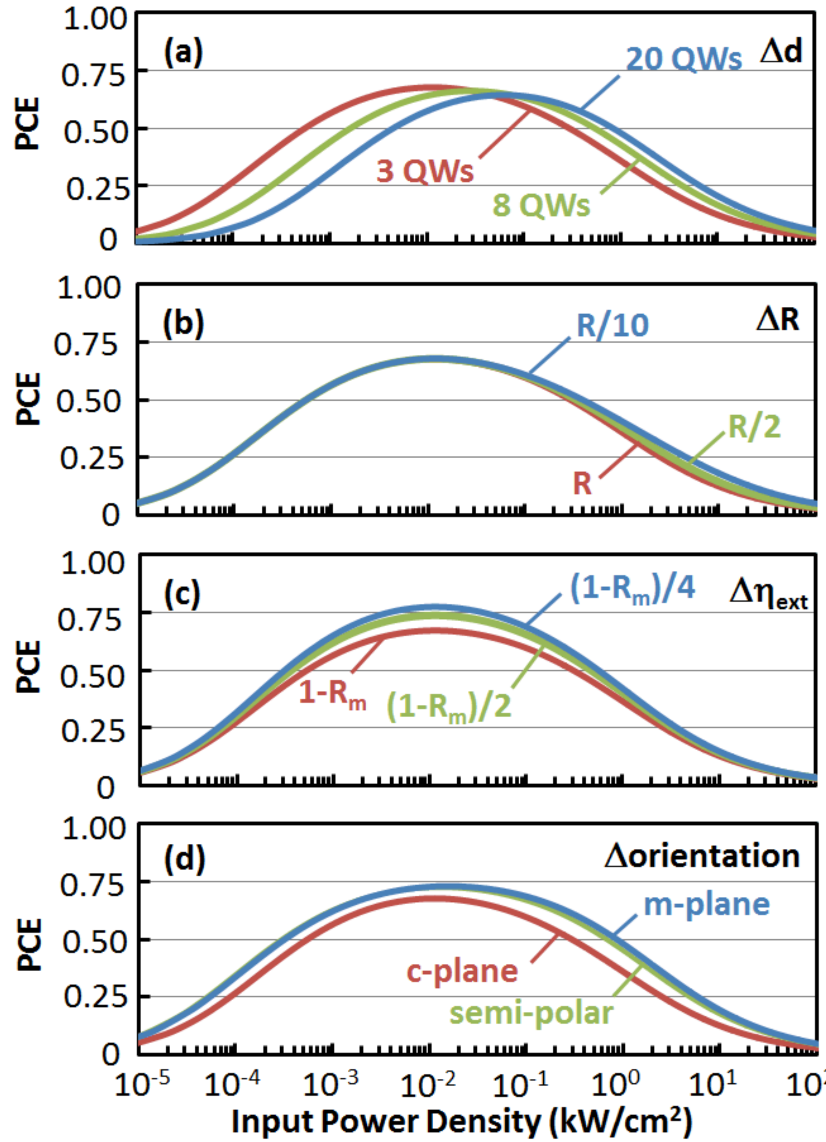


Increased extraction efficiency:

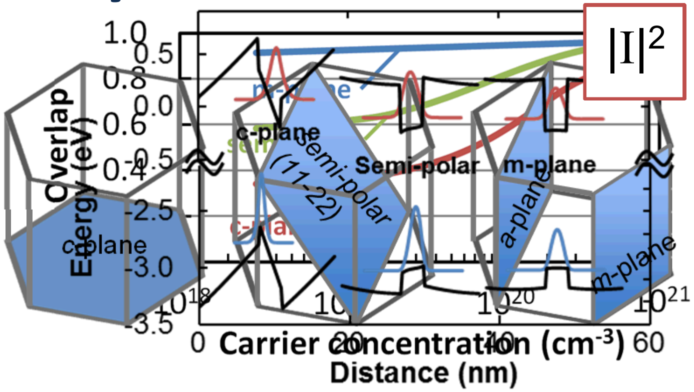


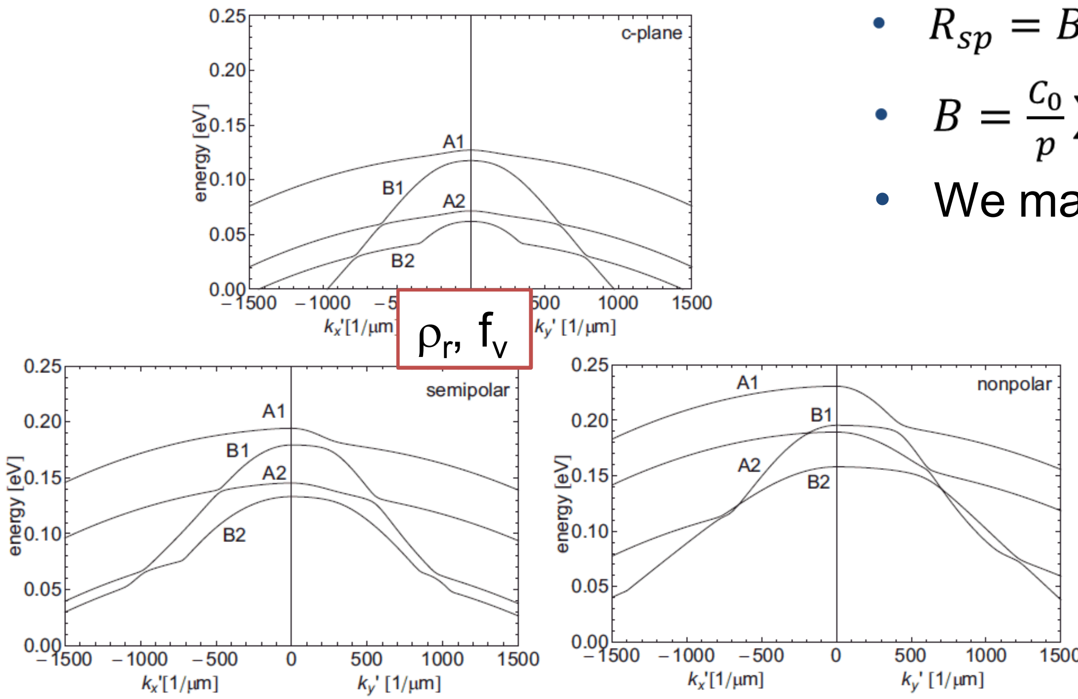
Change crystal orientations:





Crystal orientation

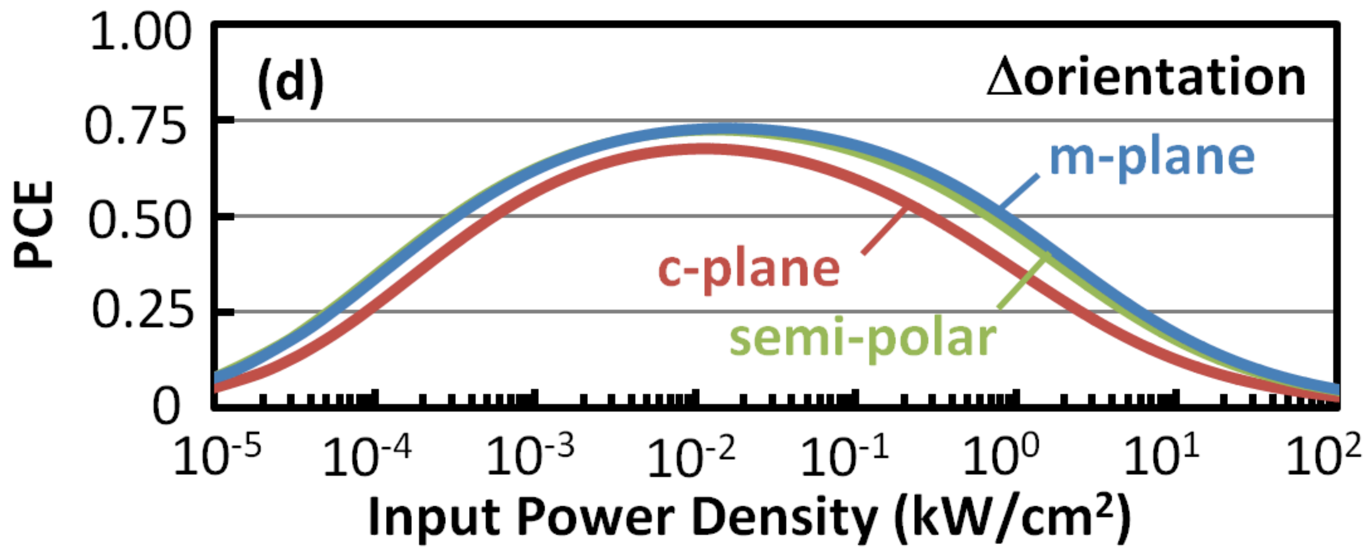




- $\eta_r = \frac{Bn^2}{An+Bn^2+Cn^3}$
- $R_{sp} = Bnp = \frac{\pi q^2}{n_{opt} c \varepsilon_0 m_0 \omega} \sum |I|^2 |\hat{e} \cdot p|^2 \rho_r f_c f_v$
- $B = \frac{C_0}{p} \sum_{i=A1,B1} |\mathrm{I}|^2 \rho_{r,i} f_{v,i}$
- We made similar arguments for A and C.

