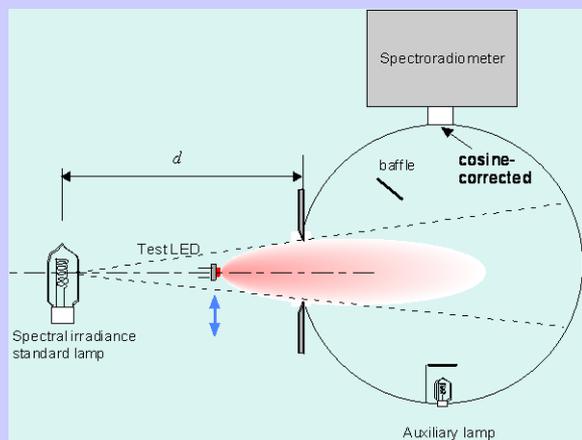


Standardization of LED measurements; New Publication of CIE Technical Report # 127:2007



*Kathleen Muray PhD.
(INPHORA Inc. USA);)*

CONTENTS

- Introduction: The report is revision of CIE TR #127:1997
- LED measurement problems: New terminology
- Photometers for LED measurements
- Intensity measurement
- Flux measurement
- Spectral measurements

CONTENTS

- Further work in CIE; description of other Technical Committees' involvement in LED measurements and standardization

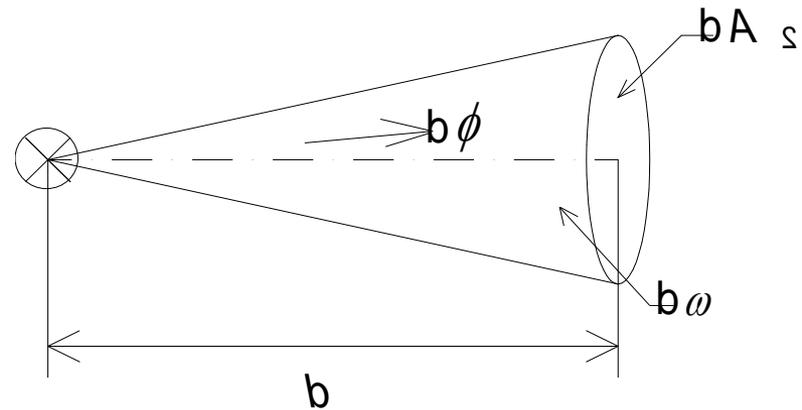
INTRODUCTION

- **Photometric light source characterization and calibration**
- Radiometric quantities
 - Radiant flux (power)
 - Radiant intensity
 - Irradiance
 - Radiance

Inverse square law

- $d\phi = I \cdot d\omega$
- $d\omega = dA/d^2$
- $d\phi/dA = E$
 $= (I \cdot d\omega)/dA$
 $= (I \cdot dA)/(dA \cdot d^2)$

 $= E = I/d^2$



QUANTITIES

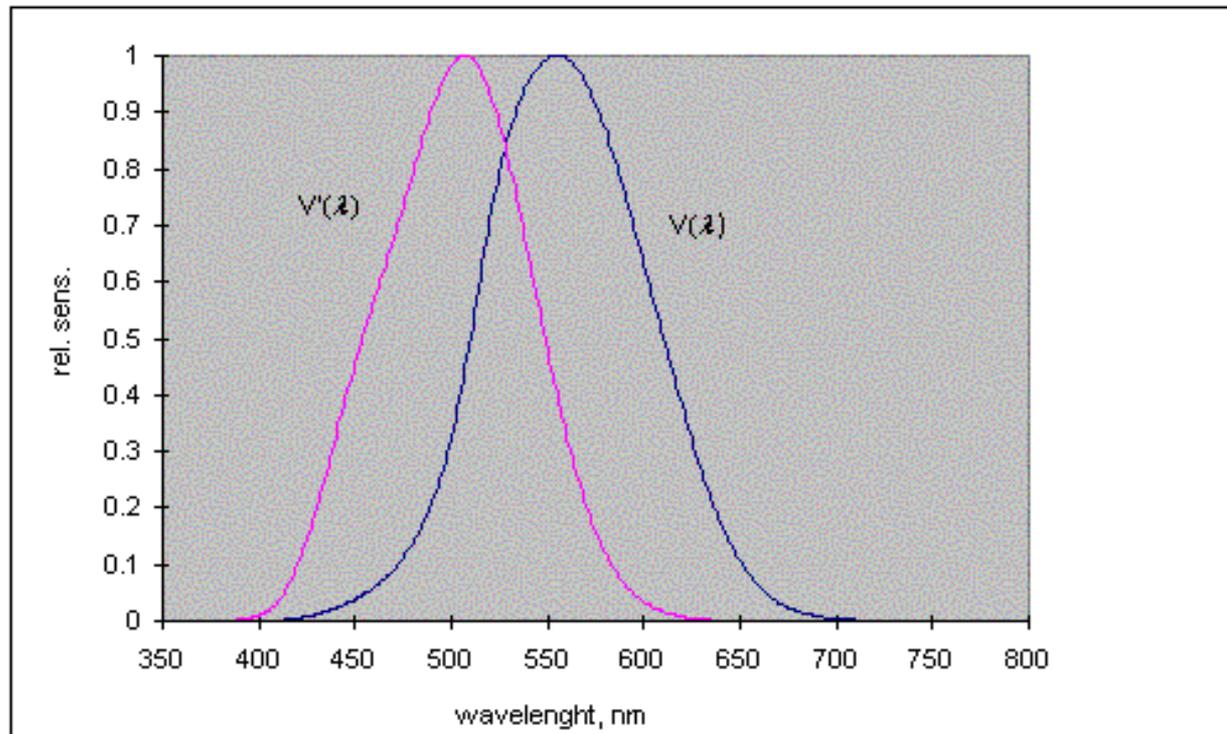
- **Lambert radiator**
- The radiance becomes angle independent
- $L(\delta) = L(\varepsilon, \phi) = \text{const.}$

