

# Solid-State Lighting with III-nitride Laser Diodes

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service  
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interest*

IWN, Wroclaw, Poland 27th August 2014



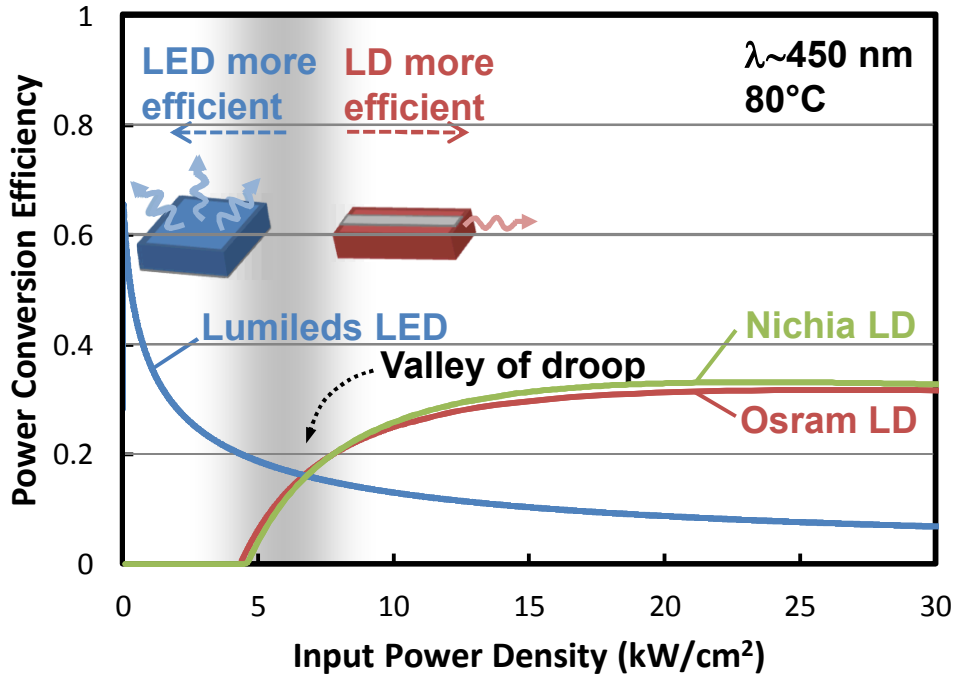
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# Outline

- 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

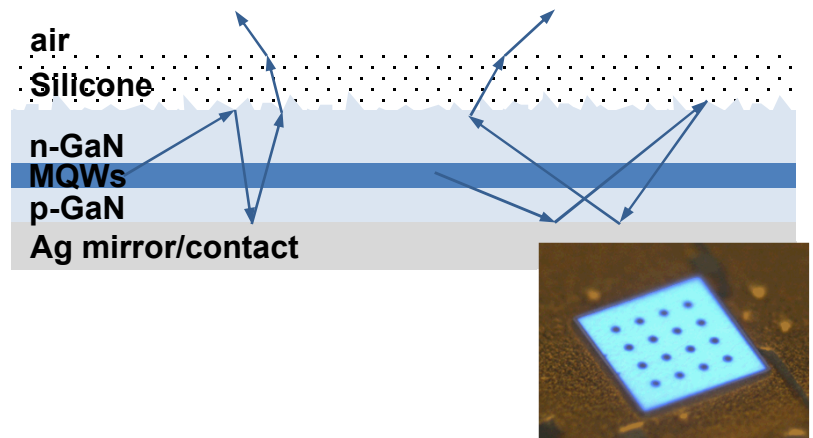
# III-nitride blue LEDs vs. LDs



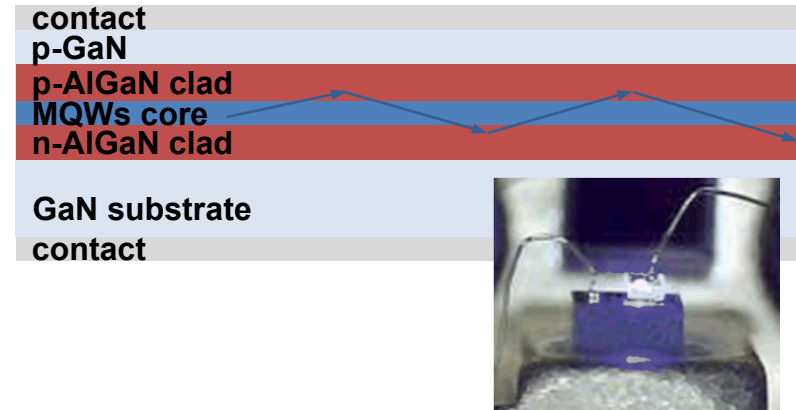
J. J. Wierer, Jr., D. S. Sizov, and J. Y. Tsao, "Comparison between Blue Laser and Light-Emitting Diodes for Future Solid-State Lighting", Laser and Photonics Review (2013).

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

## Blue LED: thin-film



## Blue LD: edge-emitter



# State-of-the-art blue LED

- Joule Efficiency:  $\eta_J$ 
  - $\eta_J = hv/qV$
  - $V = V_D + IR_s$ .
  - $V_D = n_f \frac{kT}{q} \ln\left(\frac{I}{I_0}\right)$

$R_s$	0.26 (ohms)
$I_0$	$9 \times 10^{-26}$ (A)
$n_f$	1.62

- Injection efficiency:  $\eta_{inj}$ 
  - Function of the bandstructure, carrier lifetimes, and internal and external fields.