W. G. Scheibenzuber et al. PRB, 90, 115320 (2009).

Crystal orientation



- Efficiency curve is “wider”.
- The increase in A and C limit the peak efficiency improvement.
- Efficiency droop is not fixed but improved.
- At 1kW/cm^2: PCE ~ 38% c-plane

  PCE ~ 48% for m-plane

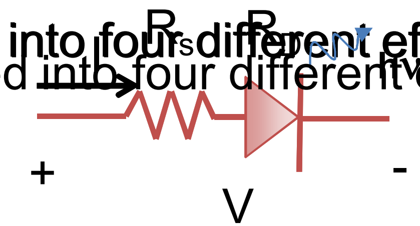
LD efficiencies

Power conversion efficiency = $\eta_J \eta_{inj} \eta_{stim} \eta_{ext}$

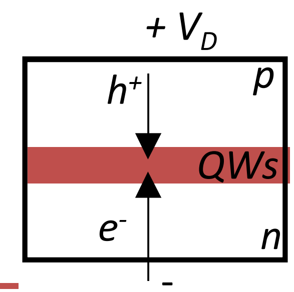
- **Power conversion efficiency can be separated into four different efficiencies:**
  1) **Joule efficiency: η_J**
  2) **Injection efficiency: η_{inj}**
  3) **Stimulated efficiency: η_{stim}**
  4) **Extraction efficiency: η_{ext}**

- Power conversion efficiency can be separated into four different efficiencies:
  1) Joule efficiency: η_J
  2) Injection efficiency: η_{inj}
  3) Stimulated efficiency: η_{stim}
  4) Extraction efficiency: η_{ext}

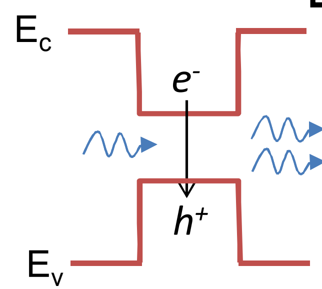
- Joule Efficiency, η_J:
  - Fraction of photon energy ($h\nu$) to input energy (V).



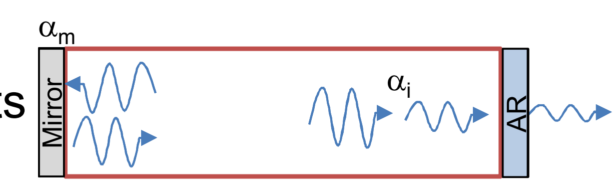
- Injection Efficiency, η_{inj}:
  - Fraction of electrons and holes that arrive at the QWs.



- Stimulated Efficiency, η_{stim}:
  - Fraction of current supplied for stimulated emission



- Extraction Efficiency, η_{ext}:
  - Fraction of produced light that exits the semiconductor



State-of-the-art blue LD

- Joule Efficiency: η_J
  - $\eta_J = h\nu/qV$
  - $V = V_D + IR_s.$
  - $V_D = n_f \frac{kT}{q} ln\left(\frac{I}{I_o}\right)$

R_s	1.02 (ohms)
I_o	6.5×10^{-24} (A)
n_f	2

- Injection efficiency: η_{inj}
  - Function of the bandstruture, carrier lifetimes, and internal and external fields.

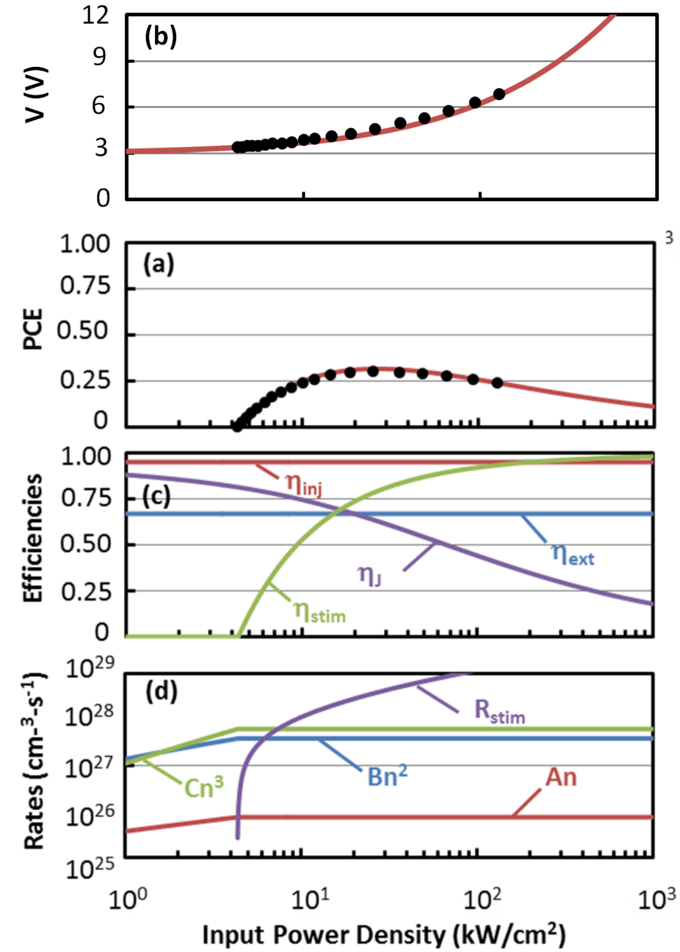
η_{inj}	0.97

- Stimulated efficiency: η_{stim}
  - $\eta_{stim} = (I - I_{th})/I$
  - $I_{th} = \left(\frac{qdA_{LD}}{\eta_{inj}}\right)\left[\left(Bn_{tr}^2 \exp\left(2\frac{\alpha_m+\alpha_i}{\Gamma g_0}\right)\right) + \left(Cn_{tr}^3 \exp\left(3\frac{\alpha_m+\alpha_i}{\Gamma g_0}\right)\right)\right]$

A, B_o, C_o, n^*, d	Same as LED
α_i	6 (1/cm)
α_m	12.1 (1/cm)
n_{tr}	1.75×10^{19} cm^{-3}
Γg_0	23.9 (1/cm)
A_{LD}	1.8×10^{-4} (cm^2)

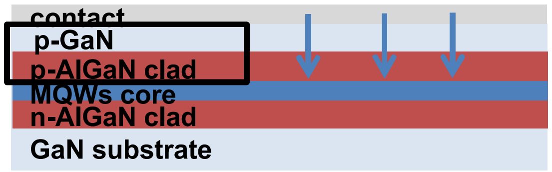
- Extraction efficiency: η_{ext}
  - $\eta_{ext} = \alpha_m/(\alpha_m + \alpha_i)$
  - Shared with η_{stim}

α_i	6 (1/cm)
α_m	12.1 (1/cm)

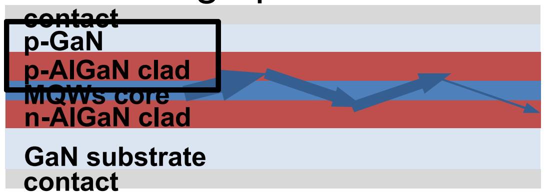


Projection of LD improvements

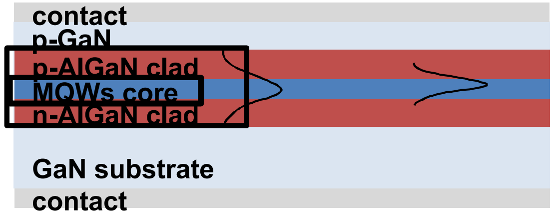
Reduced series resistance:



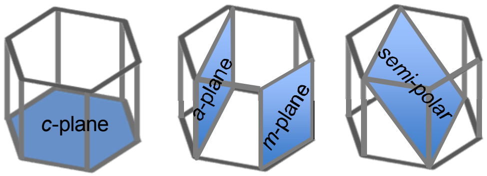
Decreasing optical loss:

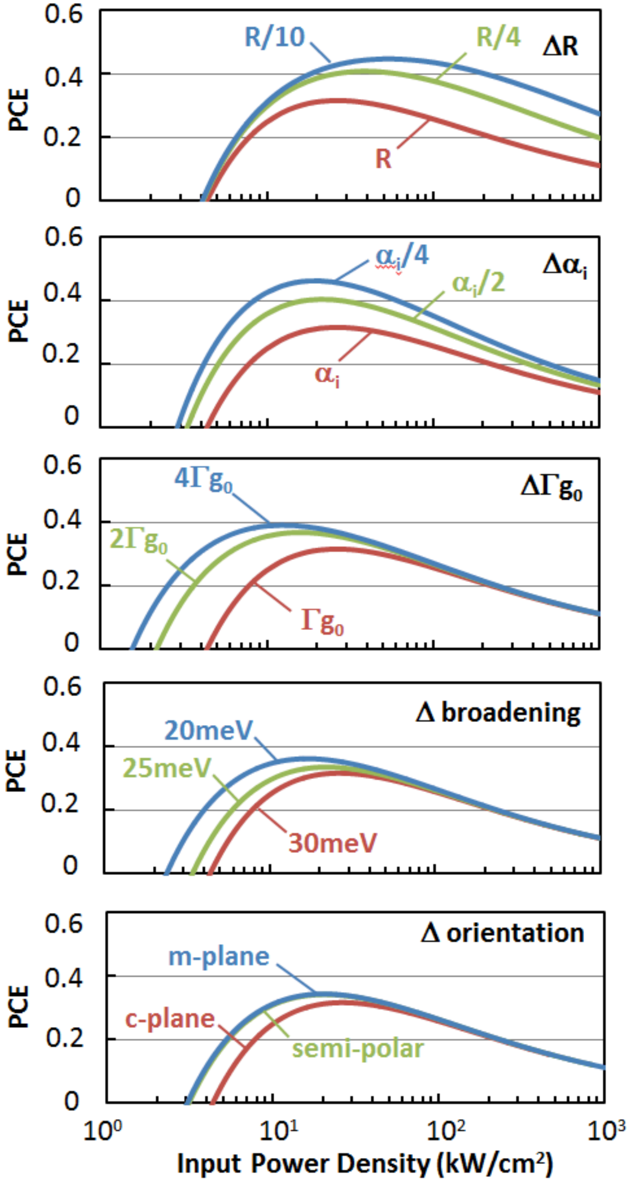


Increasing modal gain:

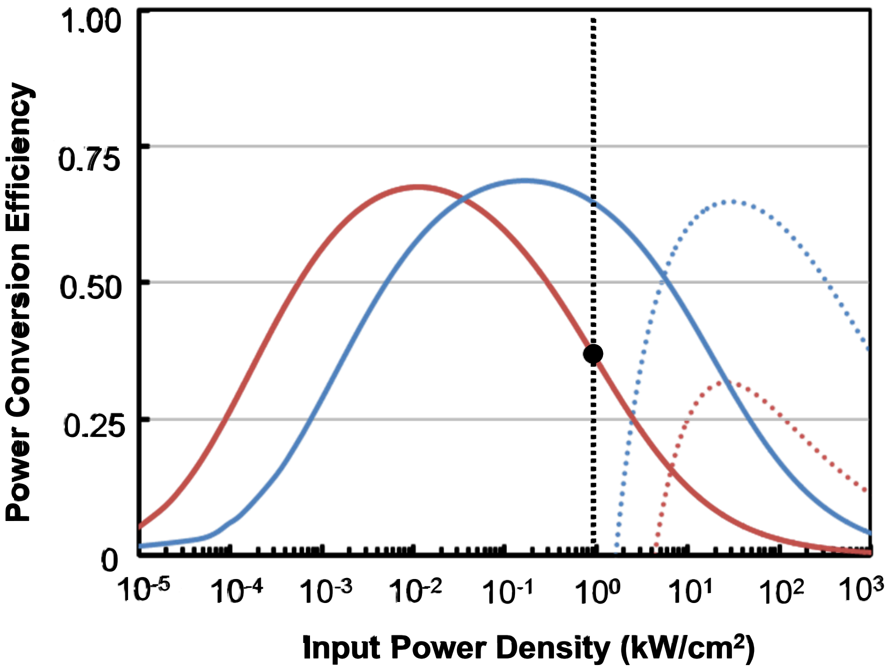


Change crystal orientations:





Projection of efficiency improvements



LED

	Now	Future
# MQWs	3	20
Rs	0.25Ω	0.025Ω
next	83%	96%
orientation	c-plane	m-plane

LD

	Now	Future
Rs	1ohm	0.1ohm
Internal loss	6/cm	1.5/cm
modal gain	23.5	94
broadening	30meV	20meV
orientation	c-plane	m-plane

- Blue LD has the potential to have similar peak efficiencies as LEDs, but at much higher output powers.
- We are investigating other methods to improve LD efficiency.

Ultra-efficient SSL: two approaches

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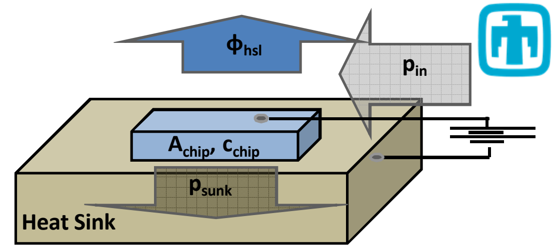


4 Heat-sink-limited white light flux

$$\Phi_{hsl} = \frac{MWLER\cdot\varepsilon_B\varepsilon_{PP}}{\left(P_{in}/A_{chip}\right)}\cdot\left[\frac{2\kappa_T\sqrt{4/\pi}\cdot\Delta T_{\max}}{(1-\varepsilon_B\varepsilon_{PP})\cdot}\right]^2$$

3 Heat-sink-limited chip area

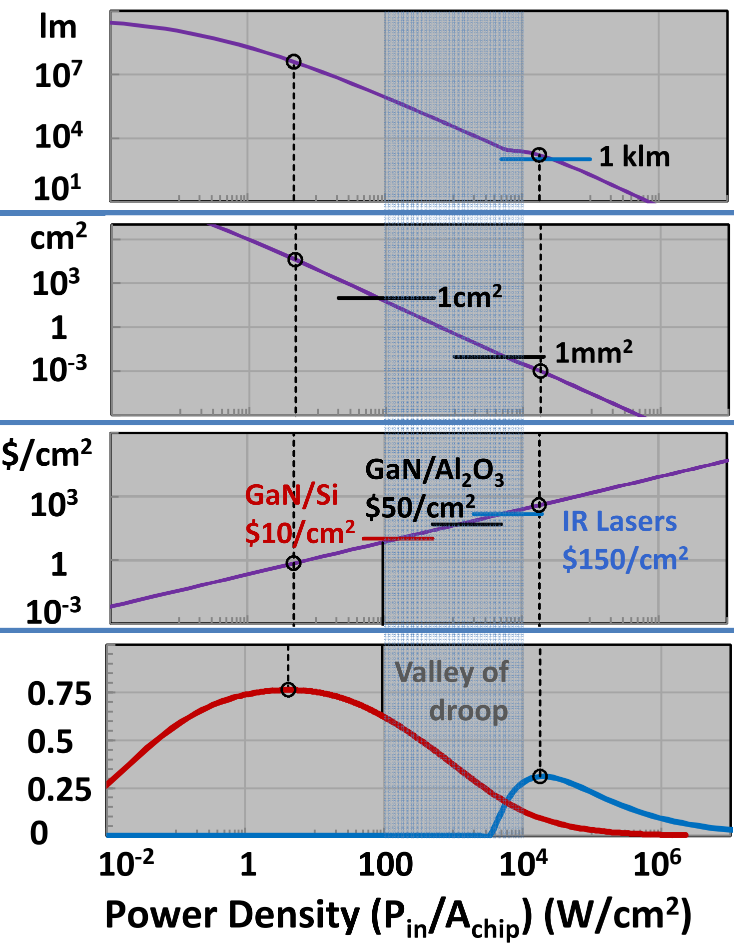
$$A_{hsl} = \left[\frac{2\kappa_T\sqrt{4/\pi}\cdot\Delta T_{\max}}{(1-\varepsilon_B\varepsilon_{PP})\cdot\left(P_{in}/A_{chip}\right)}\right]^2$$