QUANTITIES

- **Photometric quantities**
 - Weighting the visible electromagnetic spectrum according to the light sensitivity of the eye

VISION

- Spectral luminous efficiency functions



RELATIONSHIP OF QUANTITIES

- Radiant intensity
 - Watt/str
- Irradiance
 - Watt/m²
- Radiant power
 - Watts
- Radiance
 - Watt/(m².str)
- Luminous intensity
 - cd
- Illuminance
 - lux
- Luminous flux
 - Lumen
- Luminance
 - Cd/ m²

LIGHT SOURCES

- Characterization:
- Spectral power distribution
 - Chromaticity coordinates, Correlated color temperature
- Total luminous flux
 - Luminous/radiant intensity for point sources
 - Luminance/radiance for extended sources

LEDs: Unique problems

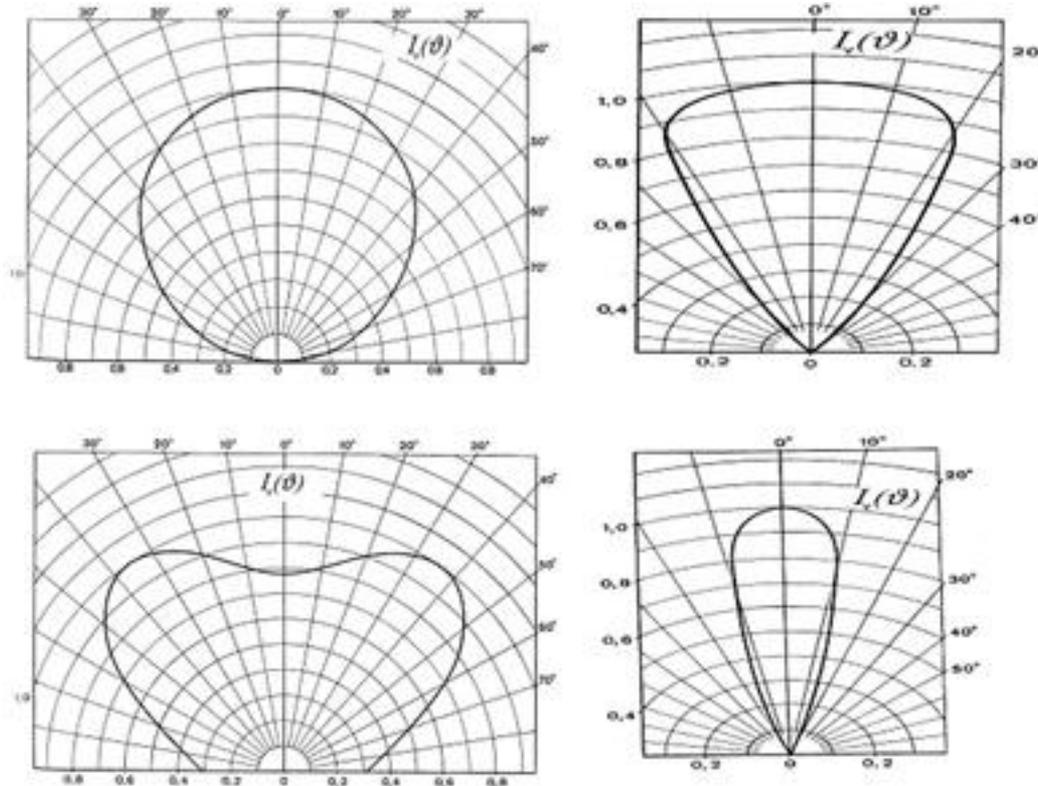
- **The small point-like LED light sources need special consideration for all measurements:**
 - Low light output
 - Narrow spectral power distributions
 - Spatial power distributions vary greatly