$\eta_{inj}$	0.97
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- Radiative efficiency:  $\eta_r$

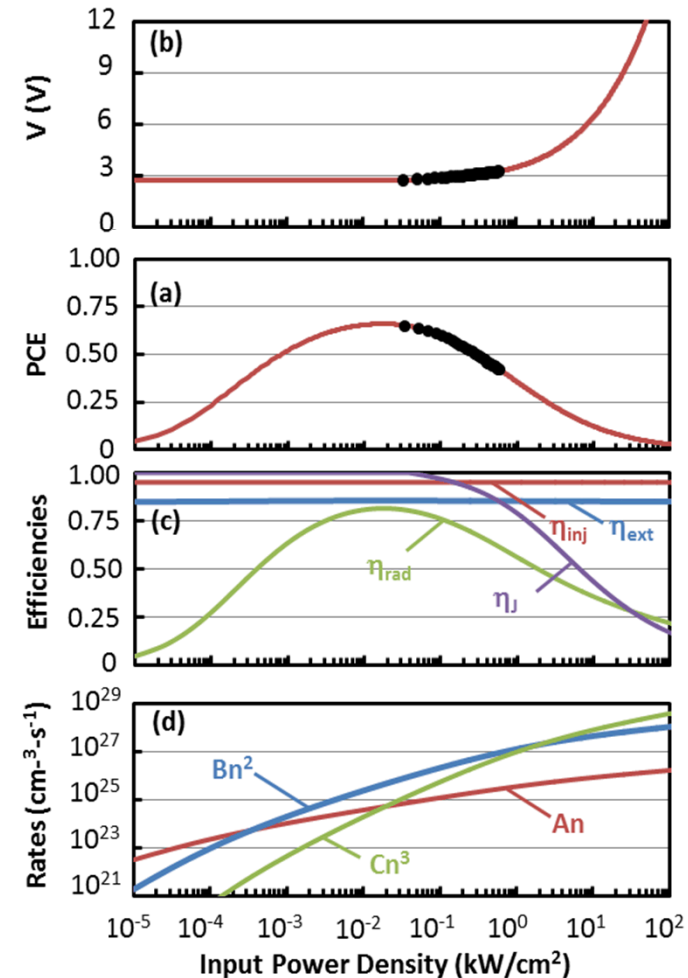
- $\eta_r = \frac{Bn^2}{An + Bn^2 + Cn^3}$
- $B = B_0 / \left(1 + \frac{n}{n^*}\right)$
- $\frac{n_{inj}I}{qdA_{LED}} = An + Bn^2 + Cn^3$

A	$2 \times 10^6$ (1/s)
$B_0$	$7.88 \times 10^{-12}$ ( $\text{cm}^3/\text{s}$ )
$C_0$	$3.15 \times 10^{-31}$ ( $\text{cm}^6/\text{s}$ )
$n^*$	$2.2 \times 10^{19}$ ( $1/\text{cm}^3$ )
d	3 x 2.5 nm

- Extraction efficiency:  $\eta_{ext}$

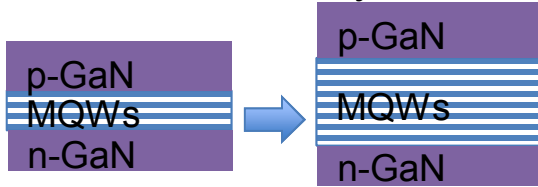
- $\eta_{ext} \cong \sum_{b=1}^{\infty} \frac{1}{2} (1 - T)^{b-1} T [R_m^{b-1} + R_m^b]$

$\eta_{ext}$	0.81
T	0.27
$R_m$	0.93

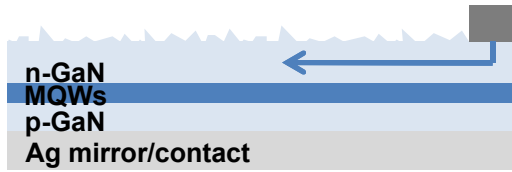


# Projection of LED improvements

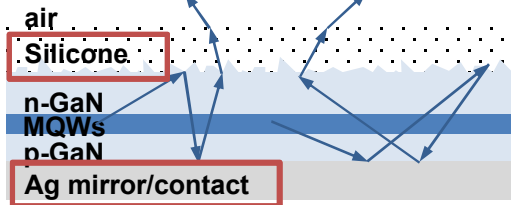
- Increased active layer thickness:



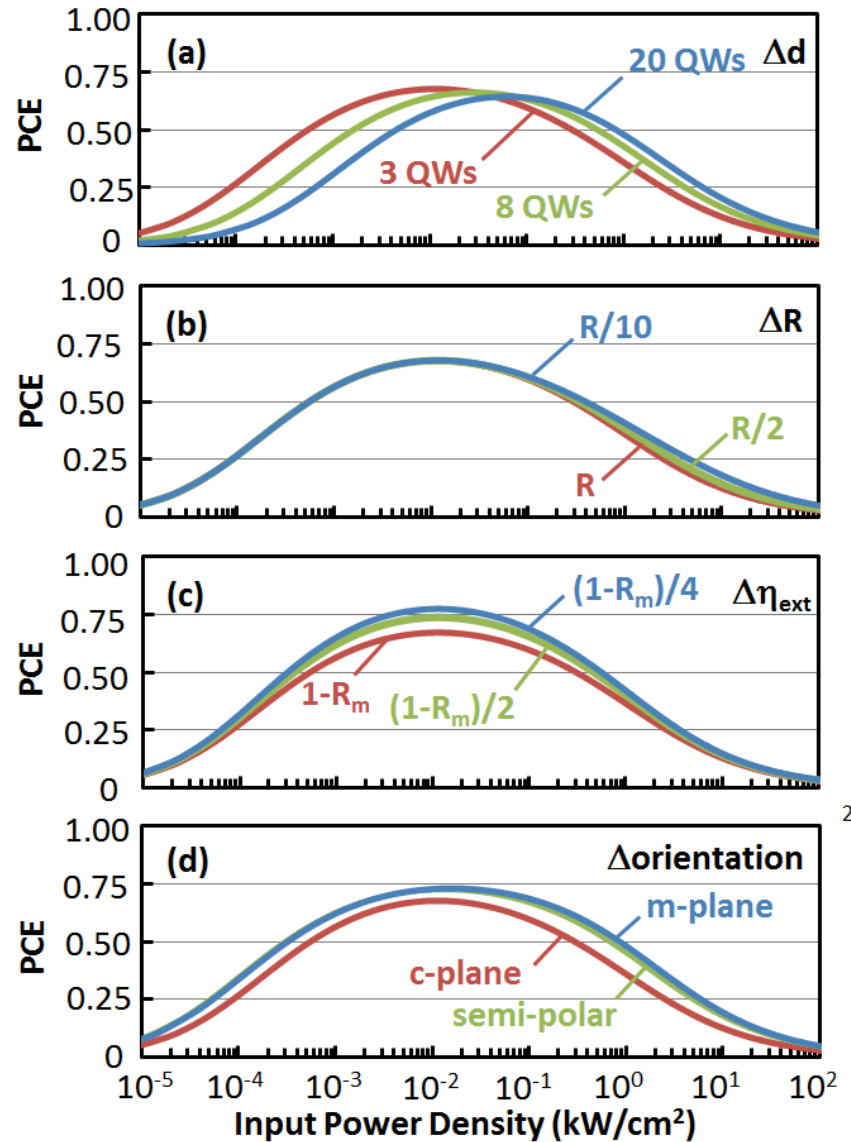
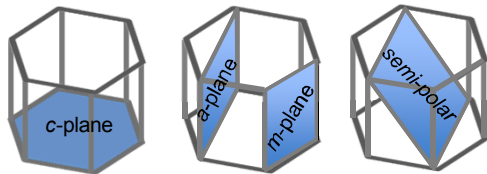
- Reduced series resistance:



- Increased extraction efficiency:

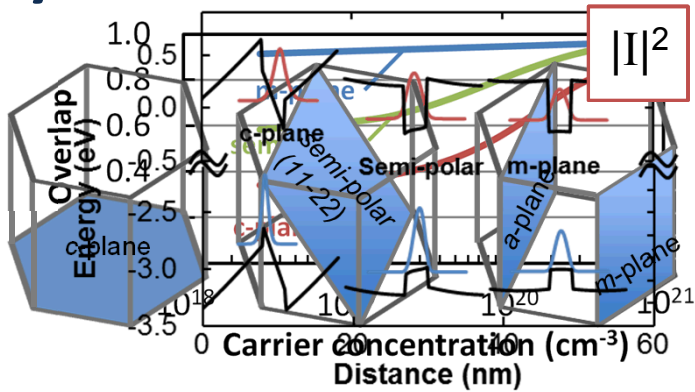


- Change crystal orientations:

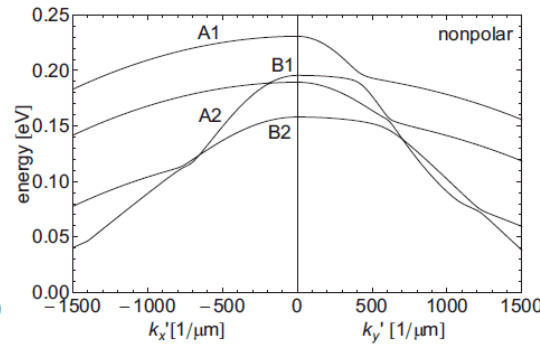
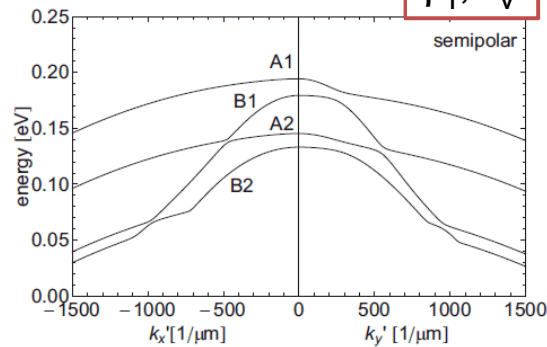
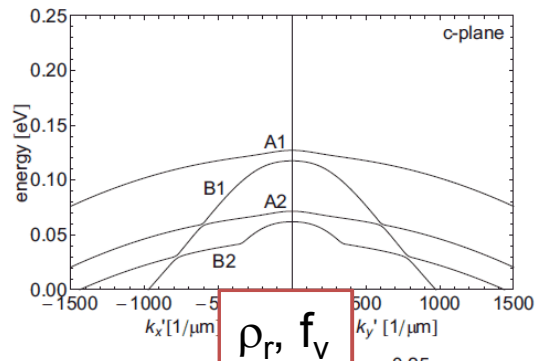