2 Chip areal cost necessary for $CoL_{cap} < CoL_{ope}/6$

$$c_{chip} = \frac{L\cdot CoE}{6\alpha}\cdot\left(P_{in}/A_{chip}\right)$$

1 Efficiency, and its valley of death

$$\varepsilon_B\,(Blue\;Emitter\;Efficiency)$$

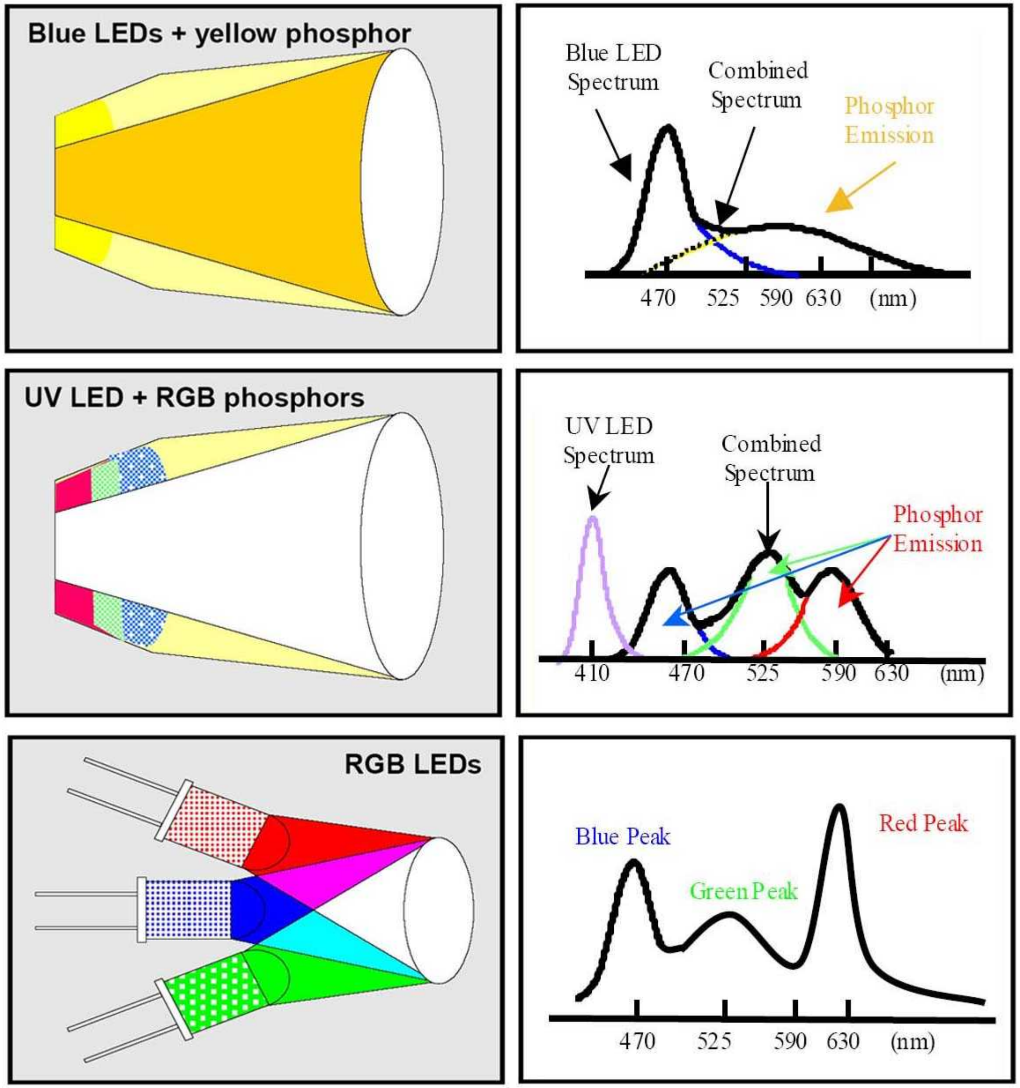


J. J. Wierer, Jr., D. S. Sizov, and J. Y. Tsao, "Comparison between Blue Laser and Light-Emitting Diodes for Future Solid-State Lighting", Laser and Photonics Review (2013).

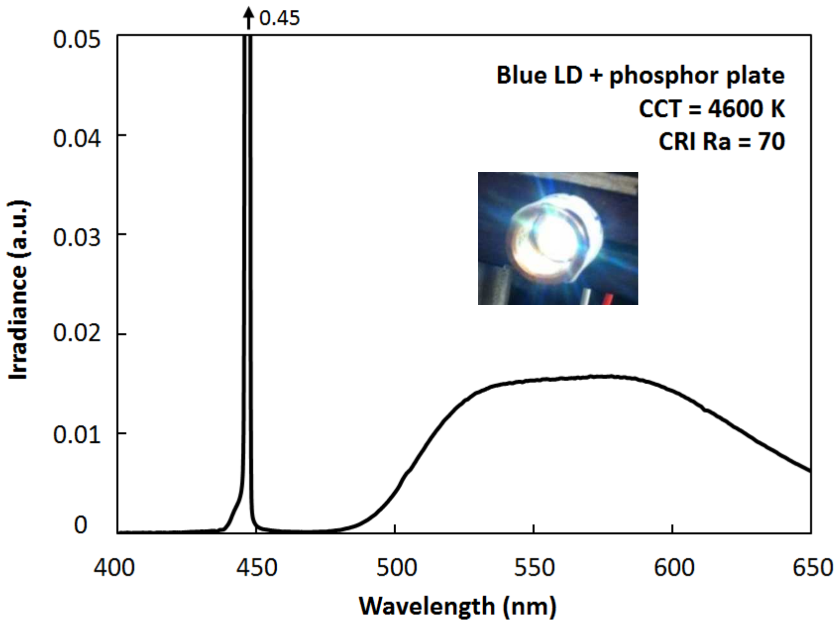
White light from LDs

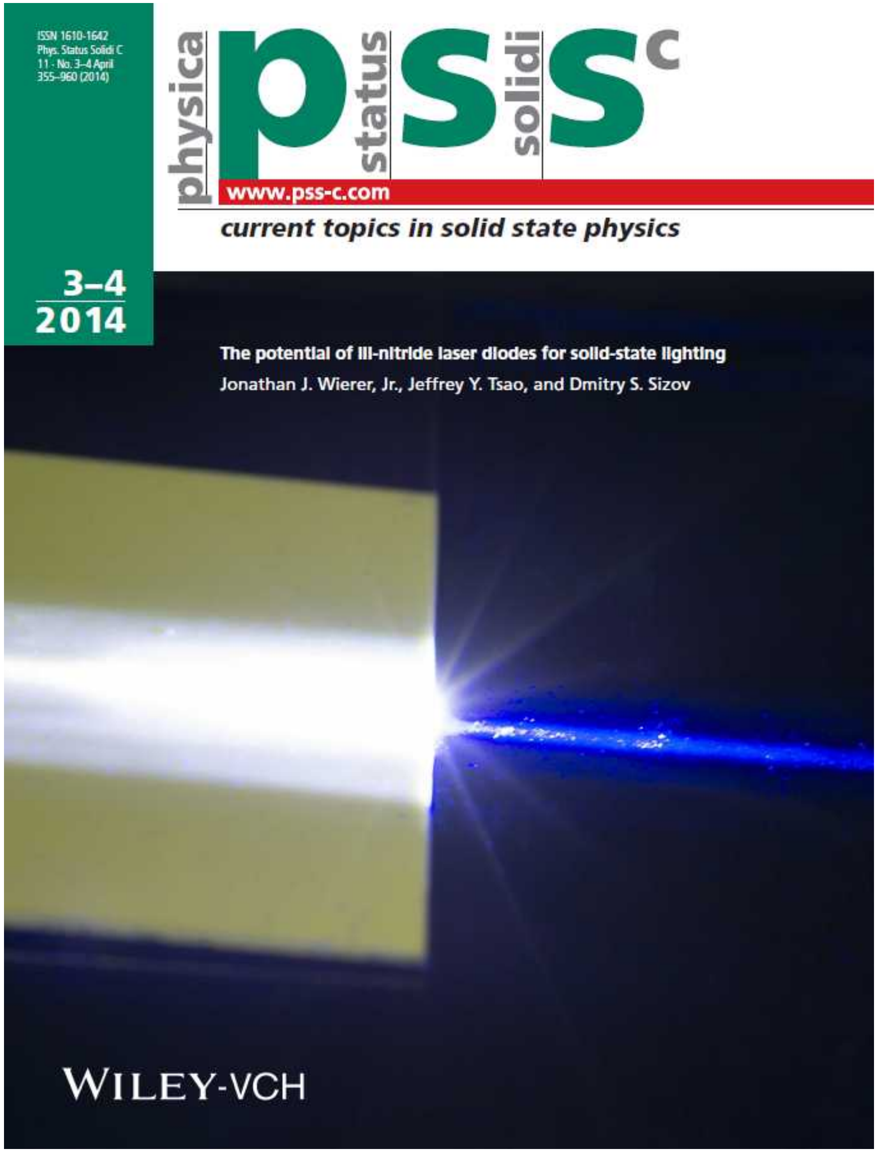
White options in LED-based SSL

- Blue LED + yellow phosphor
  - Simple
  - Decent color rendering ($R_a \sim 75$)
  - Stokes-shift loss - blue → yellow
- UV LED + RGB phosphors
  - White determined by phosphors
  - Excellent color rendering
  - Stokes-shift UV → visible colors
- Direct – RGB LEDs
  - Potentially highest efficacy
  - Very large color range
  - Most efficient – tunable white



