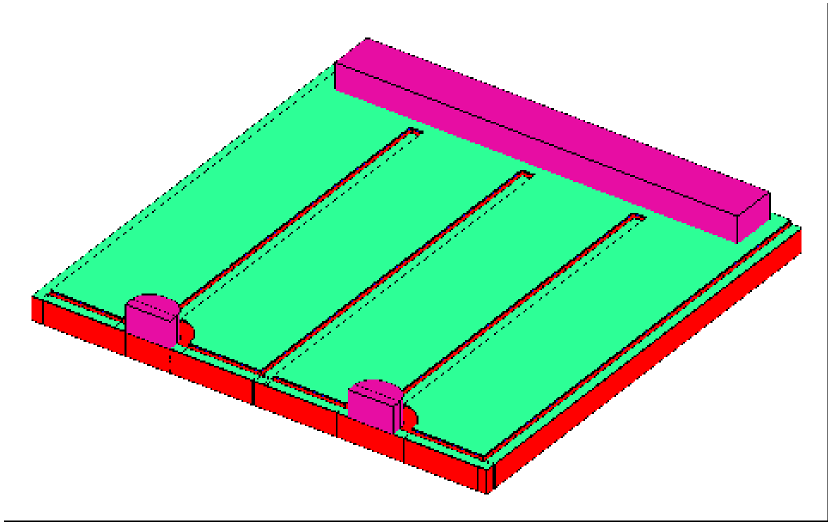
SimuLED™
Module SimuLAMP™

Engineering software package for LED design and optimization



www.str-soft.com

Prehistory of STR:

1984: Start of the MOCVD modeling activities at Ioffe Institute, St. Petersburg, Russia

1993-1996: Group for modeling of crystal growth and epitaxy at University of Erlangen-Nuernberg, Germany

History of software development

2000: Launch of development of the first specialized software
2003: First release of commercial software package
2004: First release of the software for device engineering

STR Today:

More than 40 scientists and software engineers

1 – Headquarter and R&D (consulting service and software development)
2 – Local offices
3 – Local distributors

Bulk crystal growth modeling (Si, Ge, SiGe, GaAs, InP, SiC, AlN, Al_2O_3, Optical Crystals)

Epitaxy and deposition modeling (Si, SiGe, SiC, AlGaAs, AlGaInP, AlGaInN, high-k oxides)

Modeling of device operation (LEDs, Laser Diodes, FETs/HEMTs Shottky diodes)

STR activity in software development and consulting service

Software & consulting services :

- Modeling of crystal growth from the melts and solutions: CGSim
- Modeling of polysilicon deposition by Siemens process: PolySim
- Modeling of bulk crystal growth of SiC, AlN, GaN: ViR
- Modeling of epitaxy of compound semiconductors: CVDSim
- Modeling of optoelectronic and electronic devices: SimuLED, SimuLAMP

Customer base:

- More than 160 companies and universities worldwide
- Top LED, LD and solar cell manufacturers
- Top sapphire, GaAs, GaP, GaN, AlN and SiC wafer manufacturers
- Top MOCVD reactor manufacturers

Multidisciplinary

- materials science
- physics of semiconductors
- heat transfer theory
- optics

Essentially nonlinear

- nonuniform voltage drop and IQE distributions over the active region
- self-heating in active region
- current crowding results in nonuniform light intensity distribution over the active region

Multidimensional and multiscale

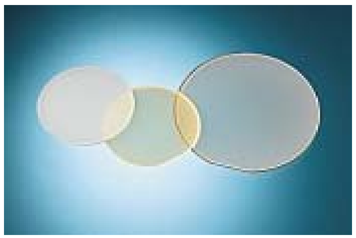
- QW thickness is ~2-10nm
- chip size is ~300µm
- luminary size is ~10mm

	General purpose software			SimuLED™
Simulation destination	Software is used as a tool demonstrating physical effects and test cases with simple geometry	Software is used by experts in modeling and users who have long-time experience in device modeling	Powerful fast engineering tool operating with actual devices designed by industry and developed by academia	SimuLED serves as a guidance for epitaxy engineers and LED designers in testing new ideas on device performance improvement
Getting started	Long time is necessary to start computations	Statement of the problem is complicated due to difficulties in geometry specification and specification of boundary conditions	The user can start computations in several hours after SimuLED installation	Intuitive User Interface operates in terms normally used by engineers. Layer by layer input of 2D layout for 3D geometry. Selection of predefined options typical for LEDs
General concept to LED simulation	Homogeneous app-roach for simulation of multiphysics and multiscale problem	Problems with uniform resolution of physical processes occurring at various spatial scales.	**Hybrid approach accounting for specific features of modern LED design**	Accurate resolution of key physical processes at each spatial scales
Computation time		Time consuming simulations		Extremely fast simulations
Hardware requirements		Special requirements to hardware		SimuLED operates on personal computers
Physical models implemented into the software	The software was developed initially for simulation of GaAs and Si-based devices	Conventional physical models used for a long time in modeling of semiconductor devices	SimuLED was initially developed as a tool for simulation of nitride-based LEDs	Both conventional and unique models of physical effects responsible for operation of modern LEDs
Materials properties		The data have to be collected by the user or there is a lack of data needed for computations		SimuLED is supplied with the database of materials properties and the user can start his computations immediately after the software installation
Hot-line support			Quick hot-line support, free software update within the license period	Interpretation of results upon customer request

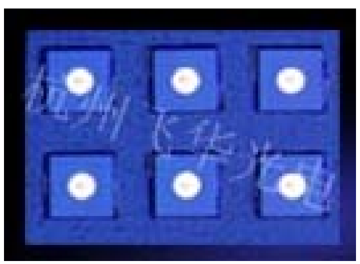
Basic tools of SimuLED™ software package

Modules for LED modeling

Epi level → Development & optimization of LED structures



Chip level → Development & optimization of LED chips



Device level → Development & optimization of LED lamps, arrays, etc.


SiLENSe

↓

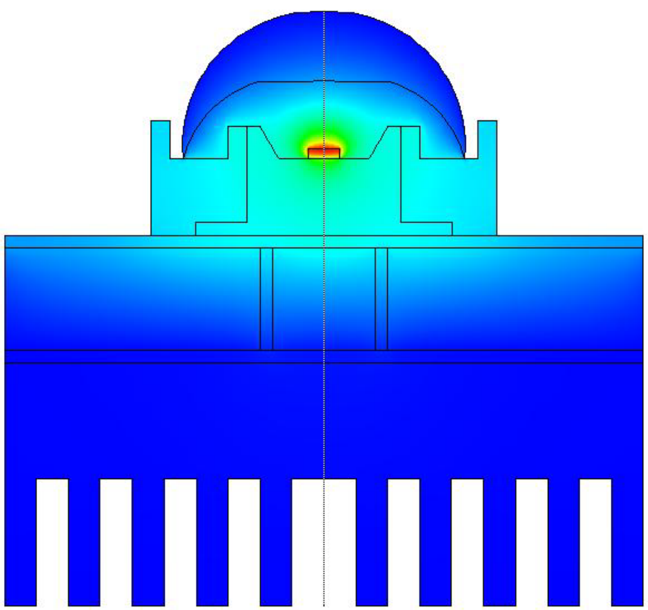
SpeCLED
RATRO

↓

SimuLAMP **New!**

Data exchange between modules is minimized.
Modules can work in standalone mode

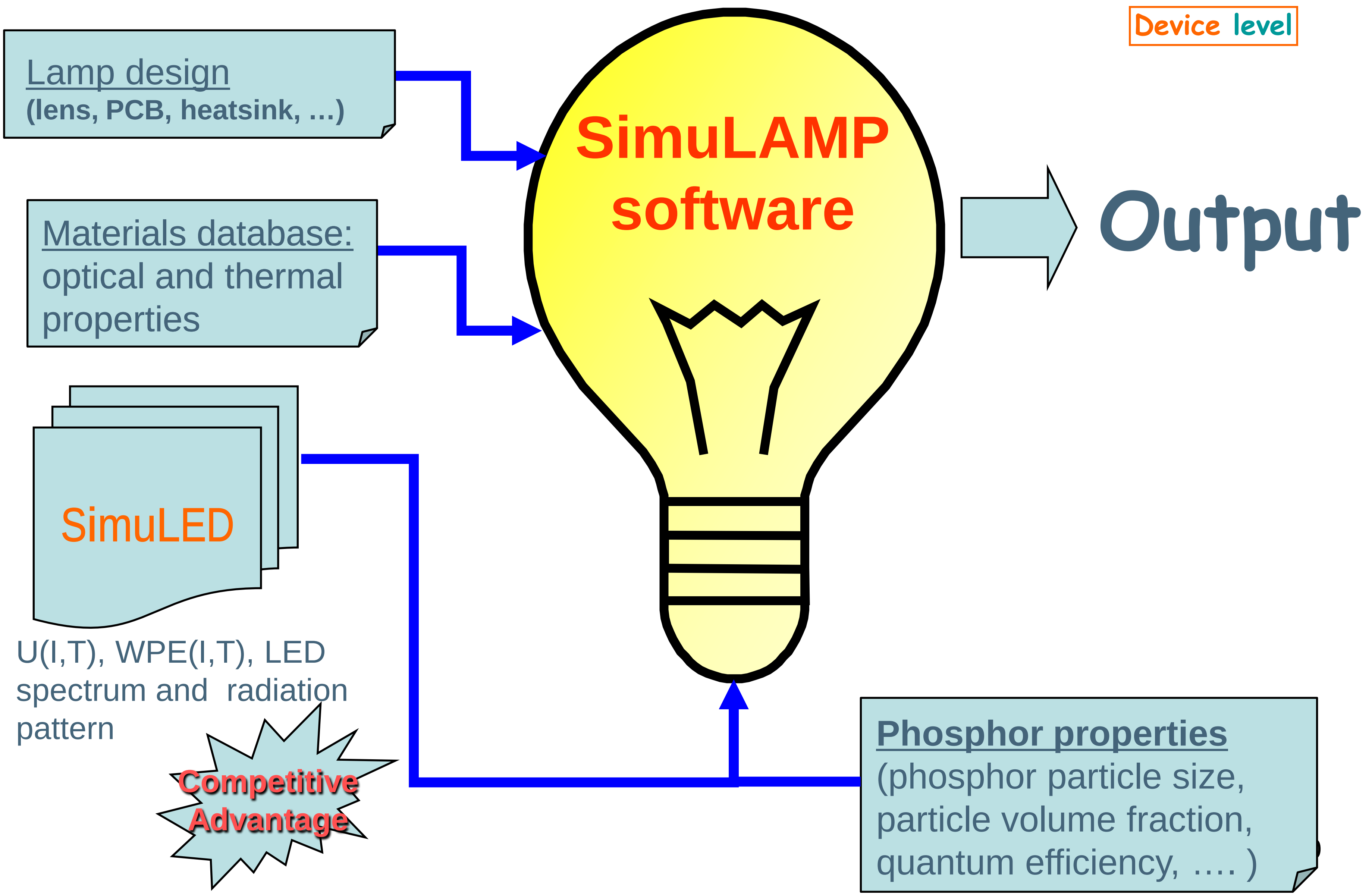
Software for Optical and Thermal Management of LED Lamps



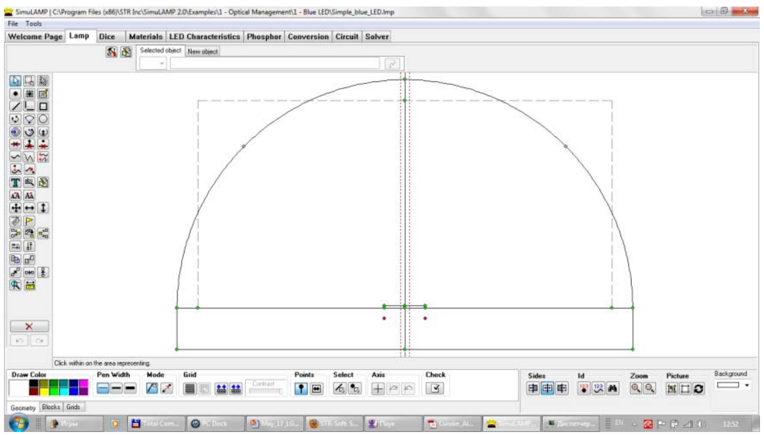
SimuLAMP™

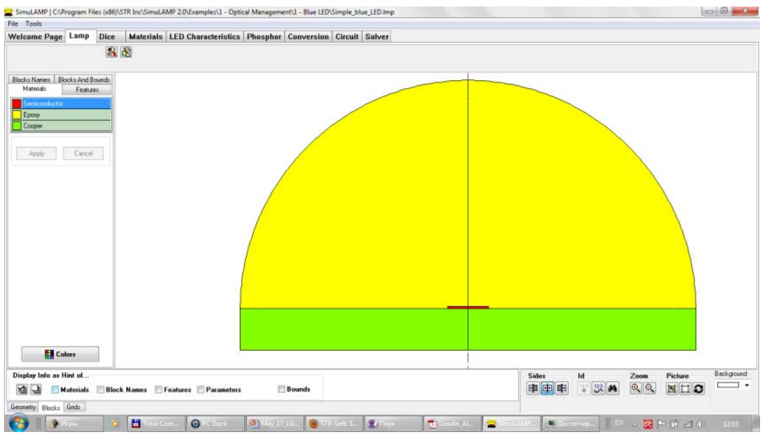
Device level

Input/Output data in SimuLAMP software

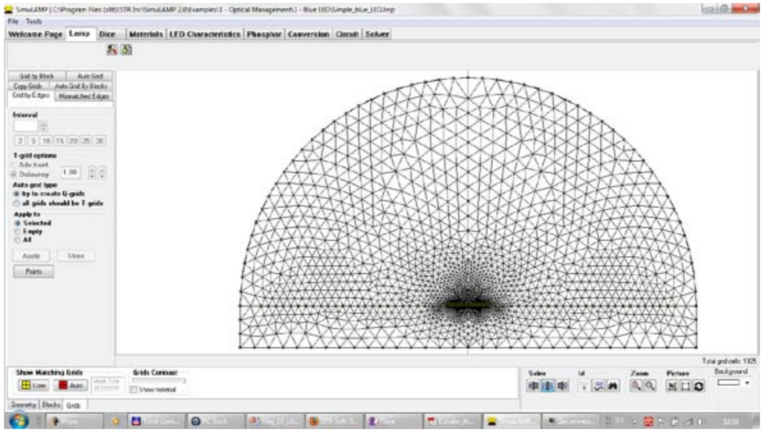


SimuLAMP software package is designed for modeling of LED lamp operation. It has user-friendly graphical user interface (GUI) allowing the user to specify the geometry and physical parameters of LED lamps, run the computations and visualize the results.