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# Crystal orientation

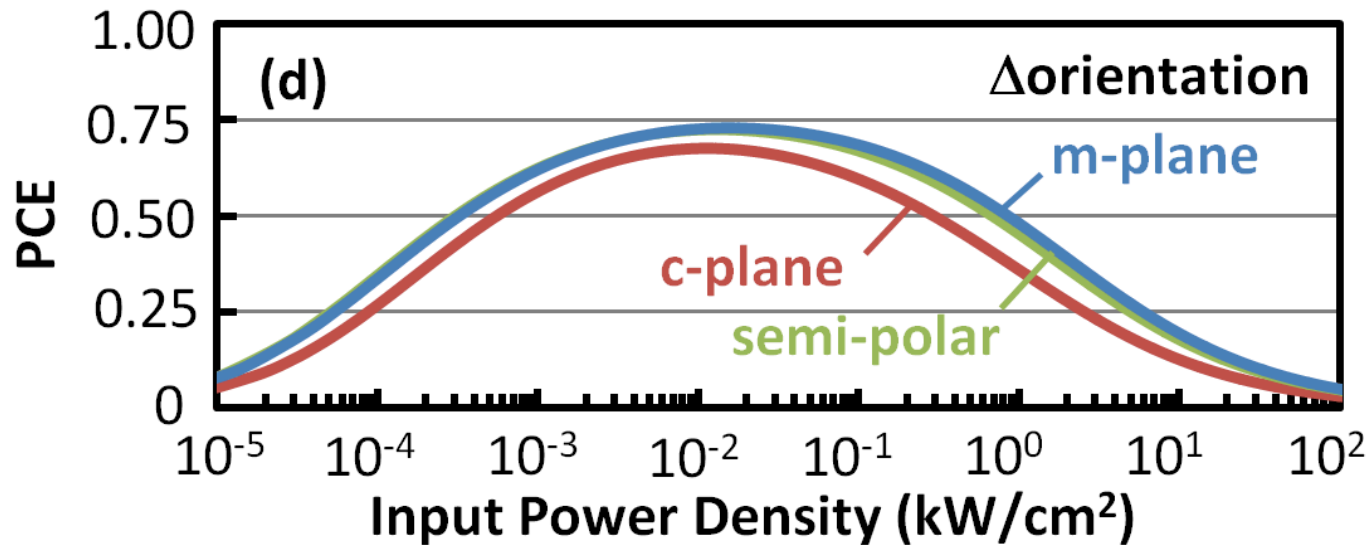


- $\eta_r = \frac{Bn^2}{An+Bn^2+Cn^3}$
- $R_{sp} = Bnp = \frac{\pi q^2}{n_{opt}c\epsilon_0 m_0 \omega} \sum |I|^2 |\hat{e} \cdot p|^2 \rho_r f_c f_v$
- $B = \frac{C_0}{p} \sum_{i=A1, B1} |I|^2 \rho_{r,i} f_{v,i}$
- Can make similar arguments for A and C.



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  $1\text{kW}/\text{cm}^2$  PCE ~ 38% c-plane
  - PCE ~ 48% for m-plane

# State-of-the-art blue LD

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

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

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

$\eta_{inj}$	0.97
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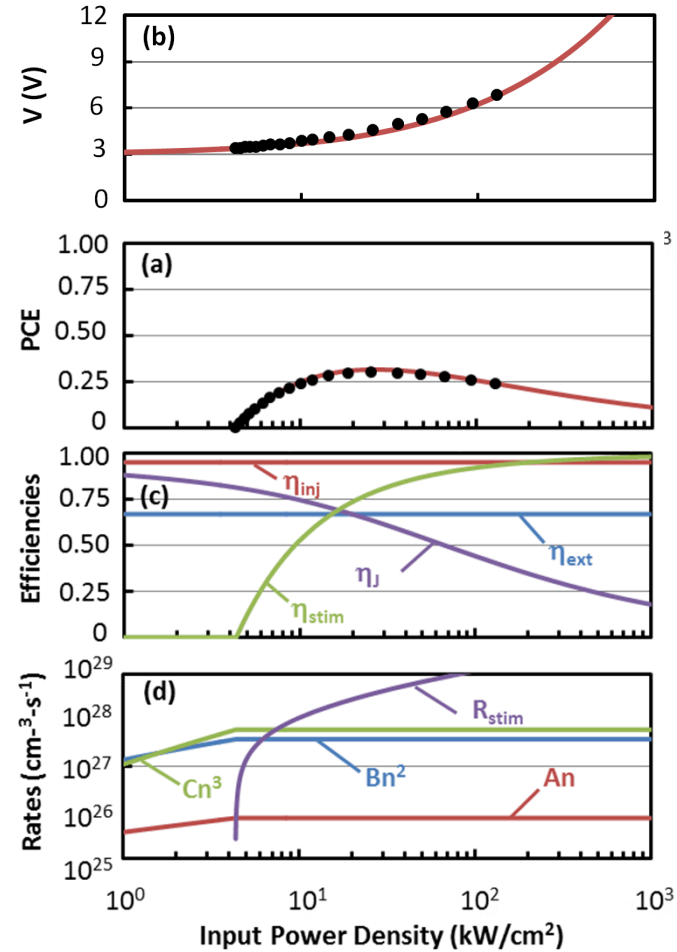
- Stimulated efficiency:  $\eta_{stim}$

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

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

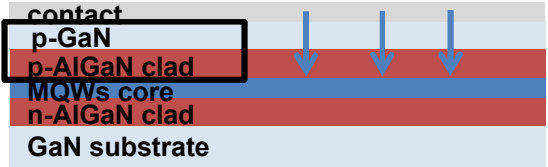
$\alpha_i$	6 (1/cm)
$\alpha_m$	12.1 (1/cm)

A, B <sub>o</sub> , C <sub>o</sub> n*, d	Same as LED
$\alpha_i$	6 (1/cm)
$\alpha_m$	12.1 (1/cm)
$n_{tr}$	$1.75 \times 10^{19} \text{ cm}^{-3}$
$\Gamma g_0$	23.9 (1/cm)
$A_{LD}$	$1.8 \times 10^{-4} \text{ (cm}^2\text{)}$

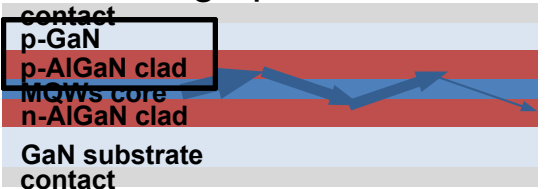


# Projection of LD improvements

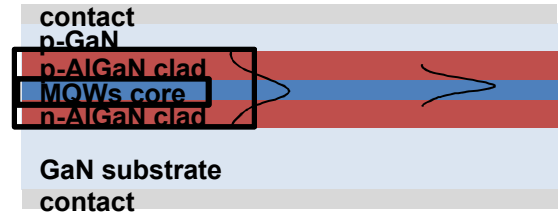
Reduced series resistance:



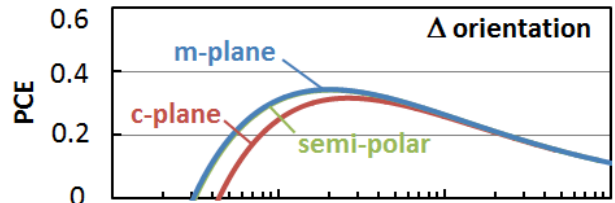
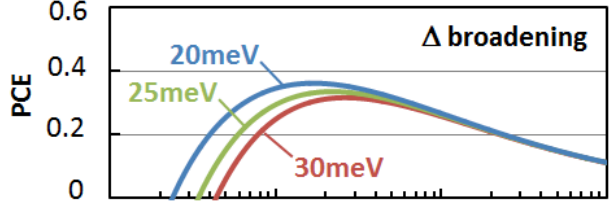
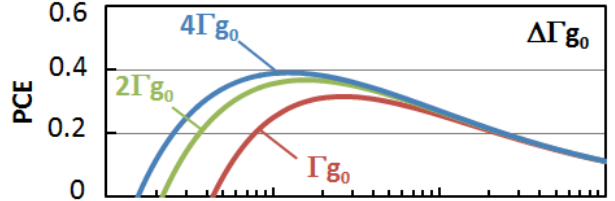
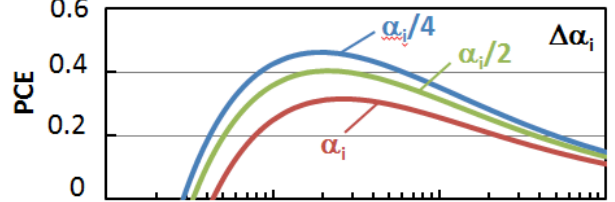
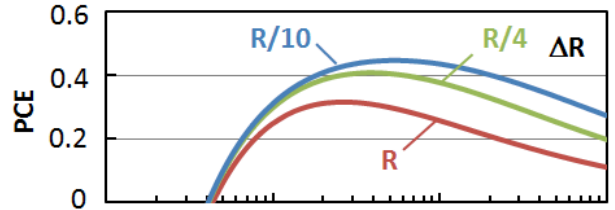
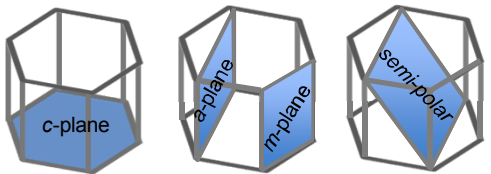
Decreasing optical loss:



Increasing modal gain:

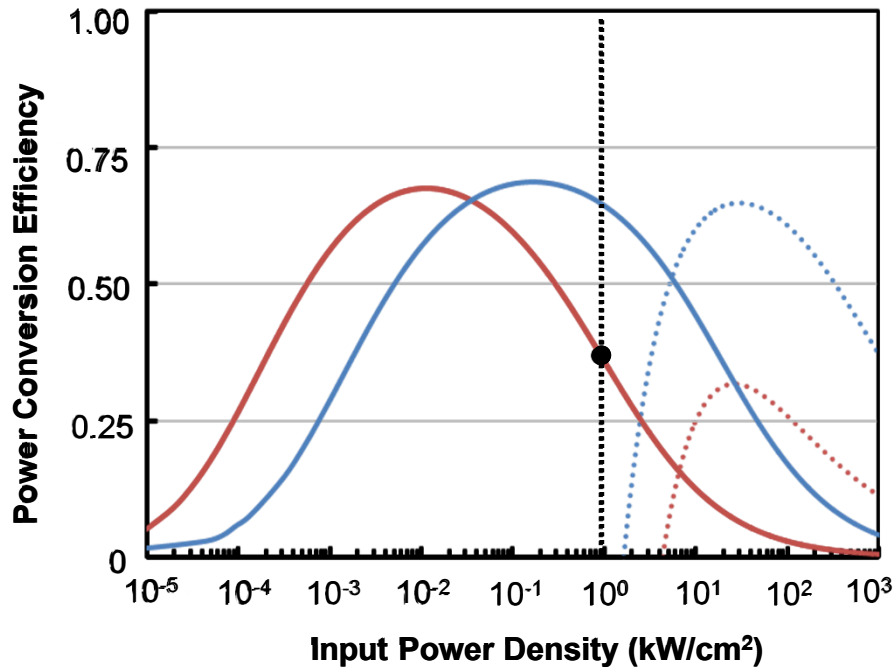


Change crystal orientations:



Input Power Density (kW/cm<sup>2</sup>)