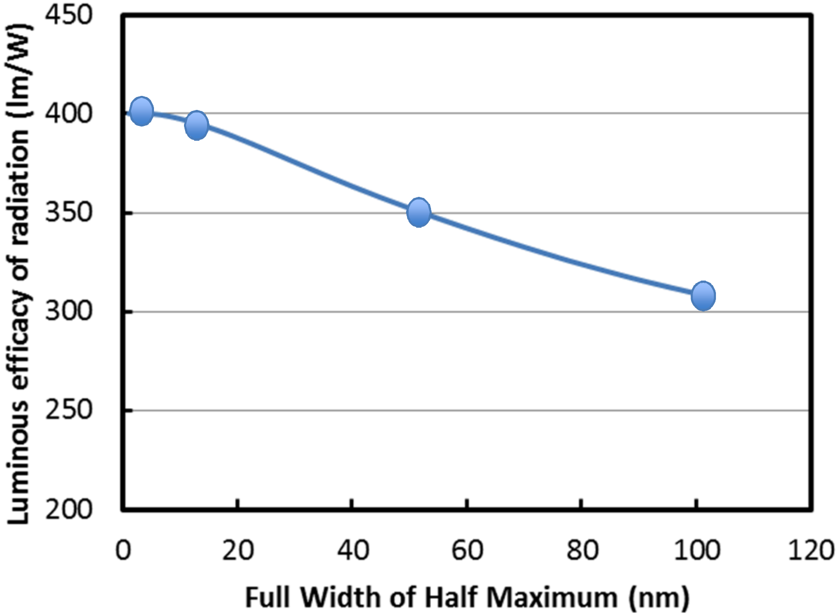
Phosphor converted LD (PC-LD) white

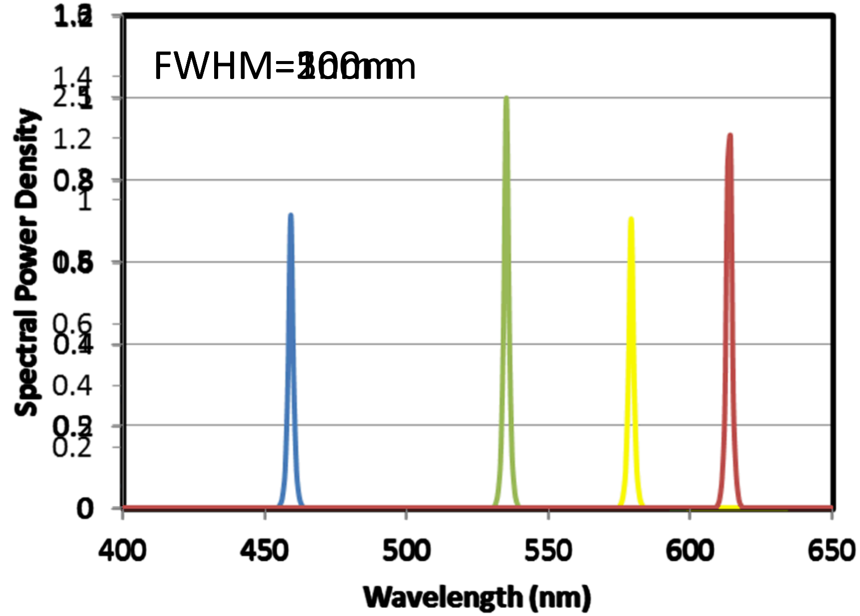




- Commercial blue LD + ceramic phosphor.
- Color temperature and rendering are comparable to PC-LED.
- Blue LDs can be used to produce white light.

High Luminous efficacies of radiation

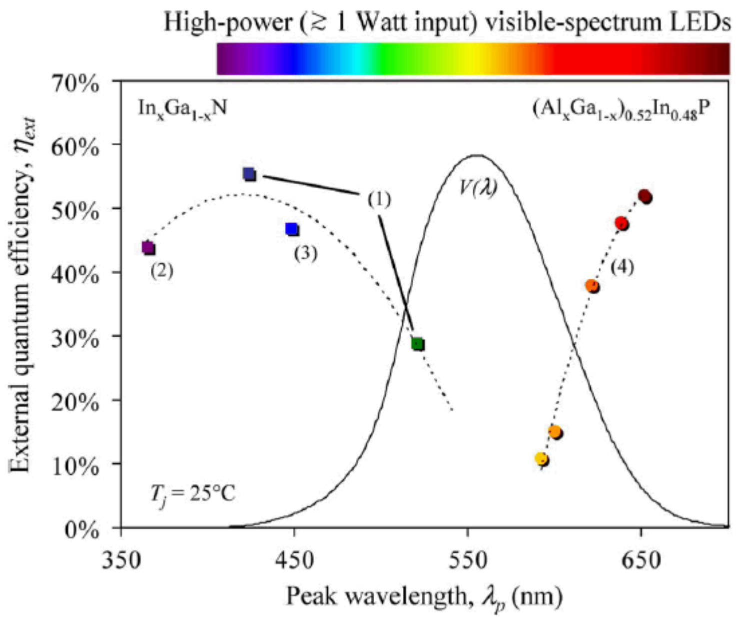




- Spiky sources give highest luminous efficacies of radiation (lm/W)
- Red/yellow power varied to give CCT=3800, Ra=85

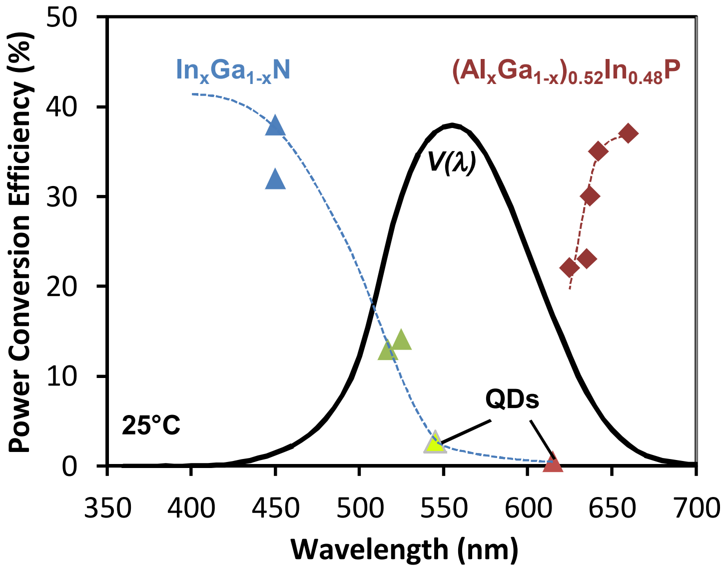
Direct emitters to produce white

LEDs



Krames, et al., IEEE J. Display Tech., June 2007

LDs



J. Wierer & J. Tsao., PSSA, 2015.

- Both LEDs and LDs suffer from the "green gap" problem.
- This limits the progress in white sources produced from direct emitters.