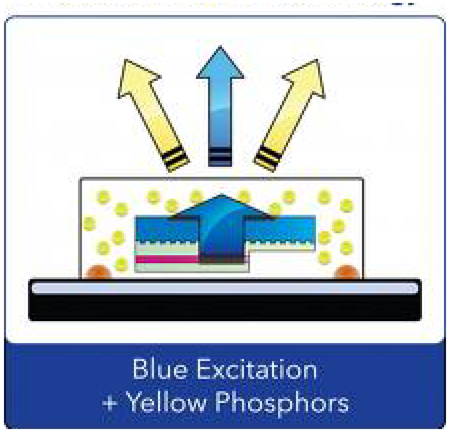




SimuLAMP can be used as a stand-alone tool or coupled with SpeCLED™ and RATRO™ software package which provides the chip I-V characteristics as a function of temperature.



Output from SimuLAMP modeling



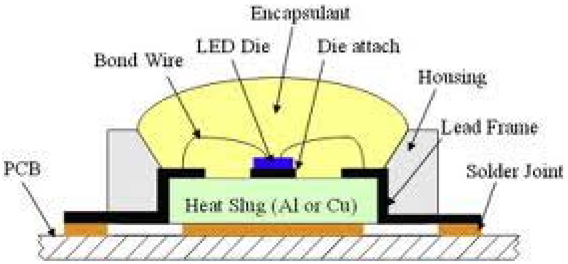
- Solution of coupled optical/thermal problem in a complex package geometry accounting for heat release in the LED chip and heat release in an encapsulant due to light absorption and Stokes shift

- Advanced model of light conversion in individual phosphor and phosphor mixtures (for white-light LED lamps)

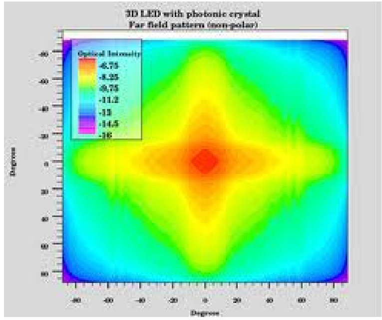
- Support of single- and multichip package configurations including RGB LEDs

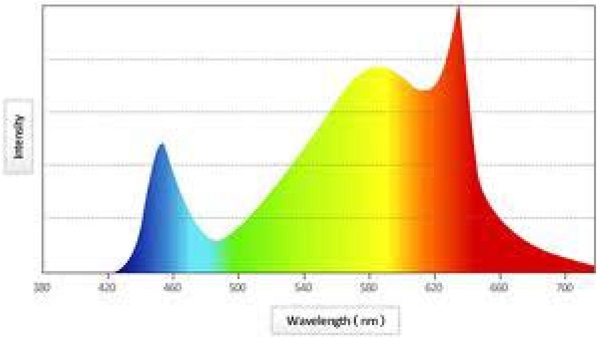
- Simulations of the electrical circuit used in operation of multi-pixel LED array

- Analysis of package operating in DC/AC/Quasi-CW modes



Competitive Advantage





Characteristics of LED lamps predicted by SimuLAMP:

- Temperature distribution over the LED package, thermal resistance

- Near-field and far-field radiation patterns

- Output light spectrum, color uniformity

- Optical losses in the package

- CRI, CCT and other characteristics of white-light LEDs

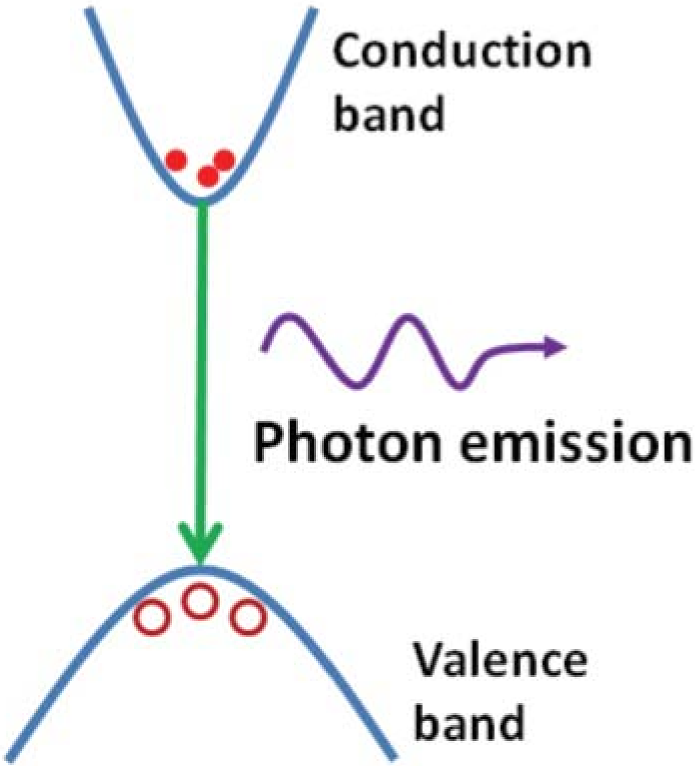
Spectral ray tracing procedure simulates propagation of photons inside the LED lamp and their extraction from the lamp

Angle: isotropic or Lambertian

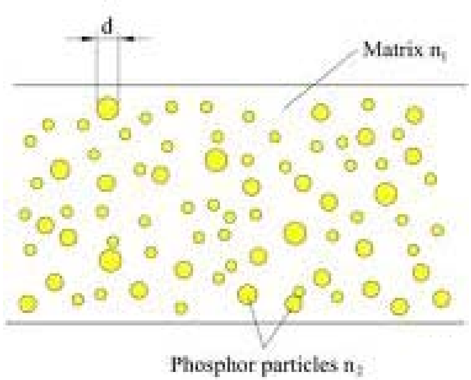
Photon wavelength is determined via random choice with the probability corresponding to the LED emission spectrum

The initial energy of the photon W_{ph} is assumed to be equal the ratio of the LED chip optical power to the number of traced rays

$$W_{ph} = W_{ph}^{\,0} \exp(-\alpha_i L)$$



There are three scattering models that can be used for calculations of scattering/absorption cross-sections and scattering pattern in **SimuLAMP** simulator.

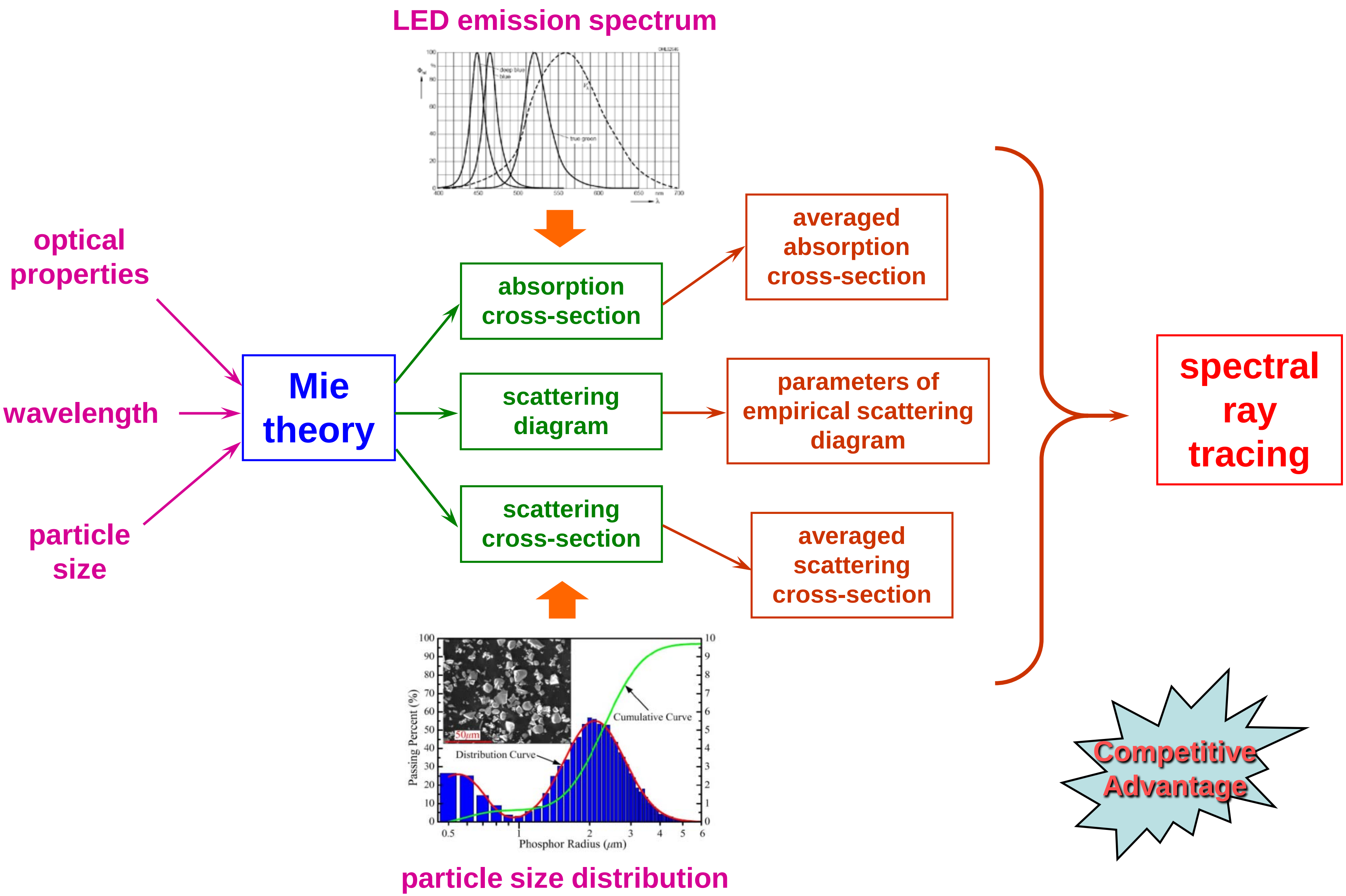


The Mie model considers the light interaction with the spherical particles of arbitrary size.

The Rayleigh model is applicable to nano-phosphors with the particle sizes much less than the wavelength of light.

The Henney-Greenstein model is based on the empirical formula for the scattering pattern, which is found to work well as the approximation for various experimental data on the light scattering by particles, dust, aerosols, etc.

Models of light conversion

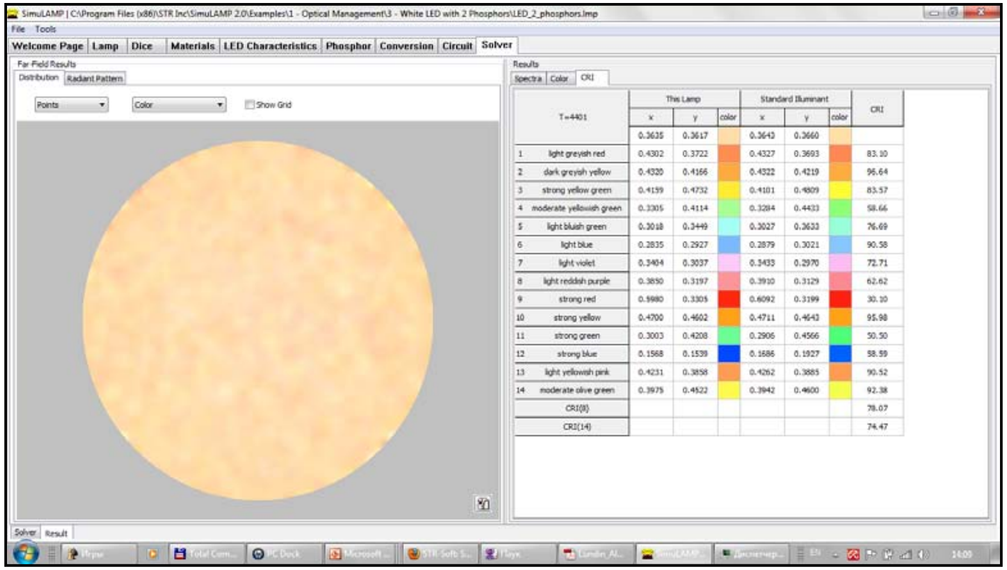


Photons with different wavelength extracted from the LED lamp are counted in the far-field zone to produce the emission spectra *S(λ)* corresponding to a certain observation angle.

These spectra are analyzed to estimate the white light quality in terms of conventional characteristics.