# Projection of efficiency improvements



## LED

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

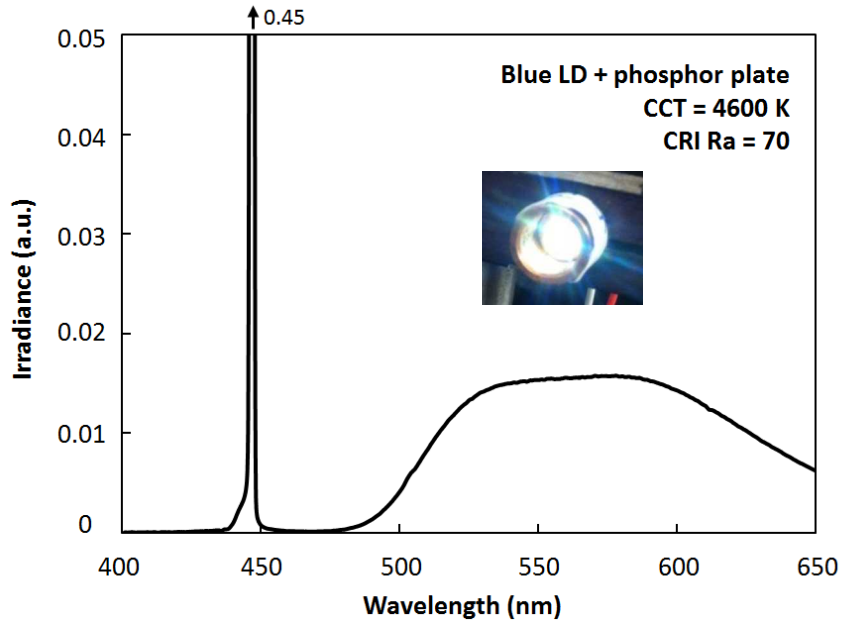
## LD

	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

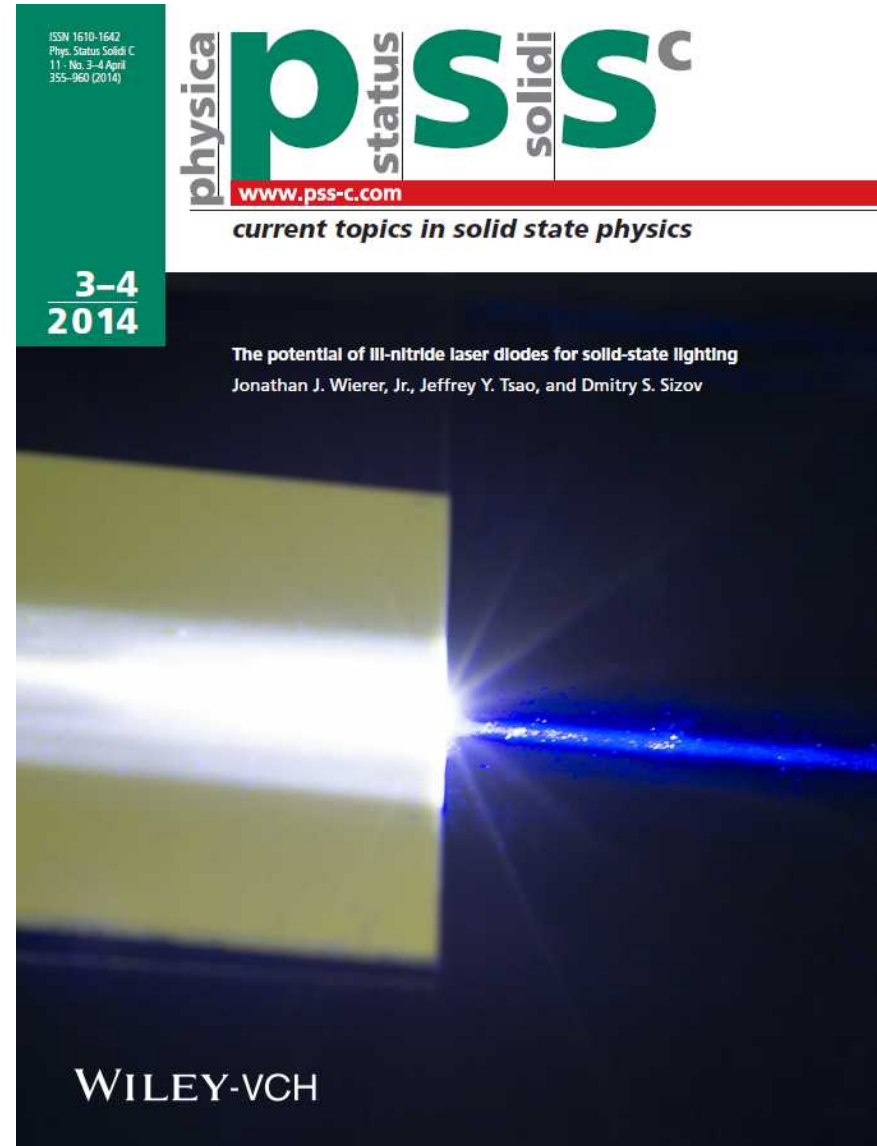
- Blue LD has the potential to have similar peak efficiencies as LEDs, but at much higher output powers.

# White light from LDs

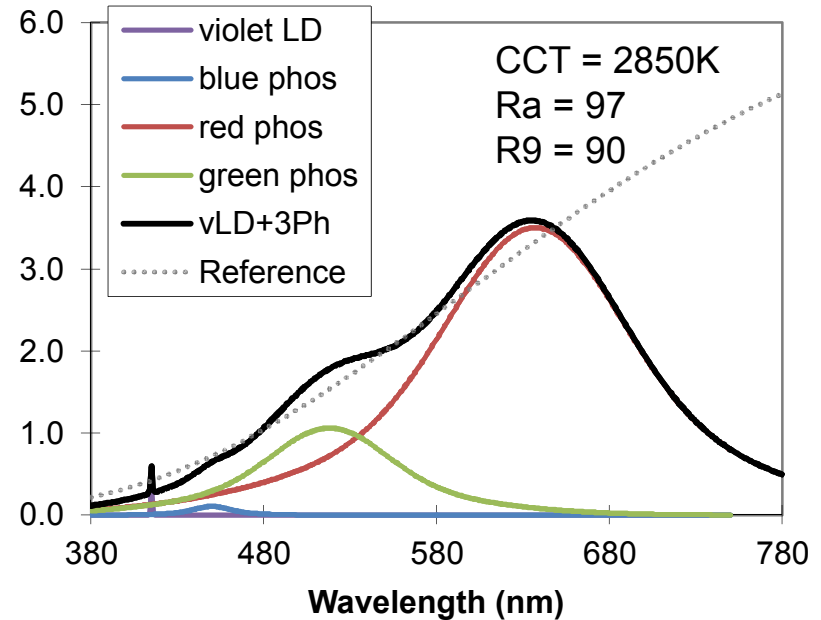
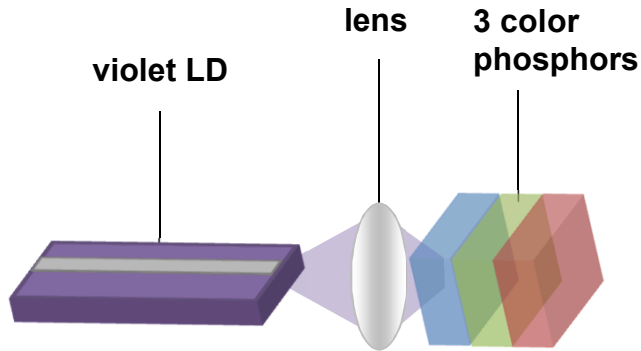
# Phosphor converted LD (PC-LD) white