Laser white color rendering

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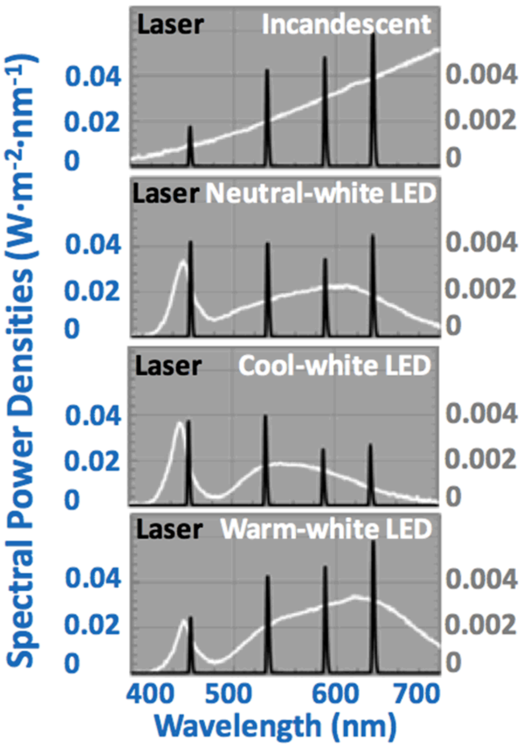
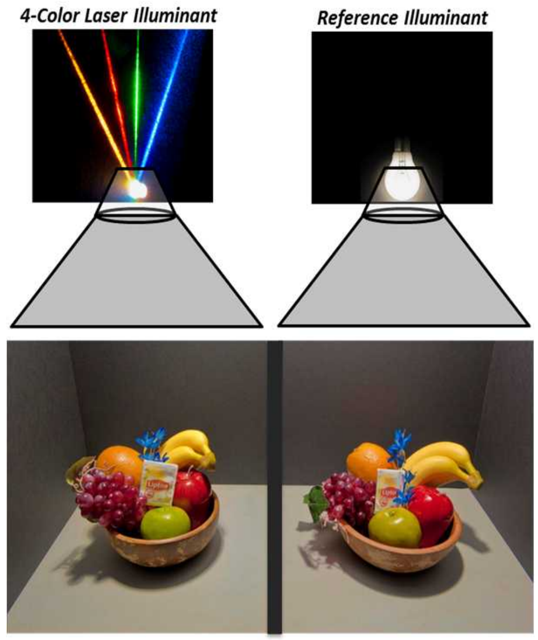
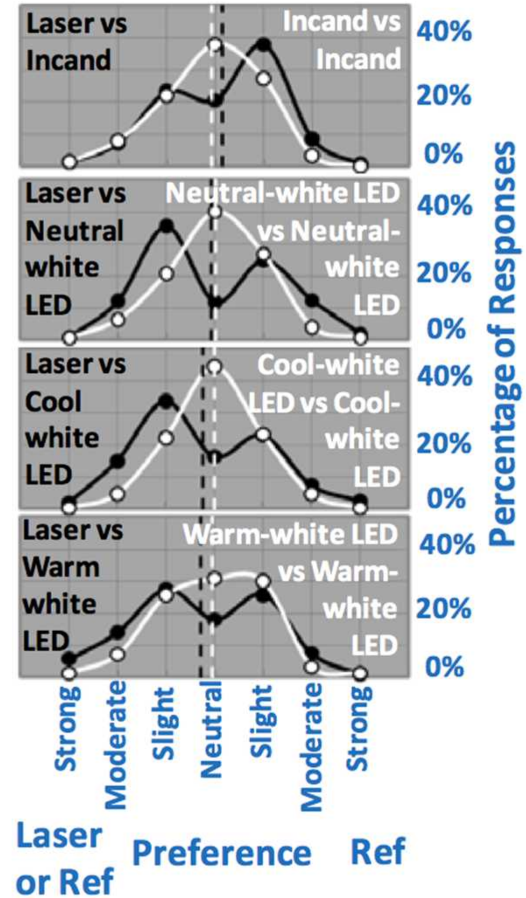




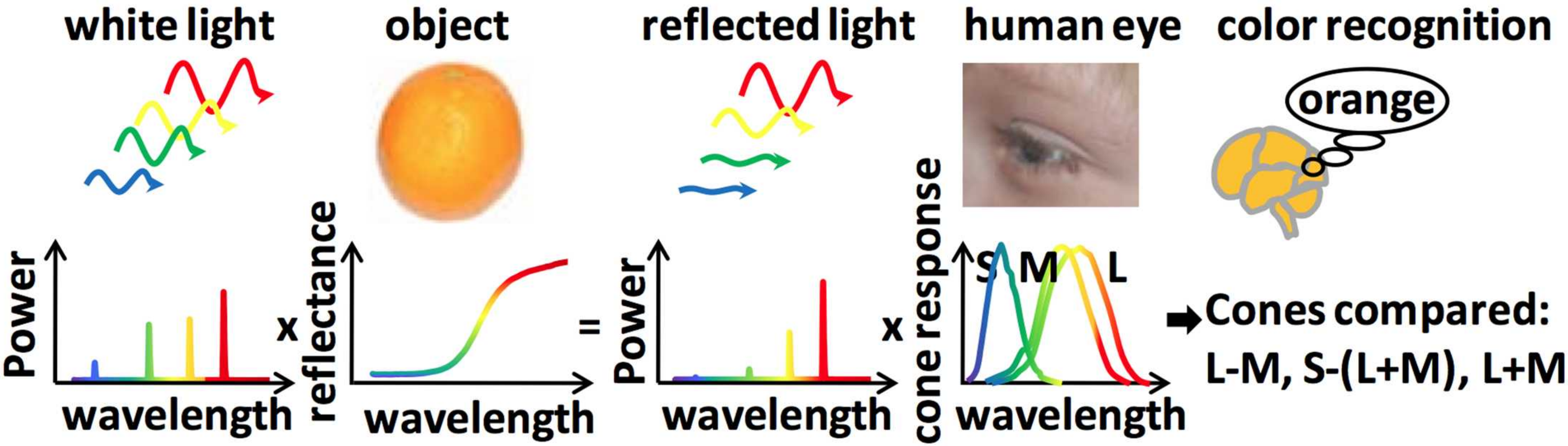


A. Neumann, J. J. Wierer, Jr., W. Davis, Y. Ohno, S. R. J. Brueck, and J.Y. Tsao, Optics Express, 19, A982, 2011.

- Only slight preferences when comparing LD and traditional sources.
- LD white is a good color rendering source. Why?