The emission spectrum *S(λ)* can be characterized by the following parameters:

- color coordinates *x* and *y* in the CIE color diagram
- correlated color temperature (CCT)
- color rendering index (CRI)



To obtain the temperature distribution inside the lamp, the heat transfer equation is solved

$$c(\mathbf{r},T)\rho(\mathbf{r},T)\frac{\partial T}{\partial t} = \nabla\cdot\left[\kappa(\mathbf{r},T)\nabla T\right] + Q(\mathbf{r},T)$$

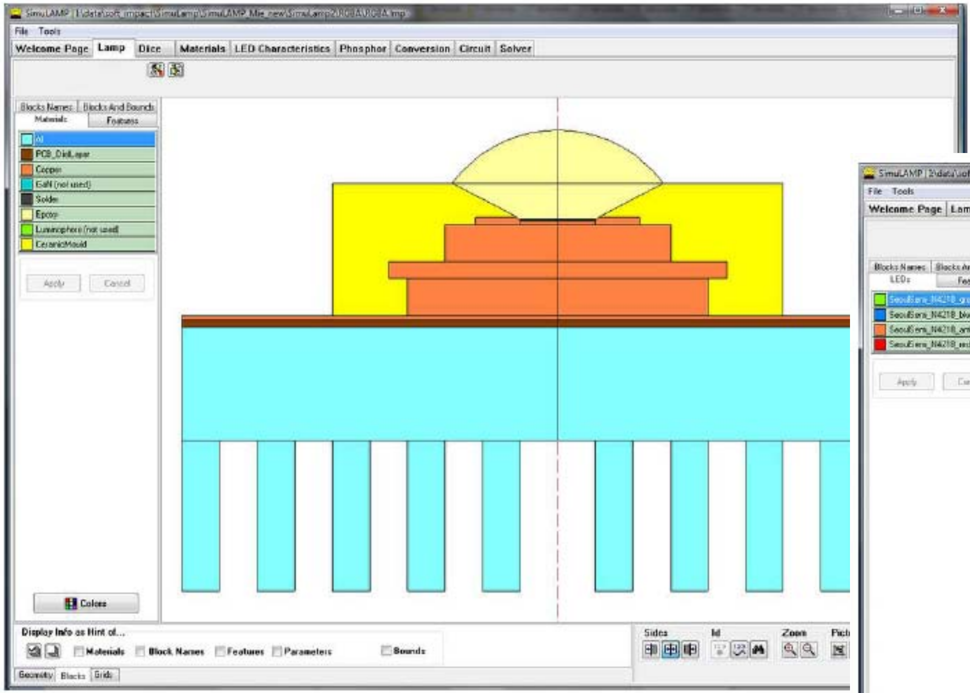
The general boundary conditions used for equation above are

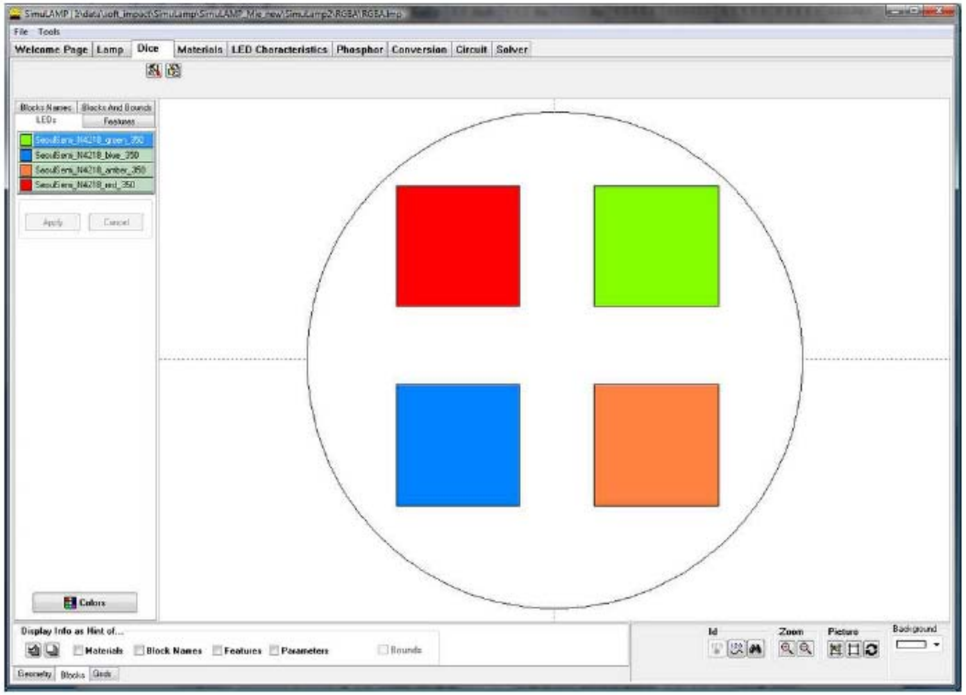
Competitive Advantage

$$-\kappa(\mathbf{n}\cdot\nabla T_s) = \alpha(T_s - T_a) + \varepsilon\sigma(T_s^4 - T_a^4)$$

There are three types of the heat source in the lamp, namely, self-heating of the LED chips, light absorption and Stokes shift release in the conversion medium, and light absorption in the lamp units and boundaries.

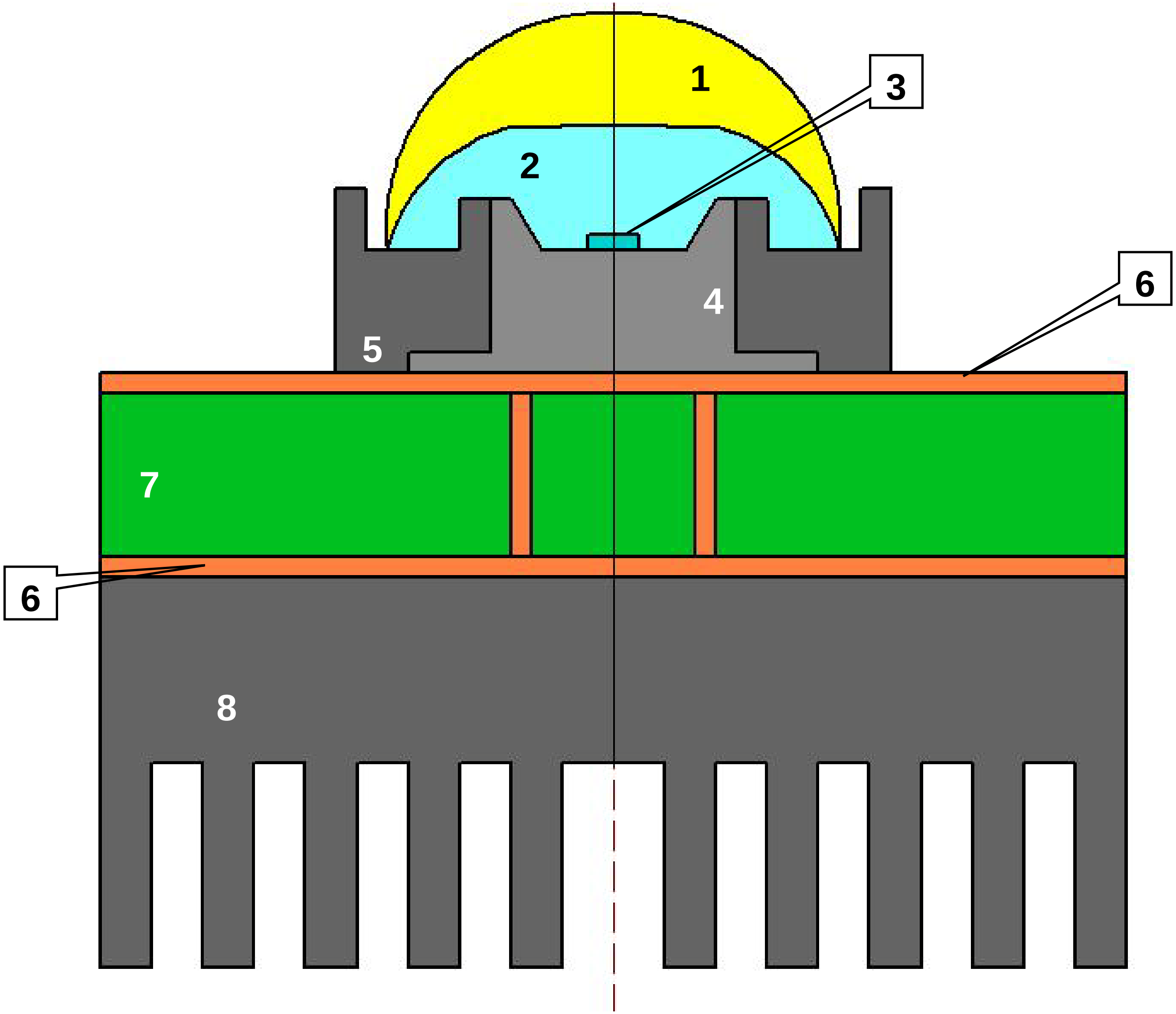
To simplify input of the geometry, the whole lamp is considered as an axisymmetric object, while the submount with single or several LED dice is simulated in a 3D way. So, the user needs to specify 2D side view of the lamp and 2D layout of the submount.





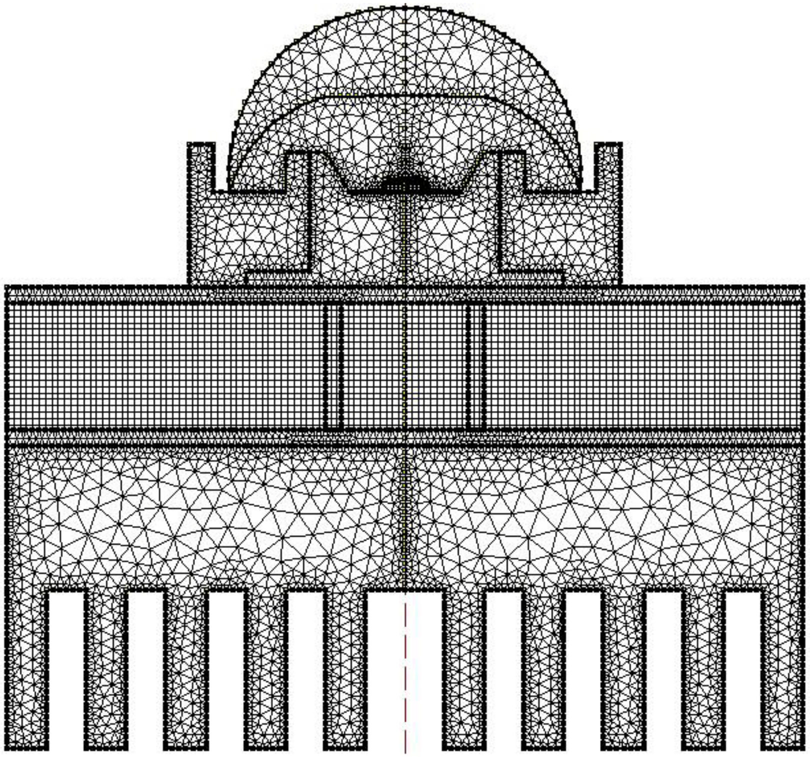
Typical design of LED lamp specified by SimuLAMP

1 - Lens
2 - Silicone
3 - Crystal
4 - Heat Sink
5 - Frame
6 - Foil
7 - Textolite plate
8 - Radiator