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



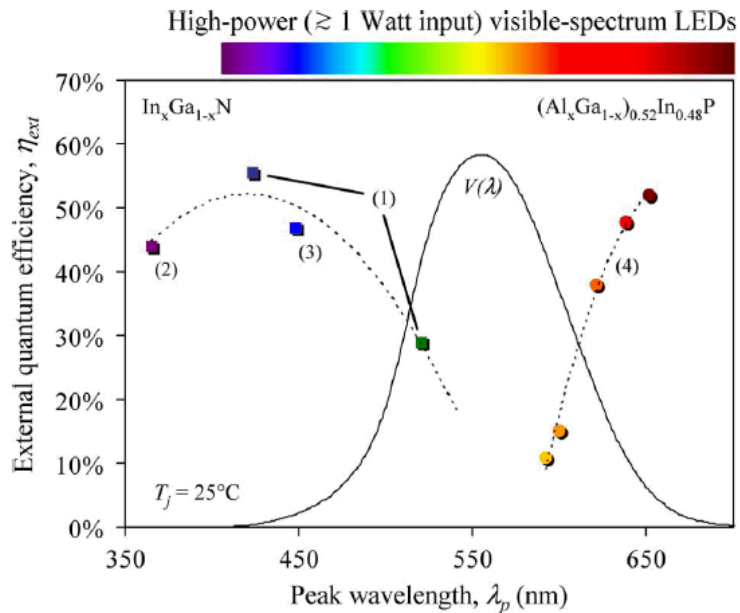
# Violet pumped PC-LD



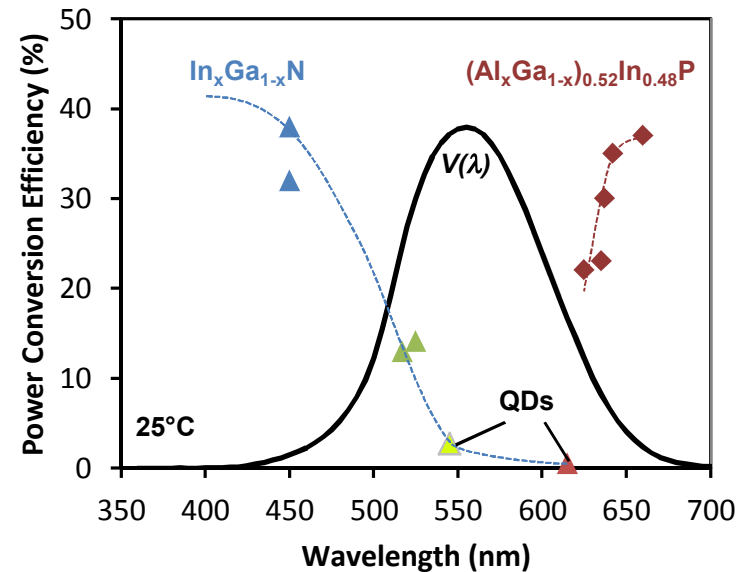
- Simulation of 415nm LD pumping 3 phosphors
  - 450 nm, 518 nm, and 637 nm
- Just like violet PC-LED solution, the violet PC-LD could also produce high color rendering white light.
- Phosphor converted solutions cannot chromaticity tune.

# Direct emitters to produce white

## LEDs



## LDs

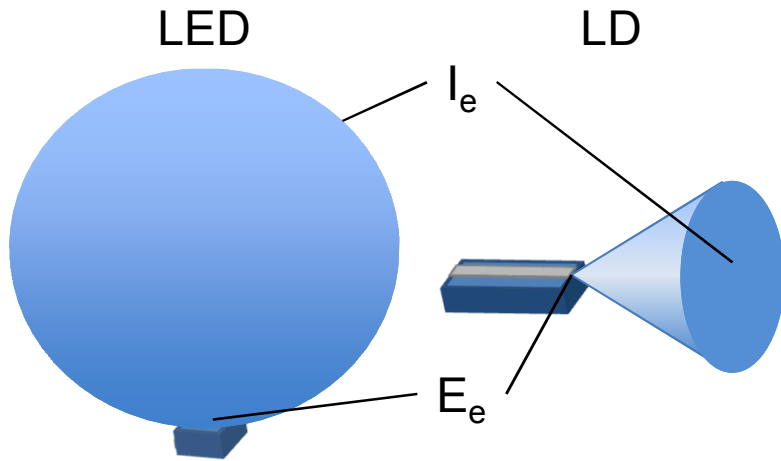


Krames, et al., IEEE J. Display Tech., June 2007

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

# LD system benefits

# Radiance of blue LEDs and LDs

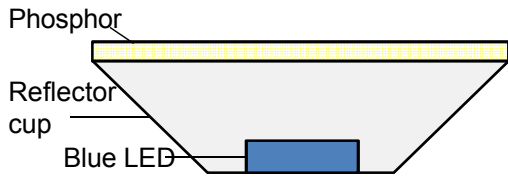


	Blue LED	Blue LD
Power (W)	1.3	2
Emitting area (cm <sup>2</sup> )	1.00E-02	1.50E-07
Emitting half angle (°)	45	15
Radiant intensity, $I_e$ , (W/sr)	0.71	9.34
Irradiance, $E_e$ , (W/cm <sup>2</sup> )	130	1.33E+07
Radiance, $L_e$ , (W/sr/cm <sup>2</sup> )	71	6.23E+07