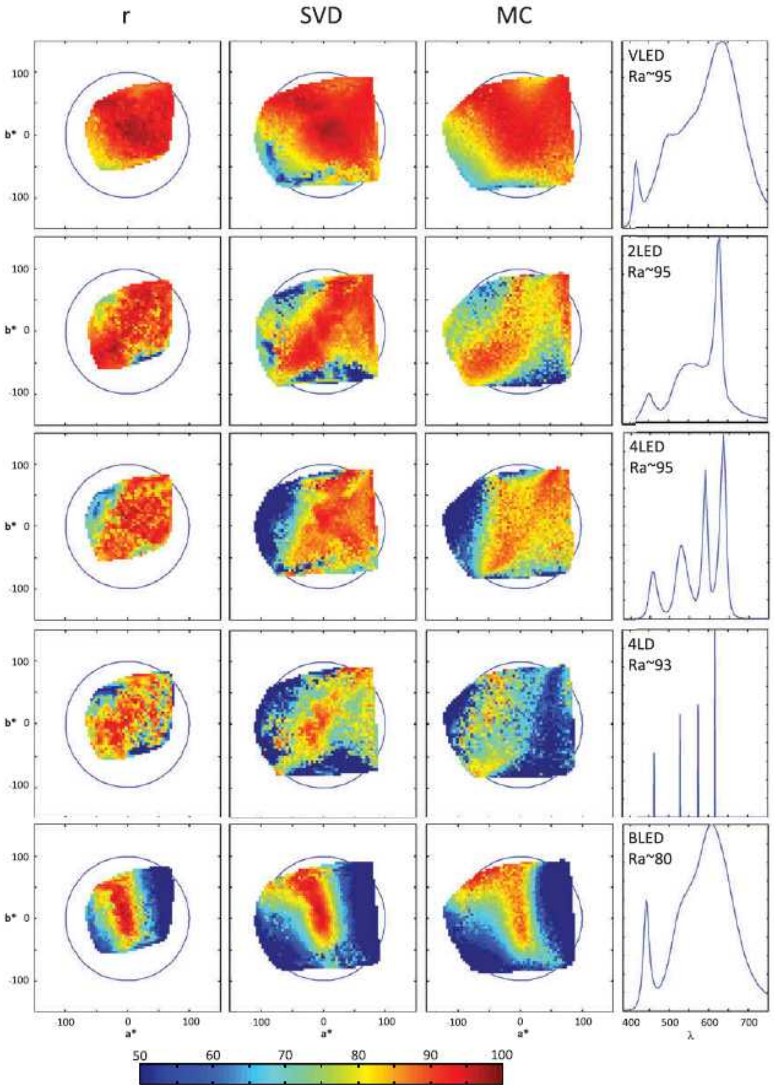
SSLS EFRC

Laser white color rendering



A. Neumann, J. J. Wierer, Jr., W. Davis, Y. Ohno, S. R. J. Brueck, and J.Y. Tsao, Optics Express, 19, A982, 2011.

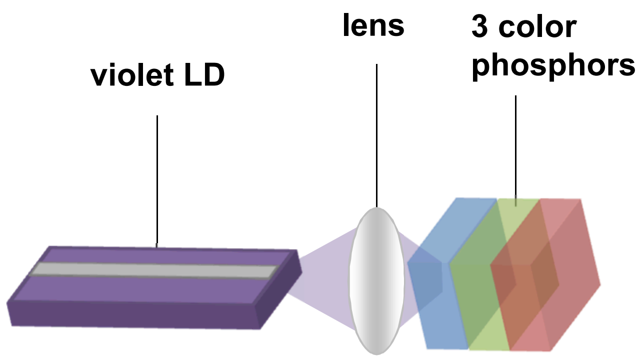
Color rendering over large data sets

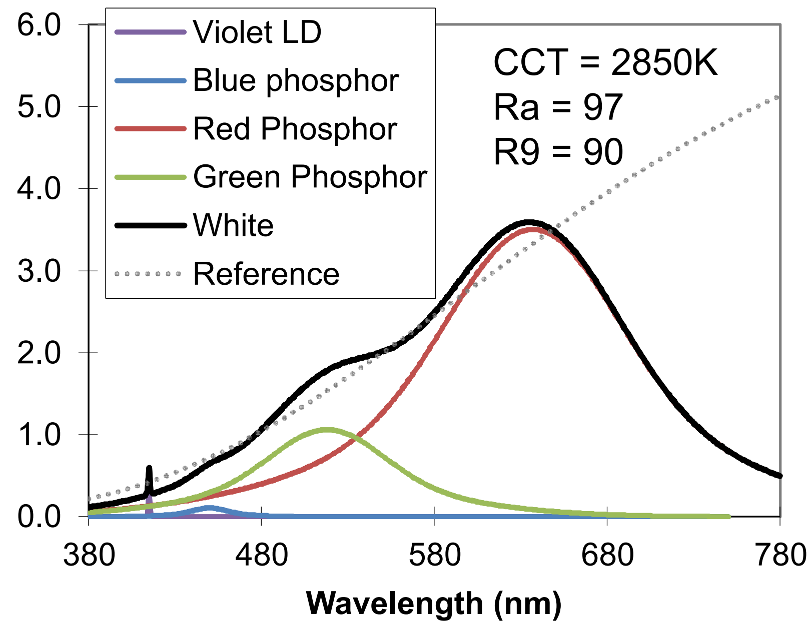


A. David, “Color fidelity of light sources evaluated over large sets of reflectance samples”, LEUKOS, **10**, 59, 2014.

- Color rendering maps for five sources and three large data sets.
- Data sets:
  - r: real world
  - SVD: synthetic/expanded
  - MC: Monte Carlo randomly generated.
- In general, spectra without gaps have good color rendering over a wider gamut.
- So does this exclude lasers from solid-state lighting?

Violet pumped PC-LD

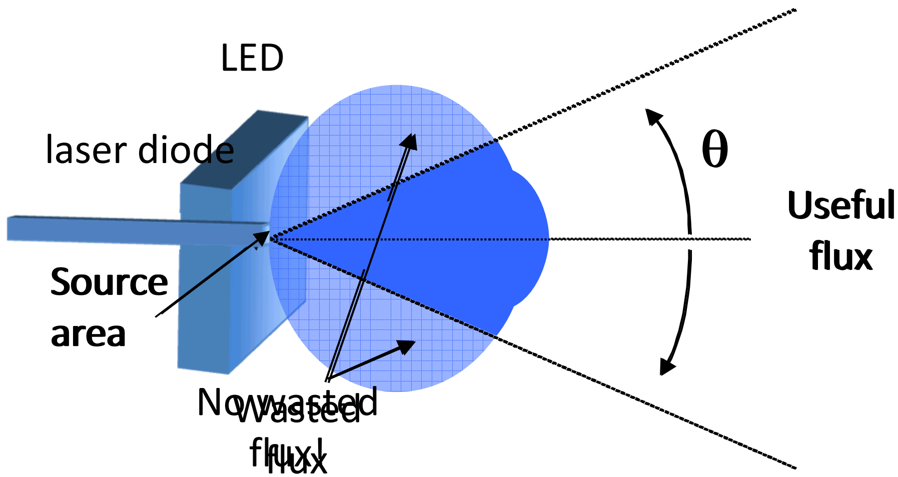


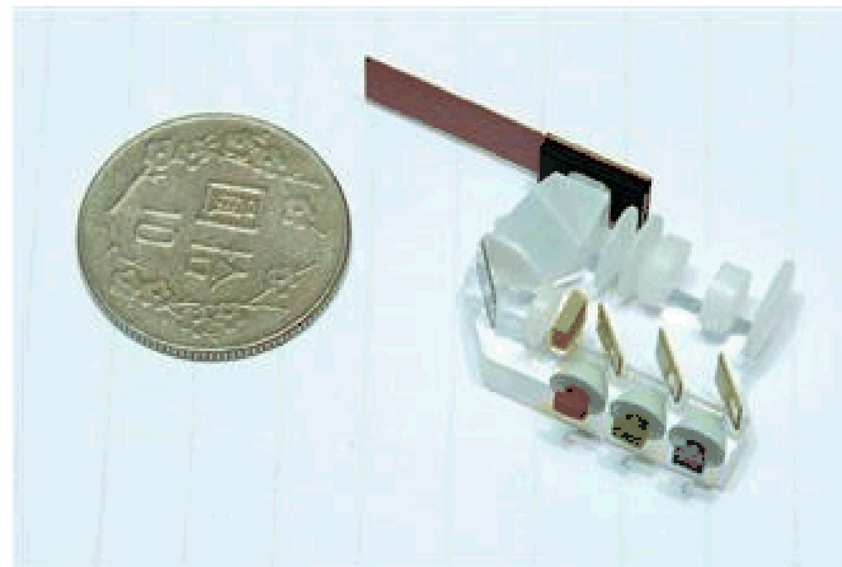


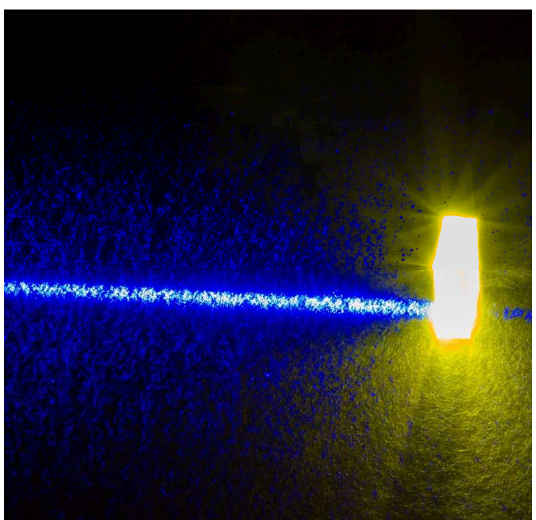
- Simulation of 415nm LD pumping 3 phosphors
  - 450 nm, 518 nm, and 637 nm
- Just like violet PC-LED solution, the violet PC-LD could also produce high color rending white light.
- Phosphor converted solutions cannot chromaticity tune.