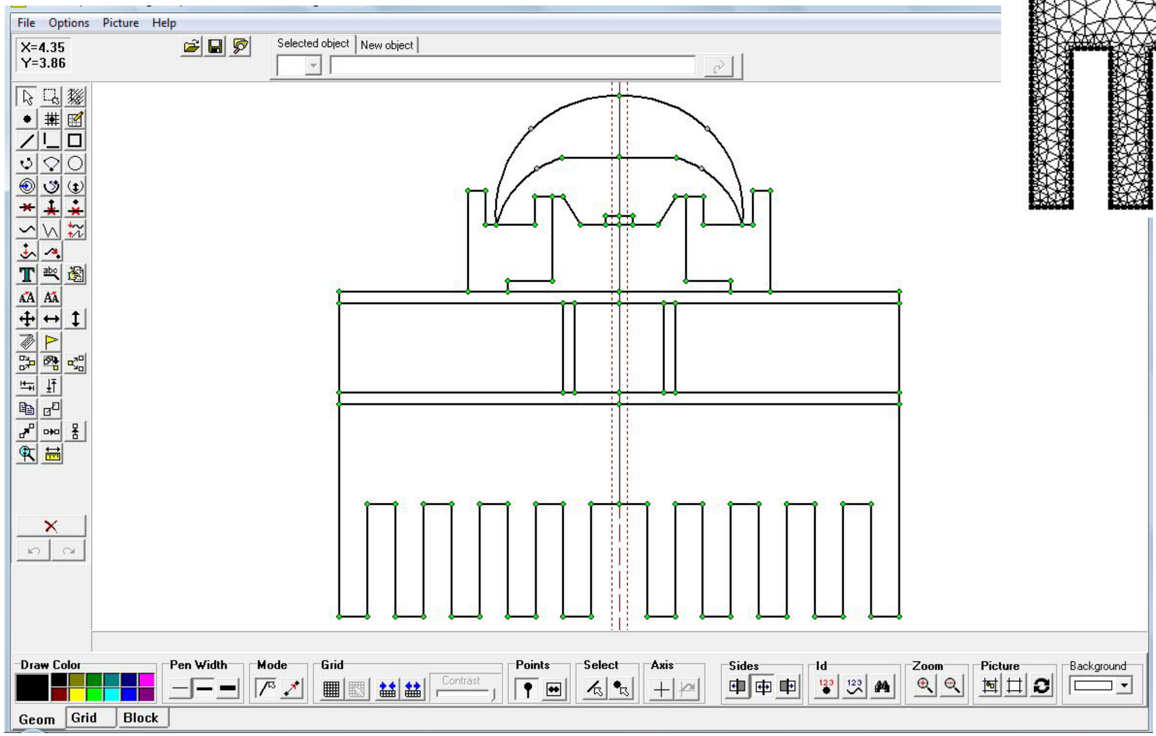


Device level

Device level



Geometry specification



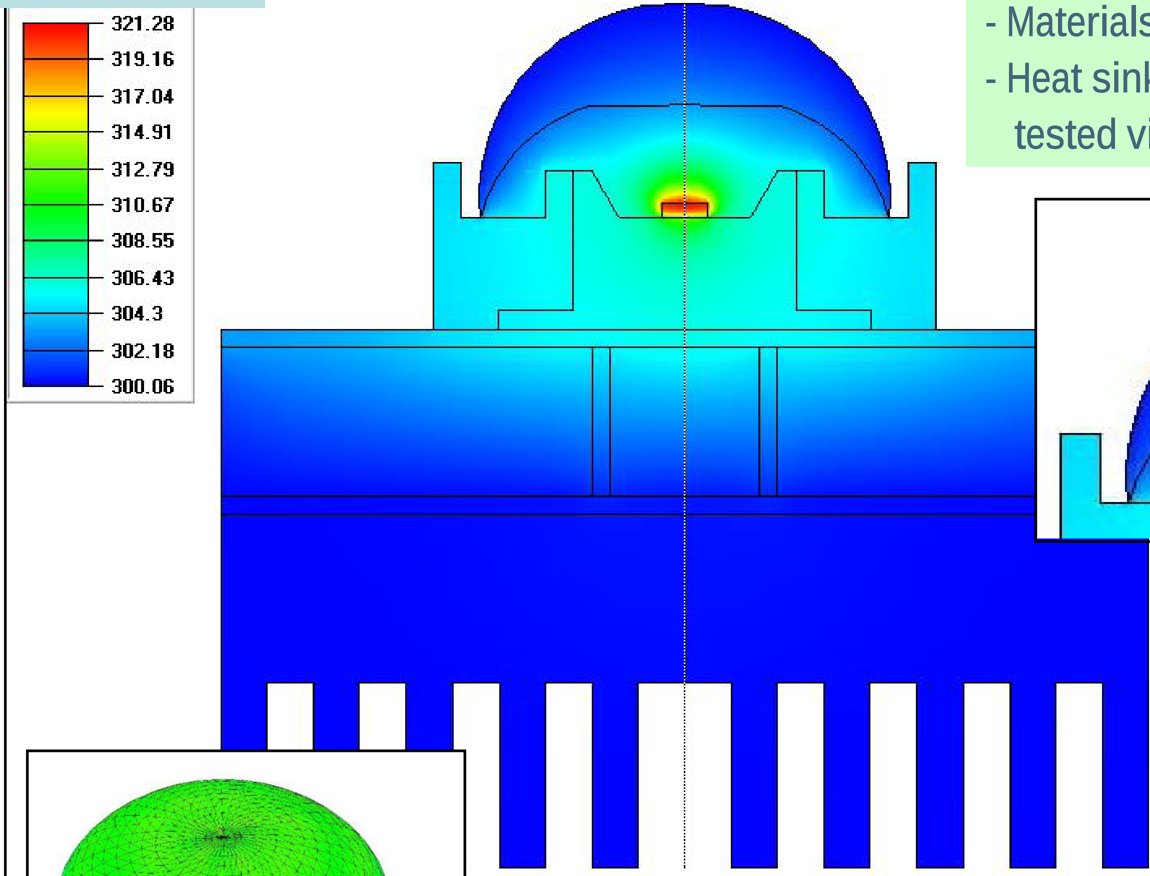
Automatic grid generation

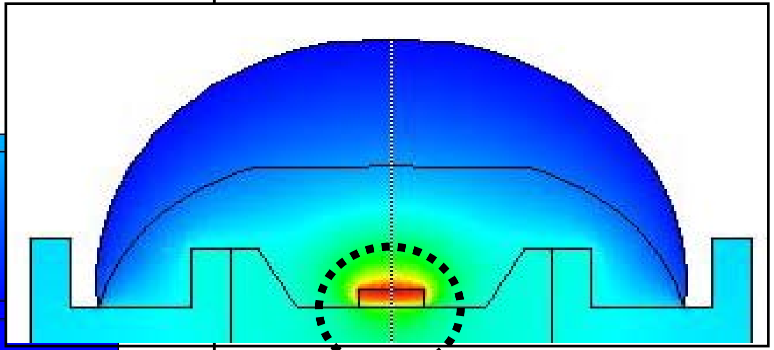
- ✓ Structured, unstructured, and combined grids are supported
- ✓ Mismatched grids are available

Temperature distribution in the lamp and near-field distribution

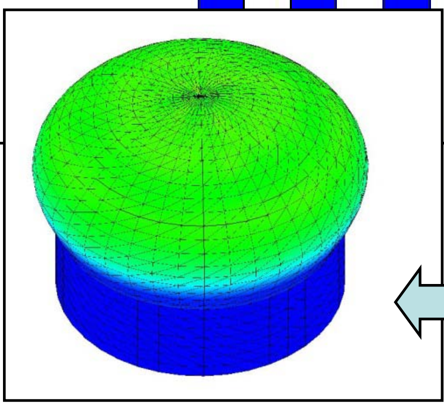
SimuLAMP allows analysis the effect of
- LED design
- Materials properties
- Heat sink design can be tested via “what if” scenario

Temperature, K

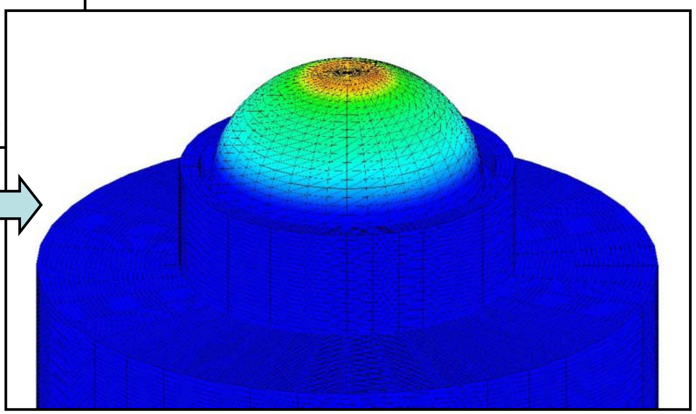




Prediction of p-n junction temperature



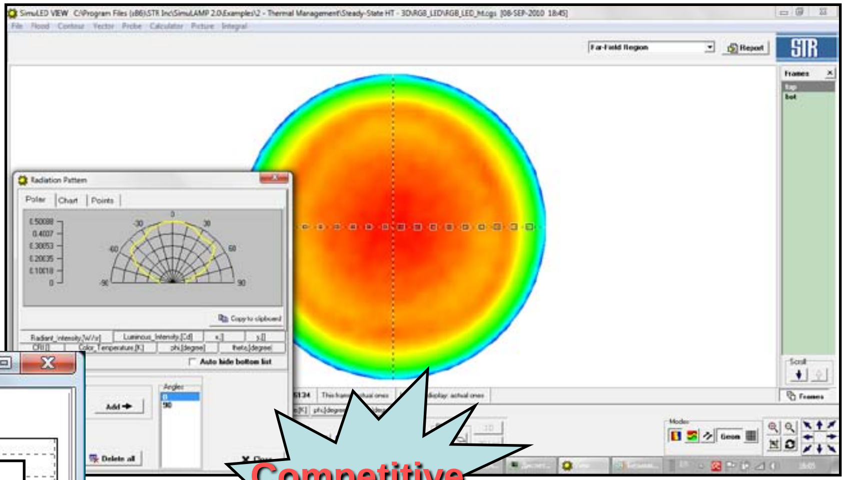
Near-field intensity distribution predicted in various lamp designs

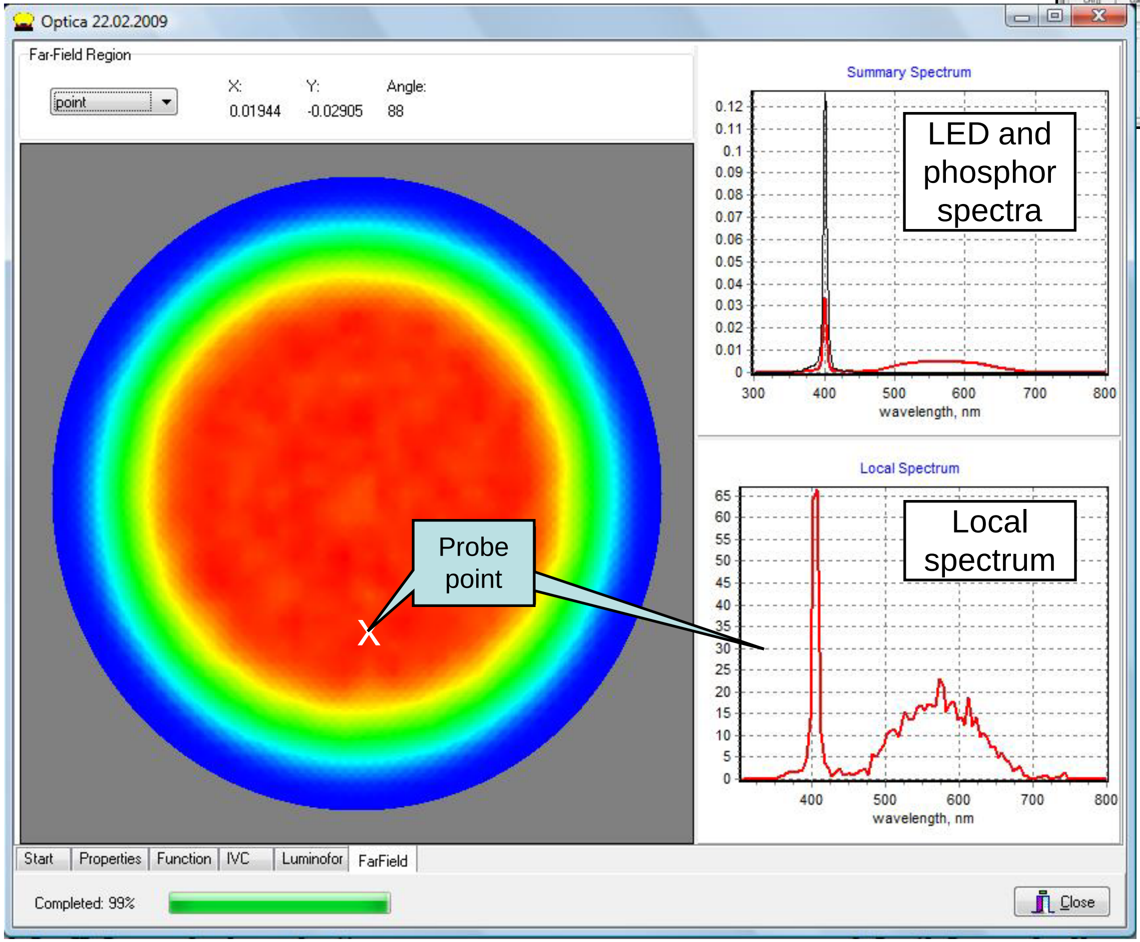


Radiation pattern and Far-field Intensity distribution

Device level

Radiation pattern predicted in computations

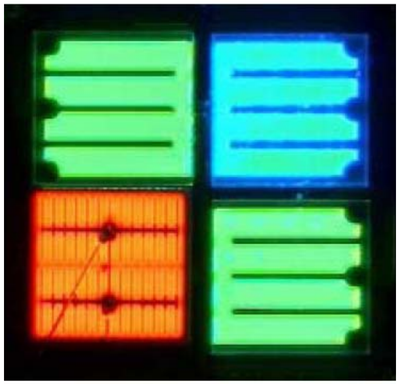




Probe tool for analysis of color uniformity

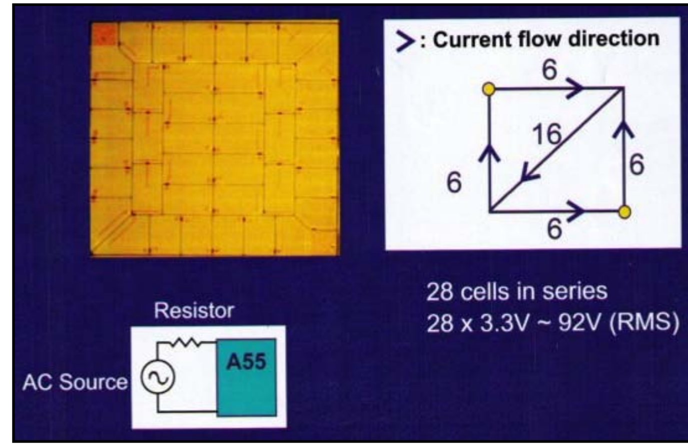
Multi-chip packages and AC LEDs

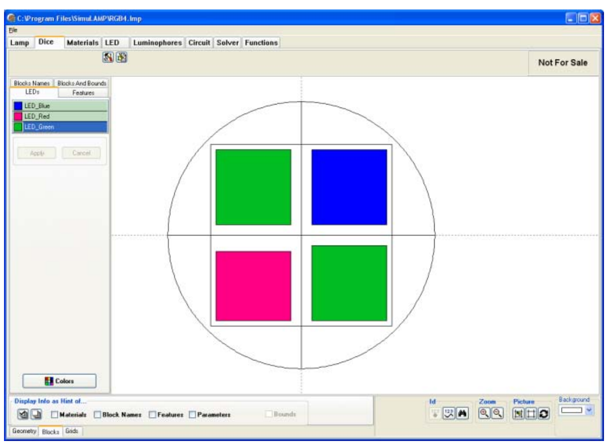
Device level

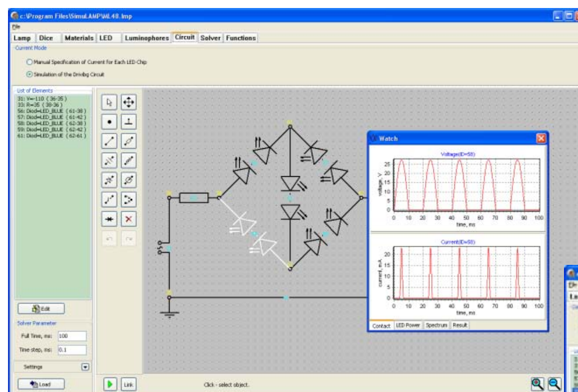


position of red, blue, and green LEDs in a multi-chip LED (Arima Optoelectronics)

interconnections in an AC LED lamp (Epistar)