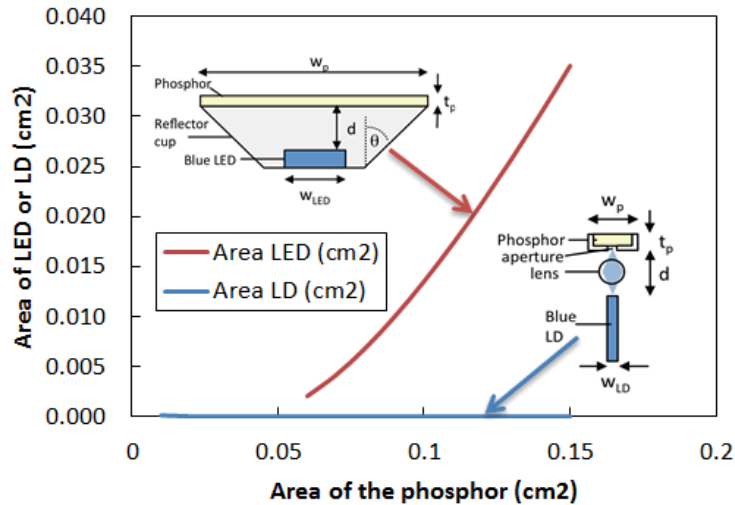
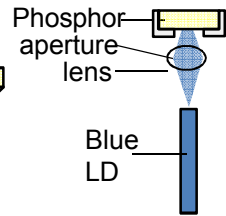
- LD benefits:
  - Irradiance (power density) is much higher in LDs.
  - Emission is directional
  - Emission is from a small aperture.
  - Superior for étendue limited optical systems (i.e. projectors).
  
- These LD benefits produce a higher radiance source and advantages when creating a white source.

# Luminance of PC-LEDs and PC-LDs

PC-LED



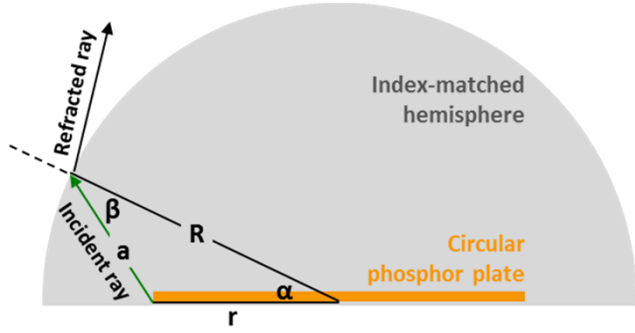
PC-LD



	PC-LED	PC-LD
<b>Power (lm)</b>	325	500
<b>Phosphor emitting area (cm<sup>2</sup>)</b>	0.09	0.01
<b>Emitting half angle (°)</b>	45	45
<b>Luminous intensity, I<sub>v</sub> (lm/sr)</b>	180	270
<b>Illuminance, E<sub>v</sub> (lm/cm<sup>2</sup>)</b>	3600	50000
<b>Luminance, L<sub>v</sub> (lm/sr/cm<sup>2</sup>)</b>	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.

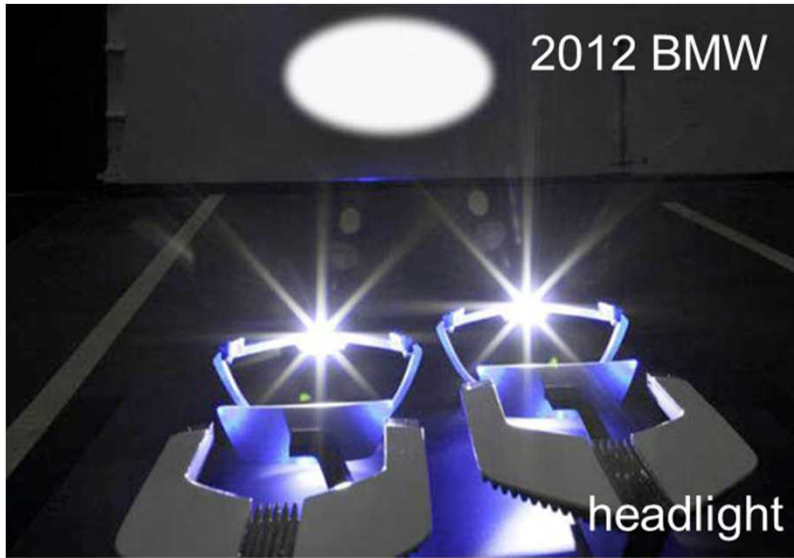
# Comparison of LED and LD luminaires



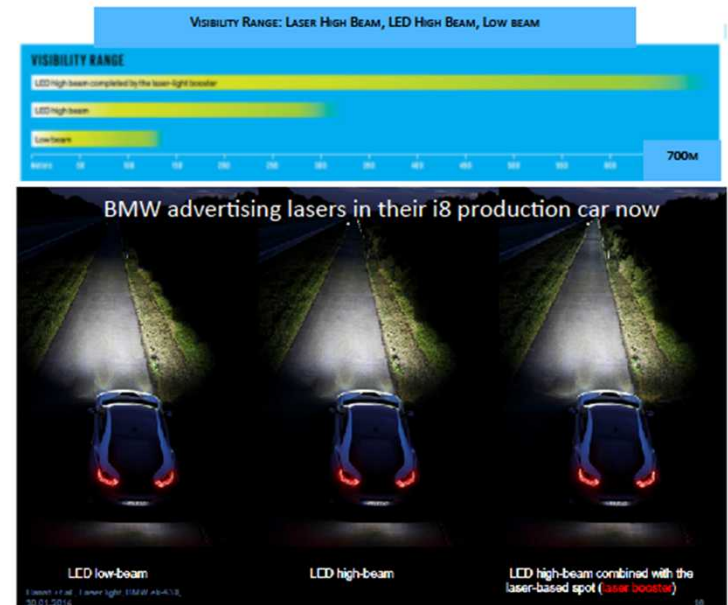
	PC-LED	PC-LD
Power (lm)	325	500
Phosphor emitting area (cm <sup>2</sup> )	0.09	0.01
Radius of lens (cm)	0.225	0.075
Area of the lens (cm <sup>2</sup> )	0.16	0.018

- 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

# High luminance laser headlights



- Can deliver white light over longer distances.
- Example is BMWs laser headlights.



# 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.
  - Smaller sources that can be projected farther.

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Thanks to D. Sizov at Corning Inc. for his contribution on LD efficiency modeling.