LD system benefits

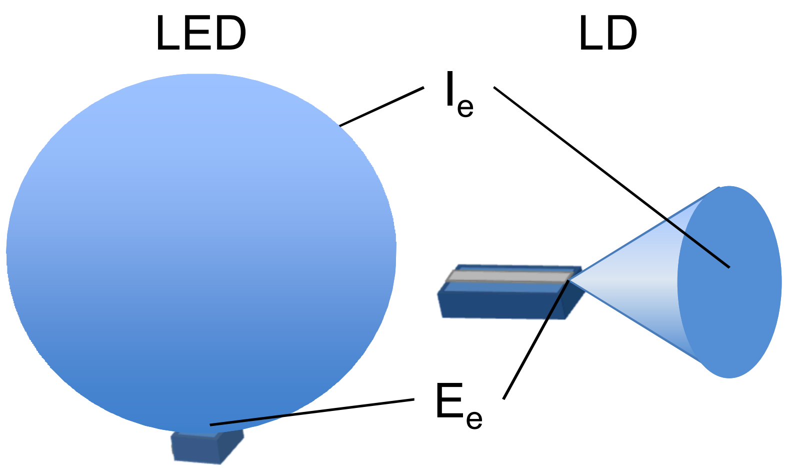
LD has superior directionality







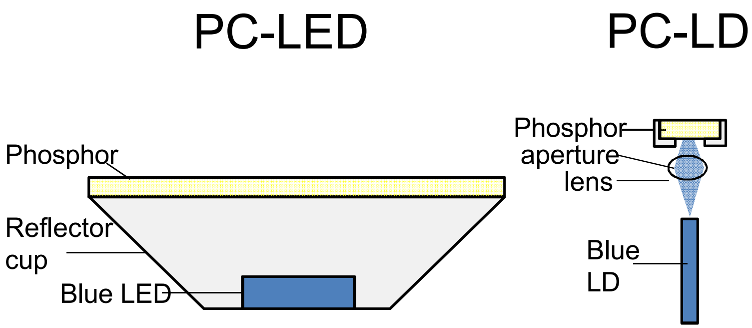
Radiance of blue LEDs and LDs



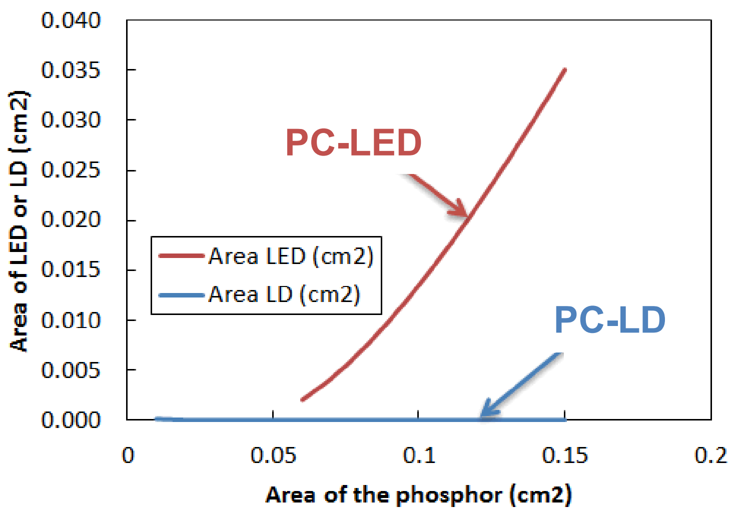
	Blue LED	Blue LD
Power (W)	1.3	2
Emitting area (cm^2)	1.00E-02	1.50E-07
Emitting half angle (°)	45	15
Radiant intensity, I_e, (W/sr)	0.71	9.34
Irradiance, E_e, (W/cm^2)	130	1.33E+07
Radiance, L_e, ($W/sr/cm^2$)	71	6.23E+07

- LD benefits:
  - Irradiance (power density) is much higher in LDs.
  - Emission is directional
  - Emission is from a small aperture.
  - Superior for ètendue limited optical systems (i.e. projectors).
- These LD benefits produce a higher radiance source and advantages when creating a white source.

Luminance of PC-LEDs and PC-LDs

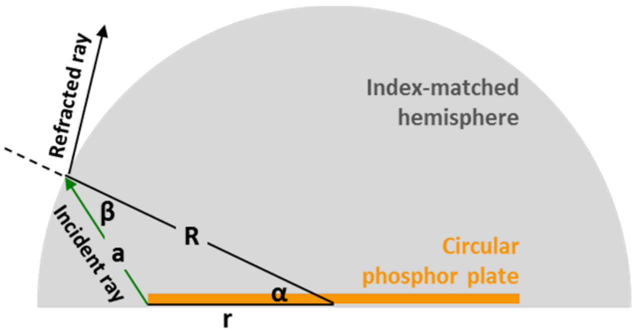


	PC-LED	PC-LD
Power (lm)	325	500
Phosphor emitting area (cm^2)	0.09	0.01
Emitting half angle (°)	45	45
Luminous intensity, I_v, (lm/sr)	180	270
Illuminance, E_v, (lm/cm^2)	3600	50000
Luminance, L_v (lm/sr/cm^2)	1900	27000



- PC-LD benefits:
  - Beam can be focused and a much smaller phosphor volume can be used.
  - Smaller phosphor leads to higher luminance.
  - Smaller luminaires.

Comparison of LED and LD luminaires

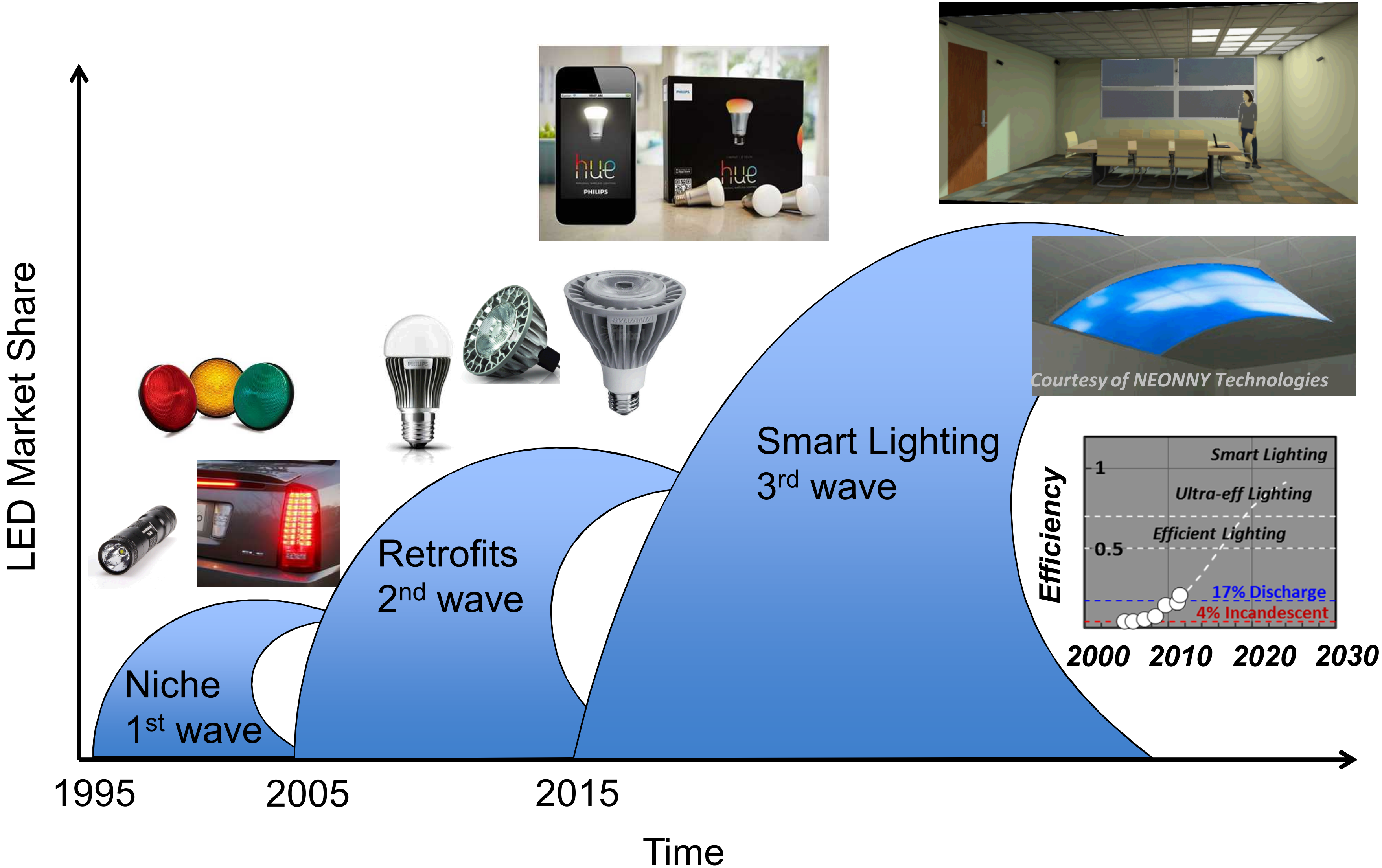


	PC-LED	PC-LD
Power (lm)	325	500
Phosphor emitting area (cm²)	0.09	0.01
Radius of lens (cm)	0.225	0.075
Area of the lens (cm²)	0.16	0.018

- What are the sizes of luminaires for PC-LD and PC-LED?
- Need to avoid total internal reflection from lens (Weierstrass condition):
  - R>rn, where n is index of the lens.
- For the PC-LD
  - Lens is 9 times smaller: microluminaire!
  - Lumens are 1.5 times larger

Market waves of solid-state lighting

Sandia National Laboratories



* Inspired from a slide by Brian Chemel, CTO, Digital Lumens

Conclusion

- LDs are not affected by efficiency droop after threshold.
  - LDs have higher efficiencies at higher input powers.
  - Modeling suggests LD peak efficiency could match LEDs.
- PC-LDs produce white light with color rendering and temperature similar to LEDs.
- LDs white sources have higher illuminance.

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