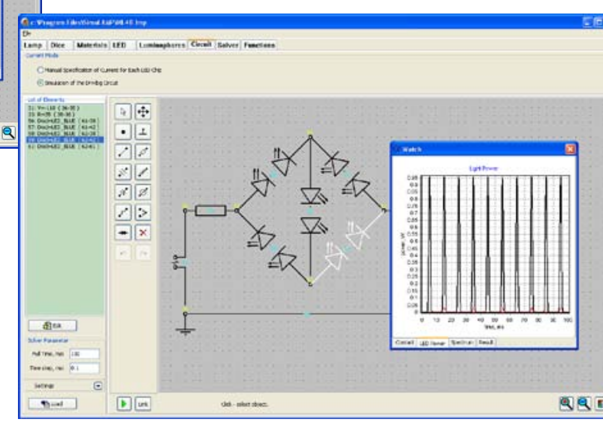


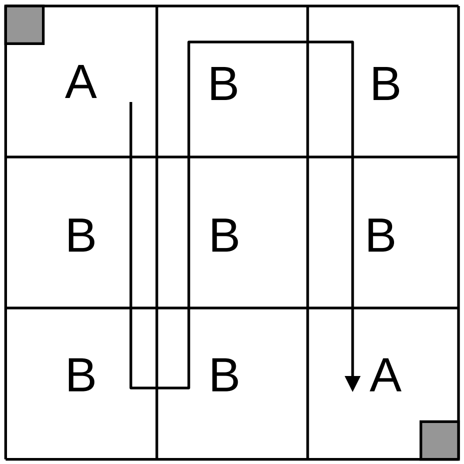




simulated current through the lamp

simulated optical power





- ✓ 3x3 chip array connected in series
- ✓ Chips are of two types, A and B

SpeCLED
Simulation of chip A
→ ***.tivc file**
for chip A
→

SpeCLED
Simulation of chip B
→ ***.tivc file**
for chip B
→

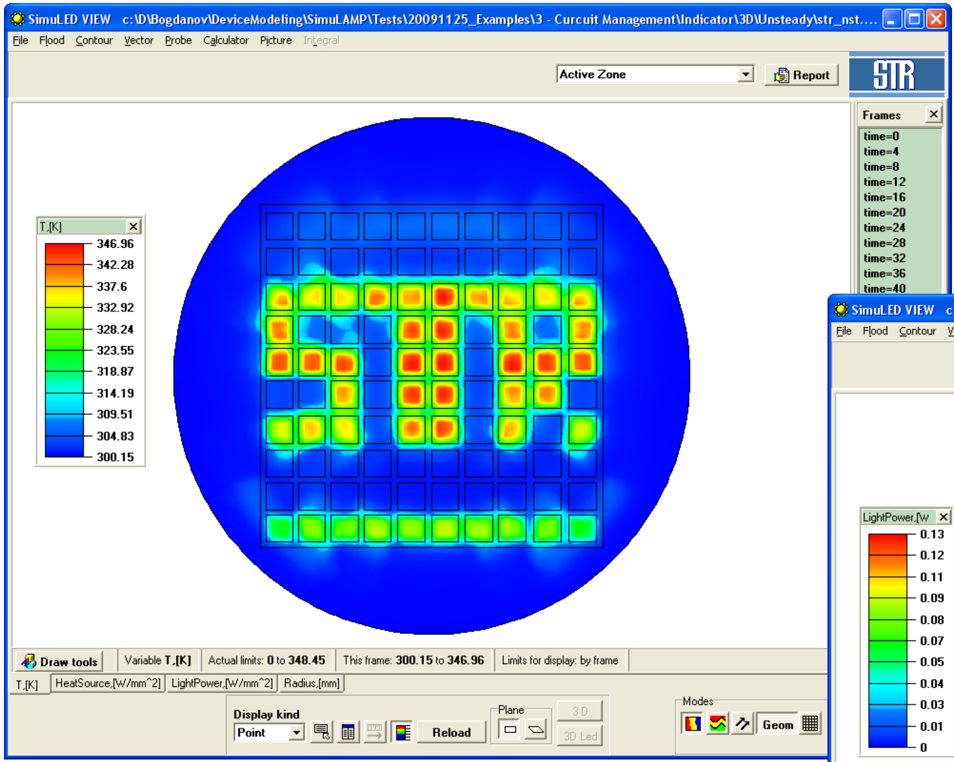
SimuLAMP
Simulation of the whole array including both electrical and thermal effects

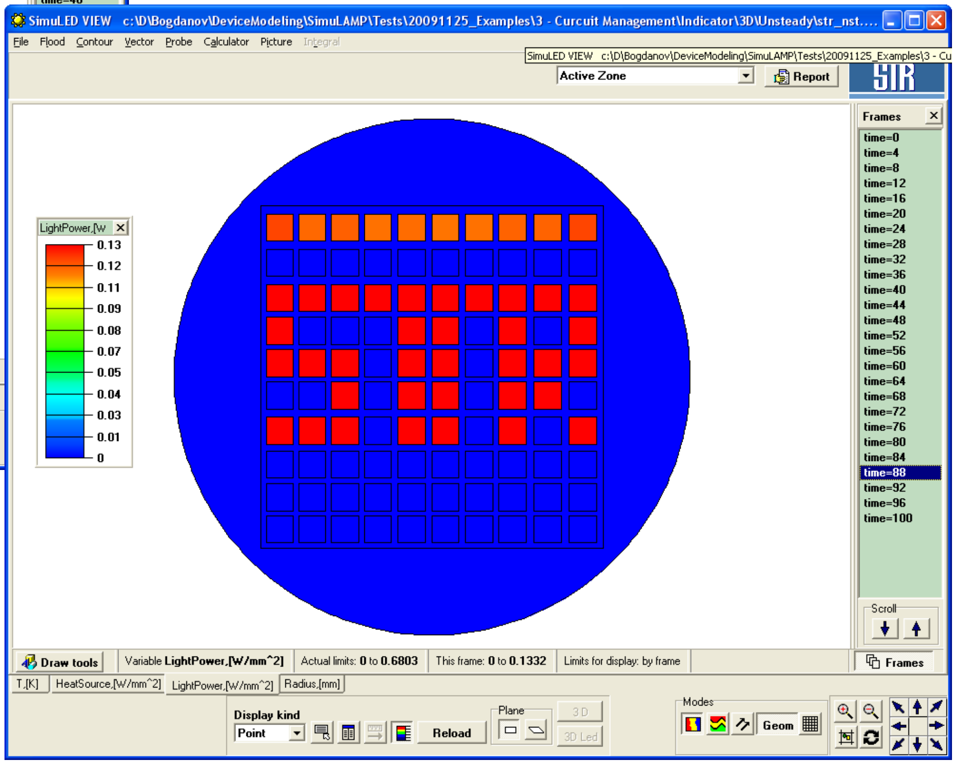
Use of all software capabilities is effective for simulation of series chip connection

DC operation of LED array integrated in a package

Operation of a lamp containing 100 LEDs in the package

light intensity distribution





temperature distribution

Device level

A Monolithic White LED with an Active Region Based on InGaN QWs Separated by Short-Period InGaN/GaN Superlattices

A. F. Tsatsulnikov[a, b, ^], W. V. Lundin[a, b], A. V. Sakharov[a, b], E. E. Zavarin[a, b], S. O. Usov[a, b], A. E. Nikolaev[a, b], N. V. Kryzhanovskaya[b, c], M. A. Synitsin[b, c], V. S. Sizov[a, b], A. L. Zakgeim[b], and M. N. Mizerov[b]

[a]*Ioffe Physicotechnical Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia*

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[b]*Scientific−Technological Center for Microelectronics and Submicrometer Heterostructures, Ioffe Physicotechnical Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia*

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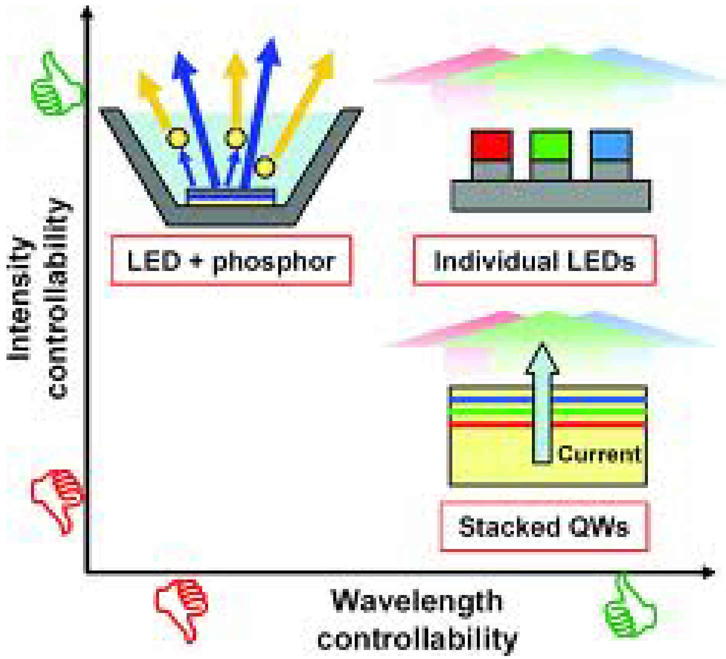
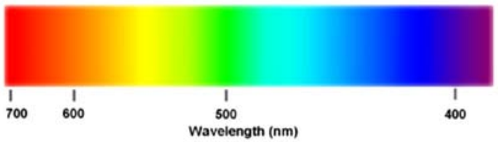
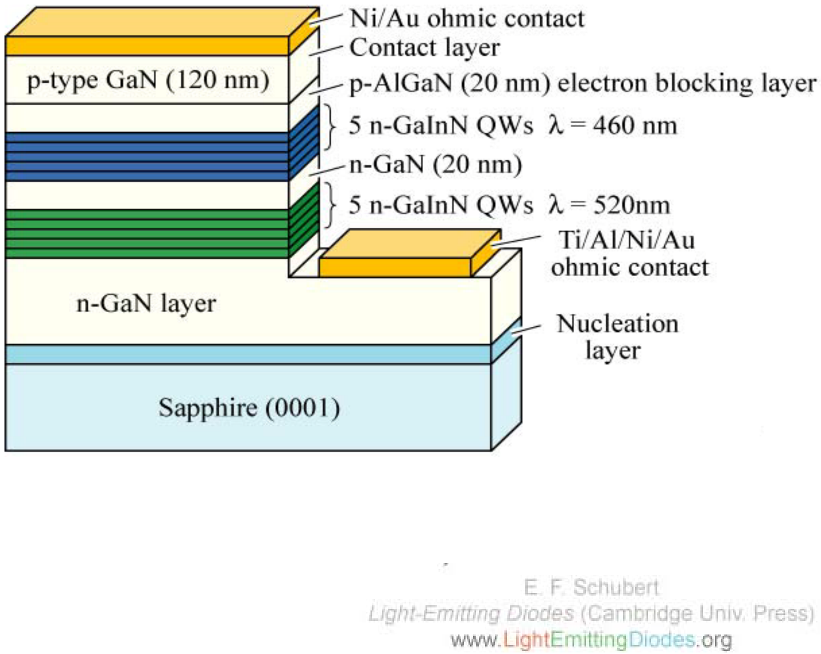
Assessment of approaches based on multi-wavelength monolithic LEDs

STR Group – Soft-Impact, Ltd. jointly with
Ioffe Physical Technical Institute, RAS





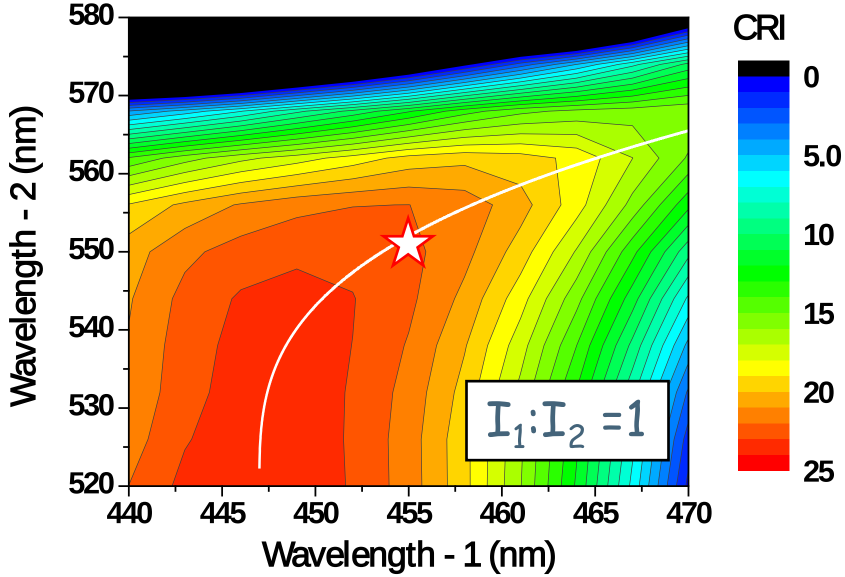
Design of a monolithic dichromatic LED with two active regions (after Li et al., 2003).

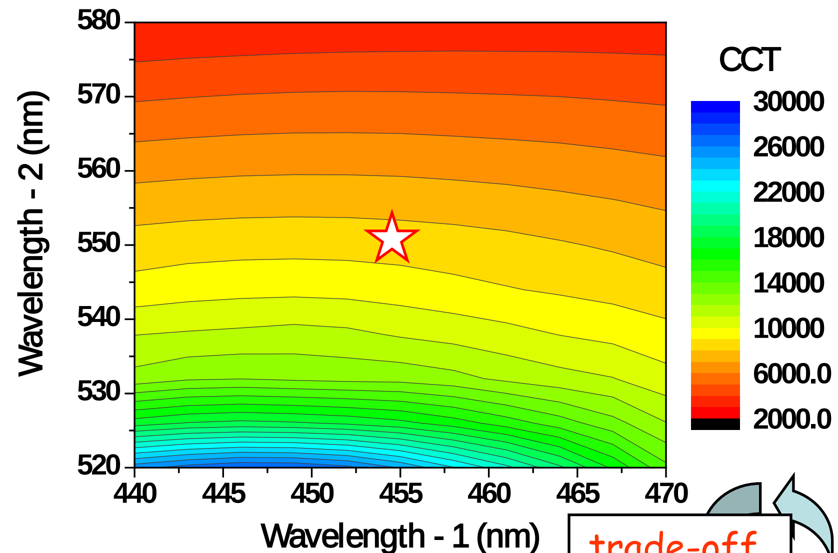


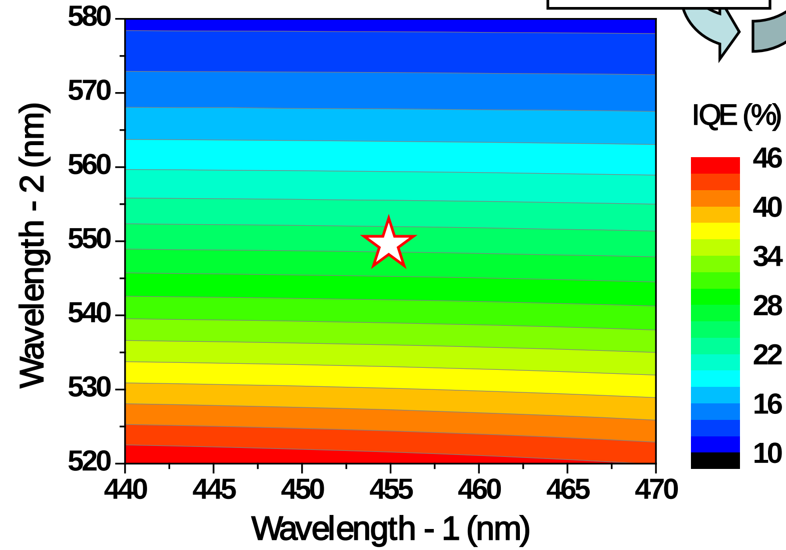
A monolithic, multi-color LED is formed with a multi-bandgap, MQW active light region emitting light in a wide spectrum of wavelength variation

Two-color monolithic LED structure: color characteristics and efficiency

How to select λ_1 and λ_2 to optimize CRI?



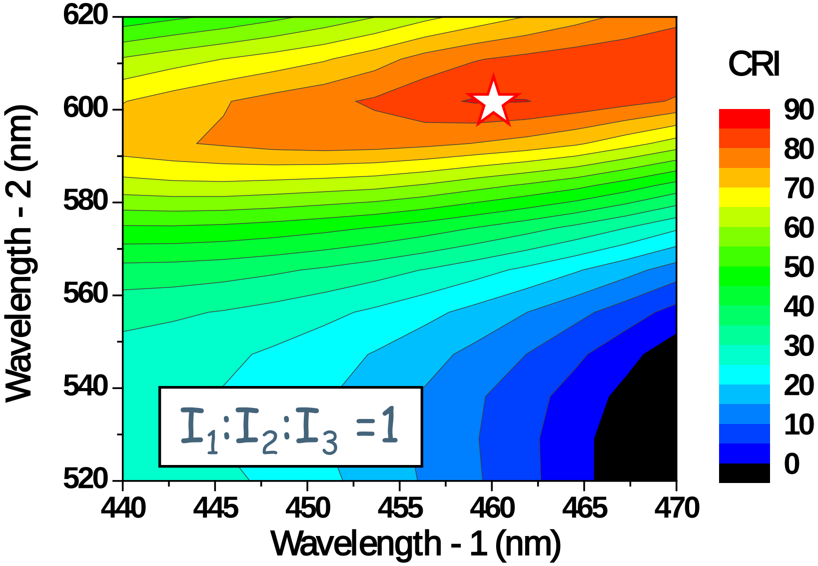


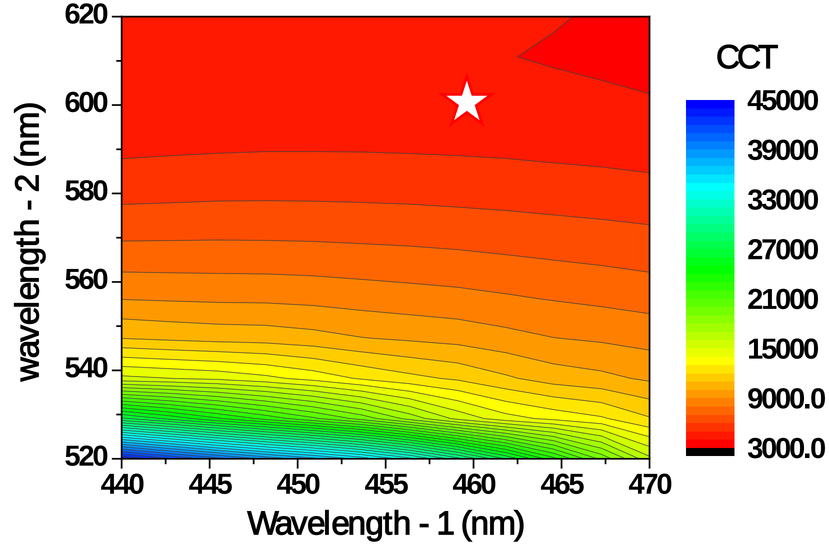


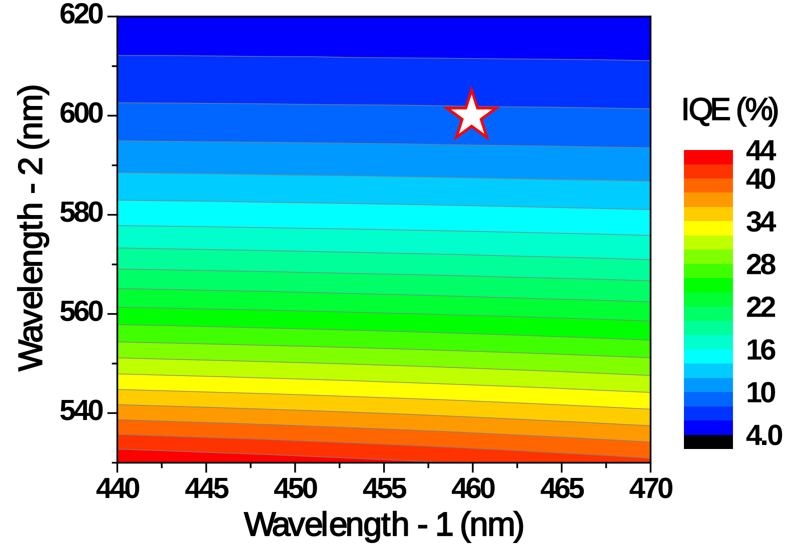
Two-wavelength LED structure may provide CRI ~24% at CCT ~8500 K, radiation efficacy ~425 lm/W, and overall IQE of ~25% → considerable efficiency improvement is required to reach practical applications

IQE = Number of photons / Number of e-h pairs <u>in all active regions</u>

$$\lambda_3 = \tfrac{1}{2}\,(\lambda_1 + \lambda_2)$$





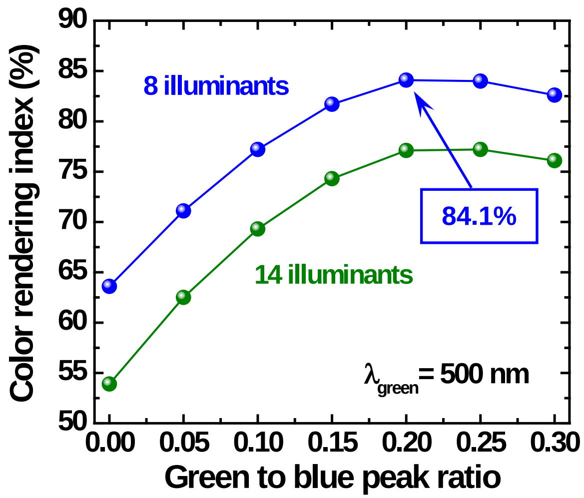


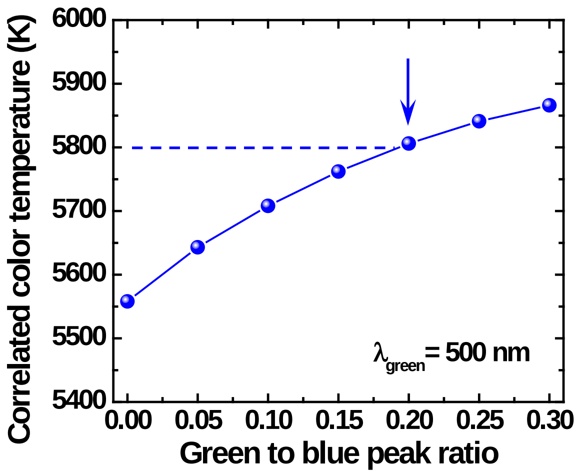
Three-wavelength LED structure may provide CRI > 90% at CCT ~4200 K, radiation efficacy ~375 lm/W, and overall IQE of ~15% → again, considerable efficiency improvement is required

No surprise. Very similar to conventional RGB, but IQE is too low. Stability can be better than for AlGaInP

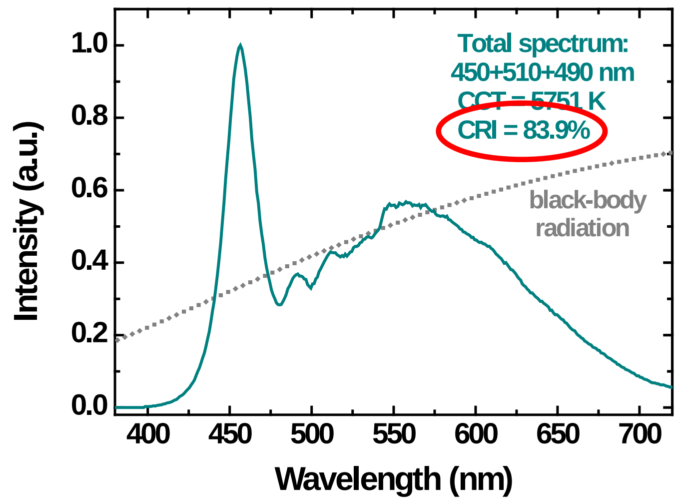
Monolithic LED with YAG:Nd3+ phosphor: CRI and CCT trends

1) **450 nm + 500 nm + YAG**





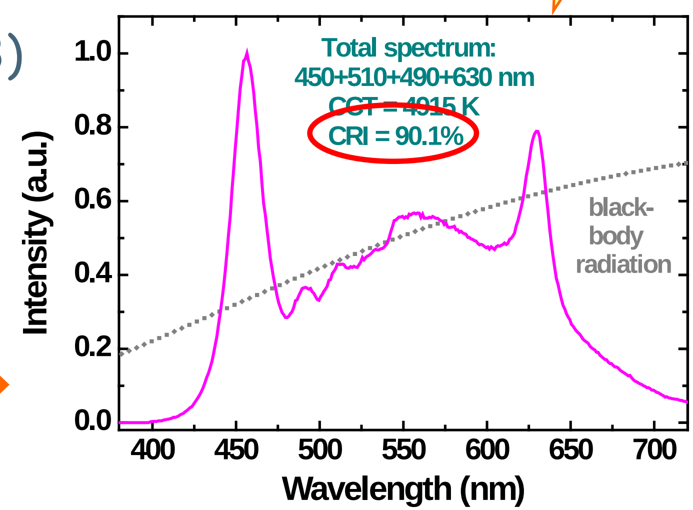
2) **450 nm + 490 nm + 510 nm + YAG**



Using of YAG:Nd^{3+} phosphor with multi-wavelength monolithic LED enables considerable CRI improvement

phosphor parameters are not optimized

3) **450 nm + 490 nm + 510 nm + 630 nm + YAG**



Role of thermal effects on chromatic characteristics of a phosphor-conversion white LED

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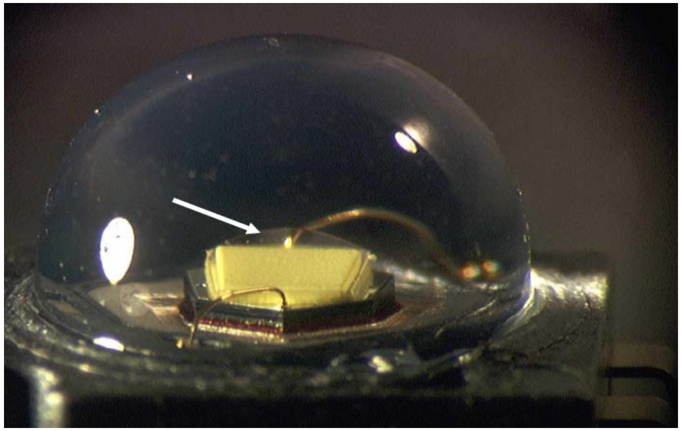
State-of-the-art light systems use extensively “smart” dimming up and down of white light and should operate in a wide range of ambient temperatures

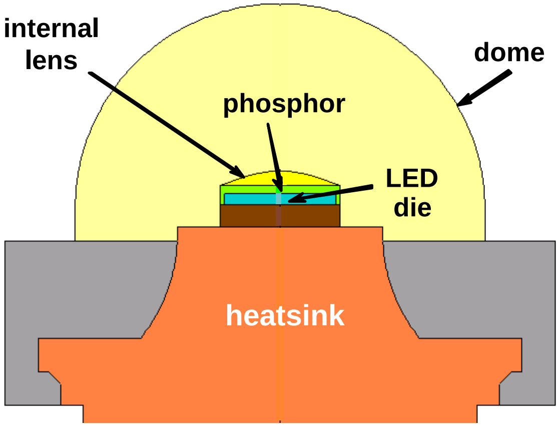
In all these cases, maintaining desirable color characteristics of the white light is quite important

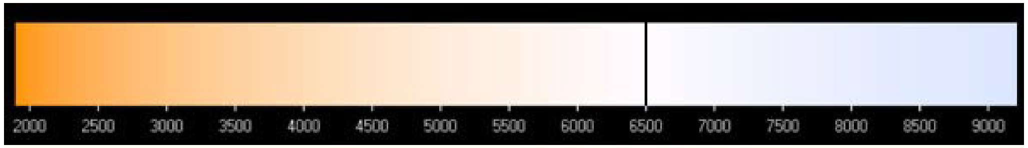
There is lack of studies aimed at understanding effects of LED operation conditions on color properties of white light

simulation of LED lamp operation has been performed with the SimuLAMP™ package:
http://www.str-soft.com/products/SimuLED/SimuLAMP/



Micrograph of the K2 Luxeon lamp by MuAnalysis, Inc., 2008

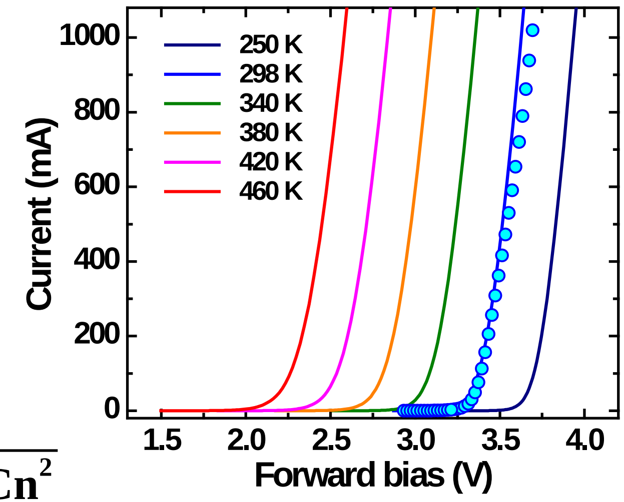




Temperature of black body, K

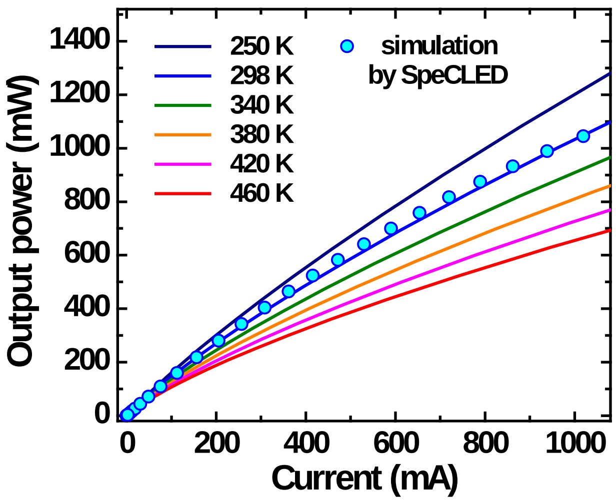
model approximations are used in the simulations fitted to the results obtained by SpeCLED:

$$V_F = m\frac{kT}{q}\ln\frac{I + I_0 \exp(-E_G/kT)}{I \ \ \exp(-E_G/kT)} + IR_S$$



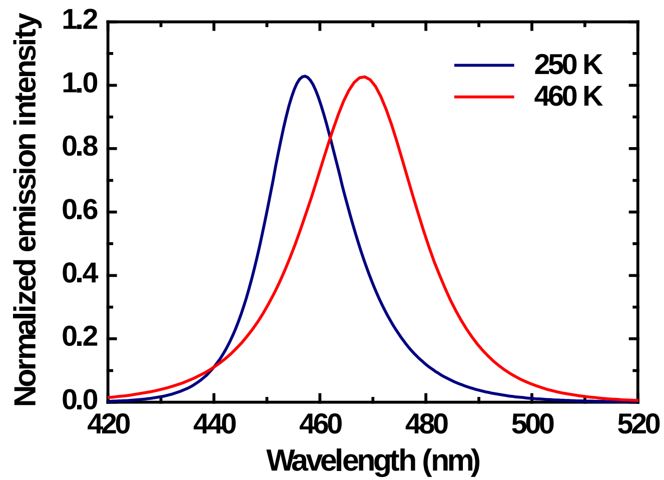
$$P_{out} = \eta_{ext} I \frac{\hbar\omega}{q} \cdot \frac{Bn}{\tau^{-1} + Bn + Cn^2}$$

$$\text{where} \quad I = qAd\left(n/\tau + Bn^2 + Cn^3\right)$$



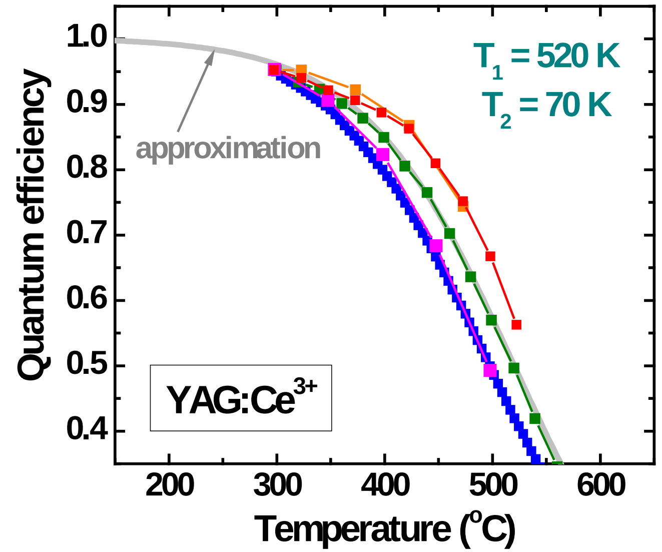
temperature-dependent parameters

$$I_R = \frac{A}{\exp\left(\frac{\lambda - \lambda_m}{\Delta_{lw}}\right) + \exp\left(\frac{\lambda_m - \lambda}{\Delta_{sw}}\right)}$$

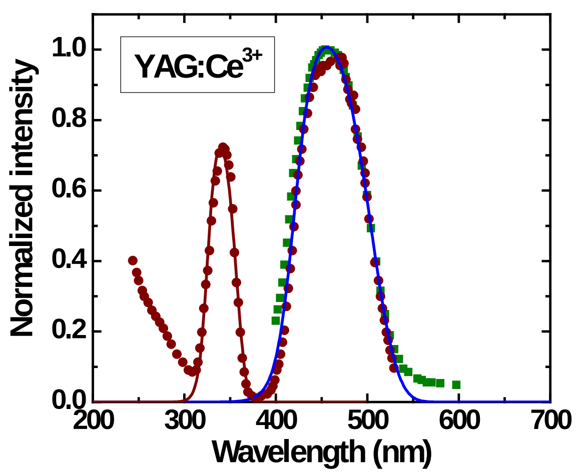


mean diameter of phosphor particle is 18 μm

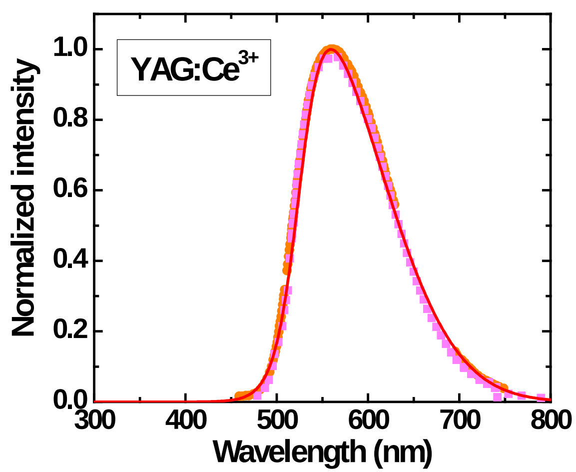
experimental data on optical properties of YAG:Ce^{3+} phosphor have been found from literature and approximated by appropriate functions

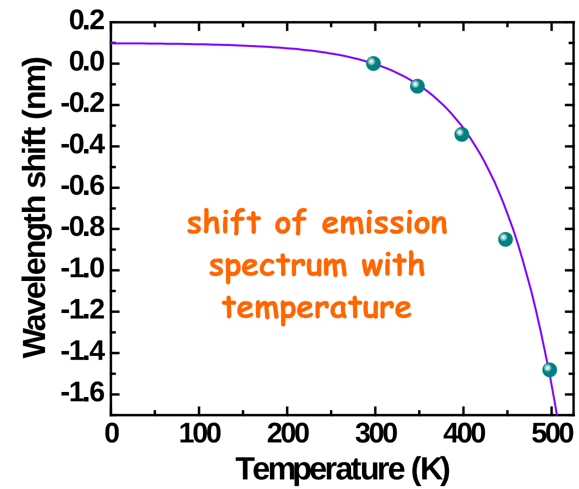


excitation spectrum



emission spectrum

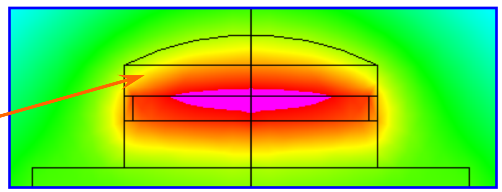


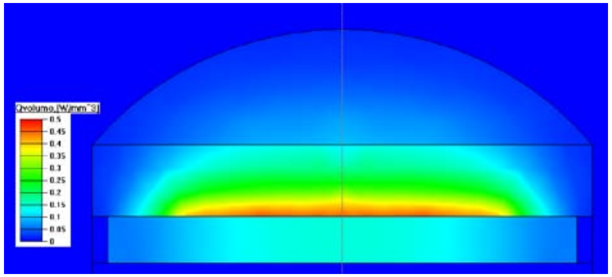


Temperature distribution in the LED lamp

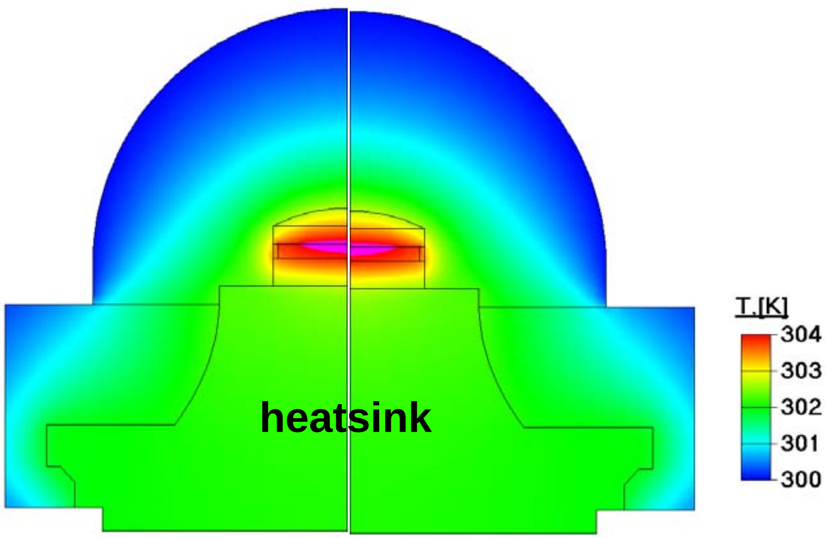
- temperature distribution in the lamp varies slightly with the current flowing through the LED but the magnitude increases with current
- conversion medium is not uniformly heated in the lamp

Temperature distribution in the conversion medium

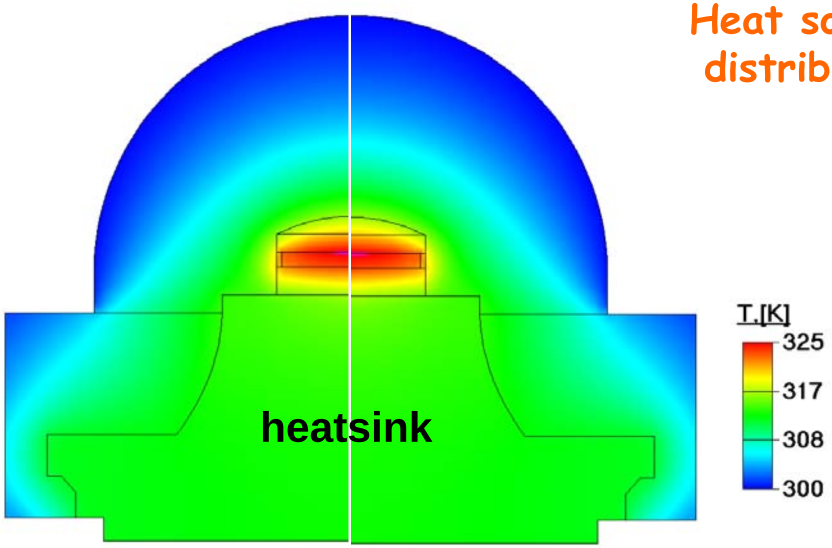




Heat source distribution

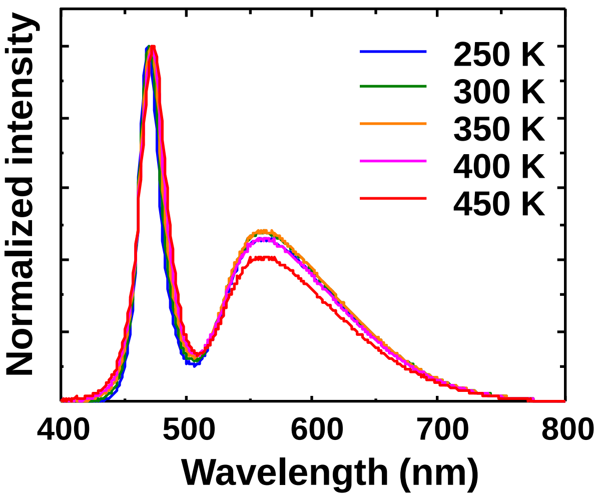


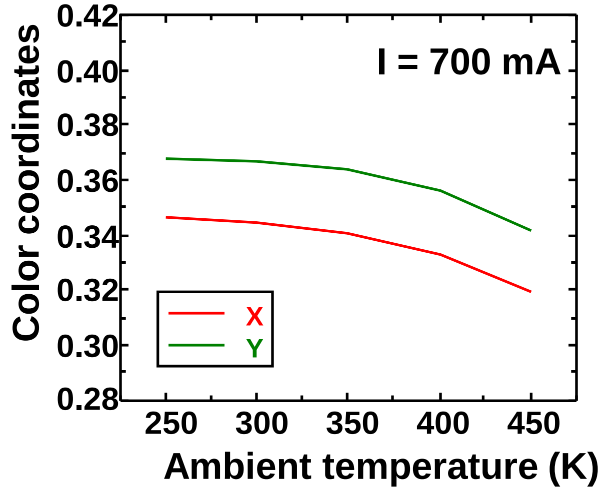
operating current of 200 mA

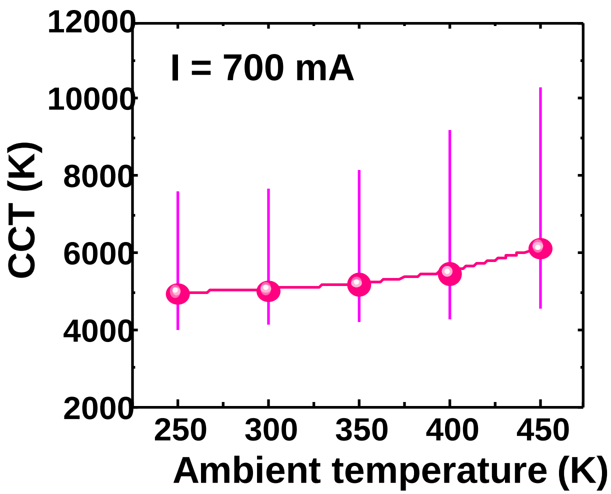


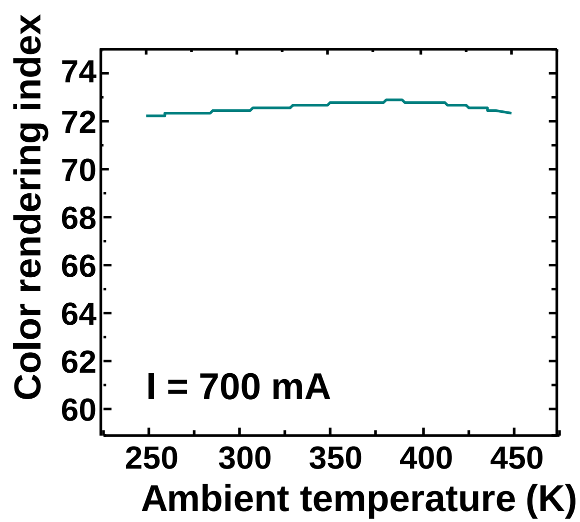
operating current of 1000 mA

Color characteristics of white light under ambient temperature variation

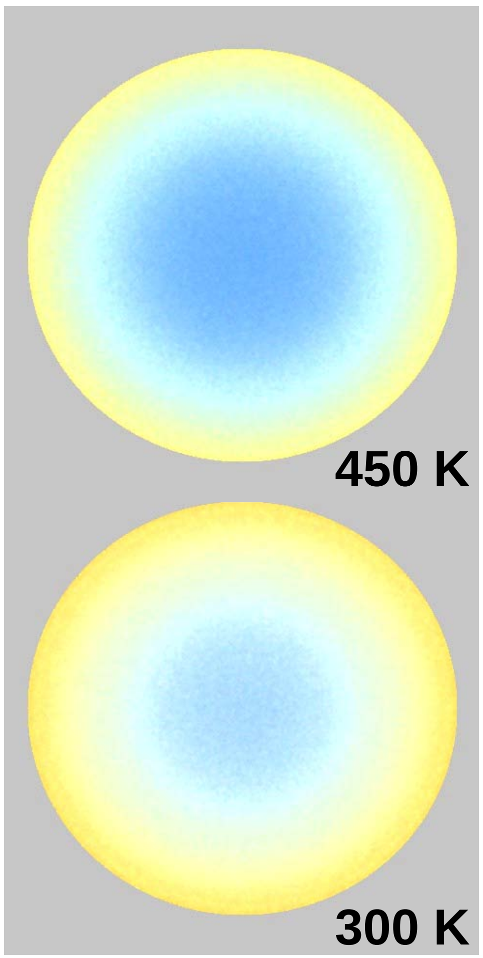






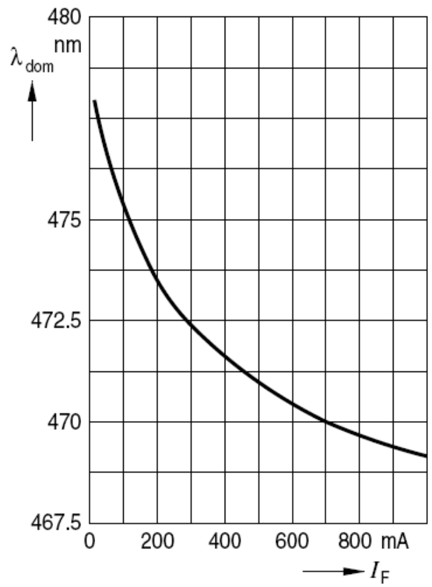


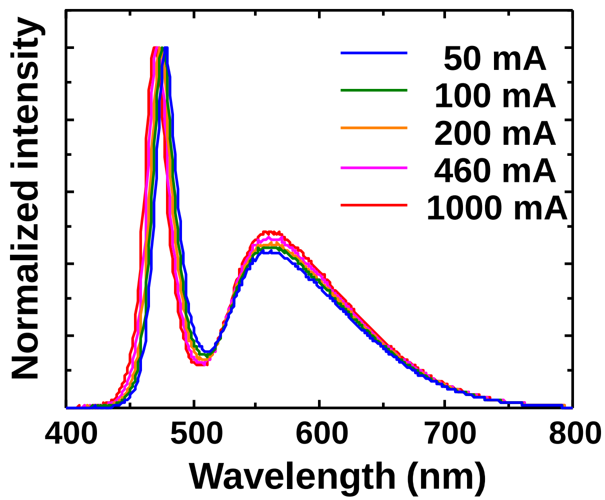
color distribution in the far-field zone

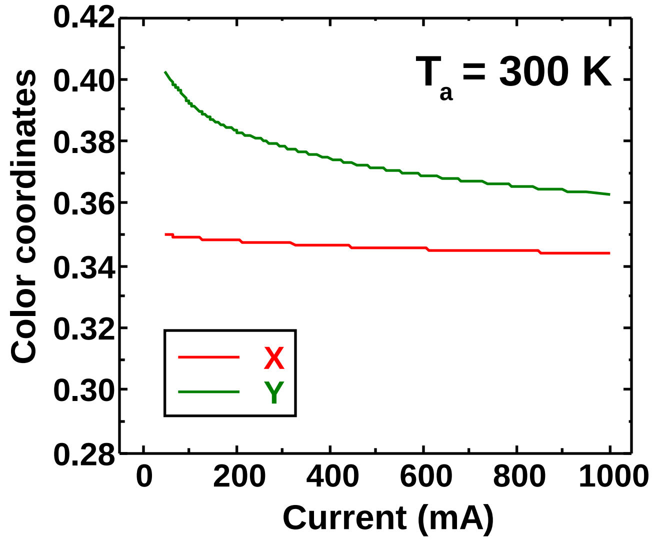


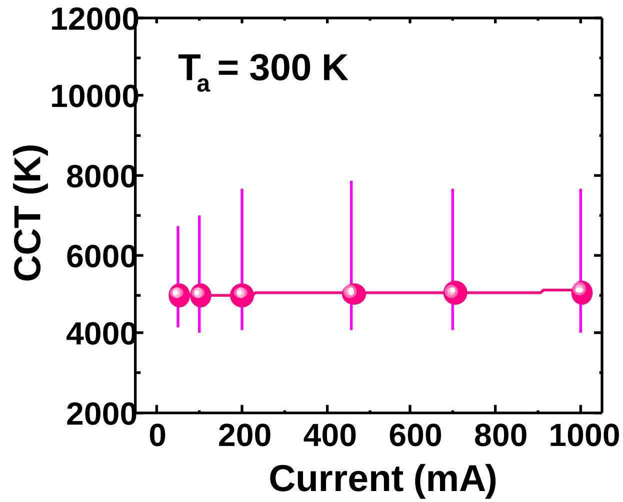
Color characteristics of white light under dimming by current variation

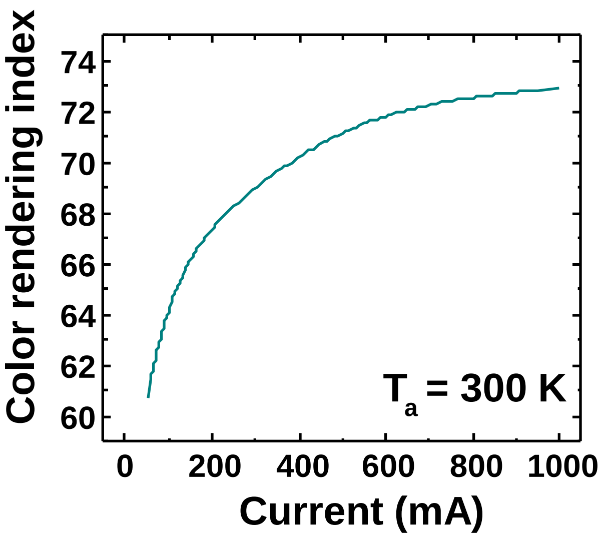
experimental blue shift of the emission spectra is used in simulations



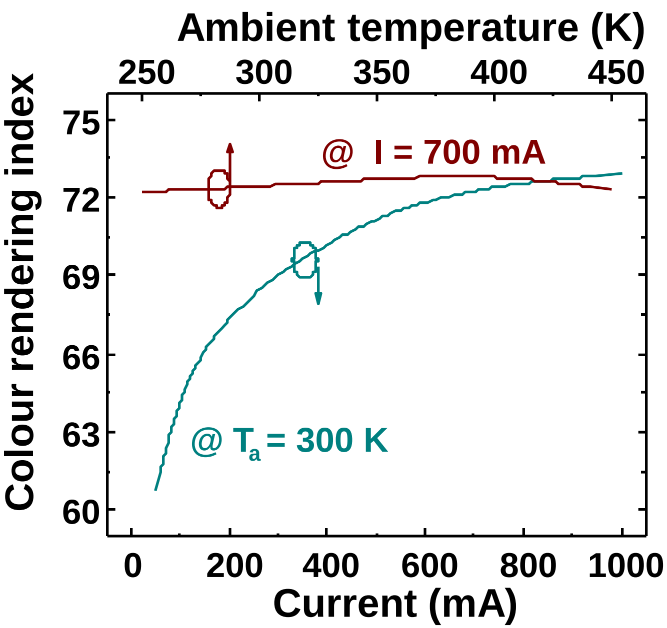






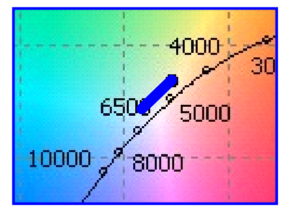


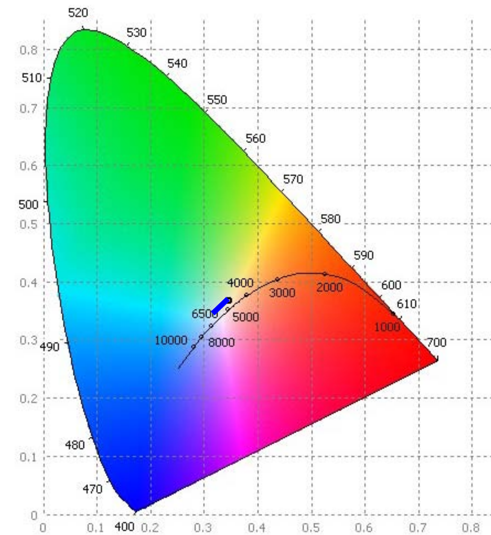
Why CRI behavior is so different under current or temperature variation?

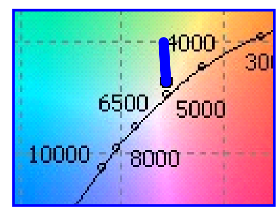


character of movement of chromatic coordinates under changing the LED operation conditions explains its effect on white light characteristics

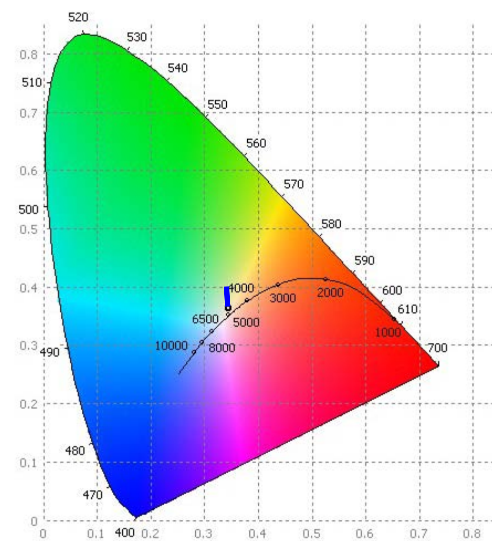
temperature variation shifts the chromatic coordinates along the black-body radiation locus, thus increasing CCT







current dimming moves the chromatic coordinates away from the black-body radiation locus



- operation conditions of LEDs affect considerably the color characteristics of phosphor-conversion white light sources
- in particular, increase in the ambient temperature results in remarkable growth of correlated color temperature of white light, keeping the color rendering index practically unchanged
- in contrast, dimming the operating current up and down influences strongly the color rendering index at nearly the same correlated color temperature
- the above effects originate from temperature/current dependent emission spectra of blue LED and yellow phosphor and temperature-dependent quantum efficiency of the phosphor

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- **Demo version**
- **Physical summary**
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