Package sizes and shapes come in great variety

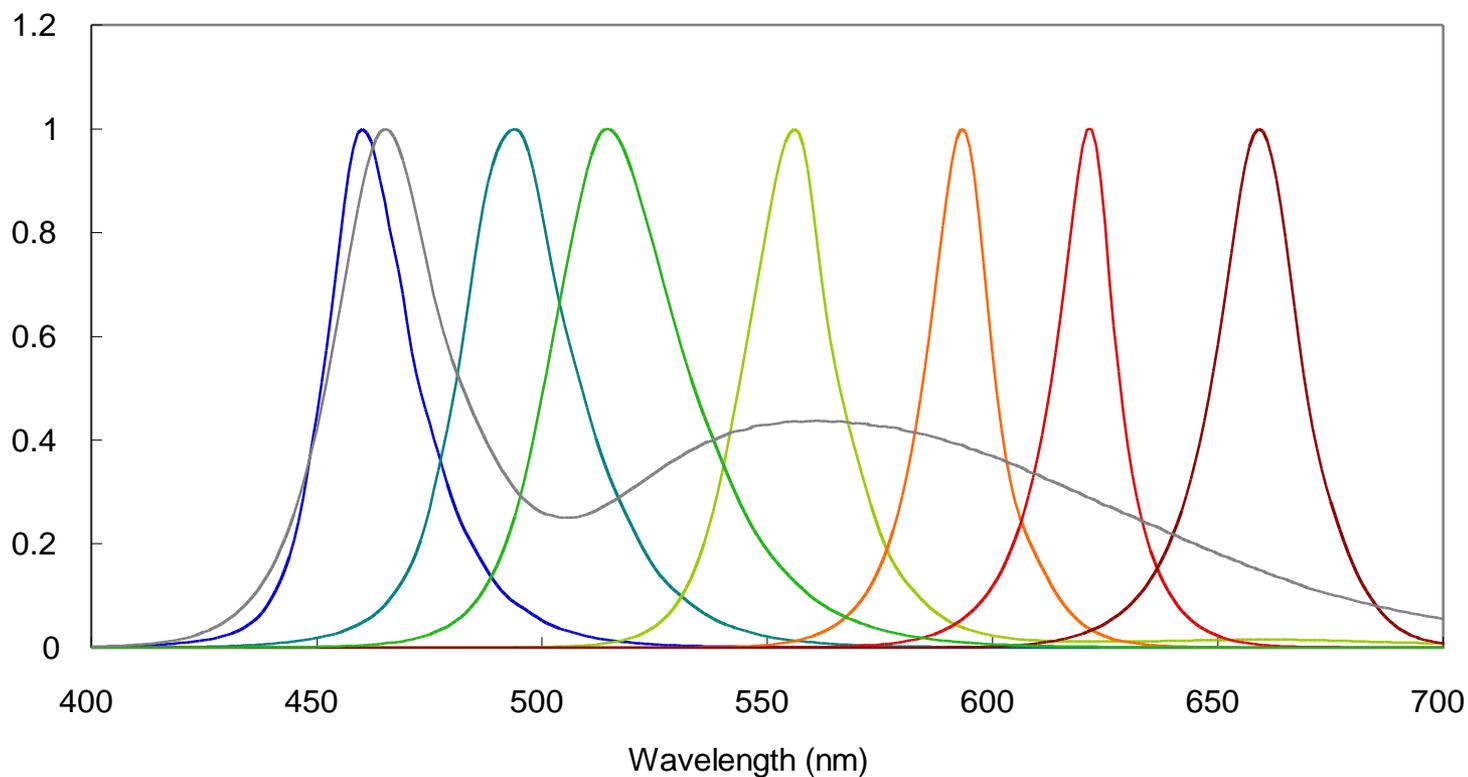
LEDs: Unique problems

- **Metrology laboratories use test-equipment usually built for larger light sources**
 - Not suited for LED testing

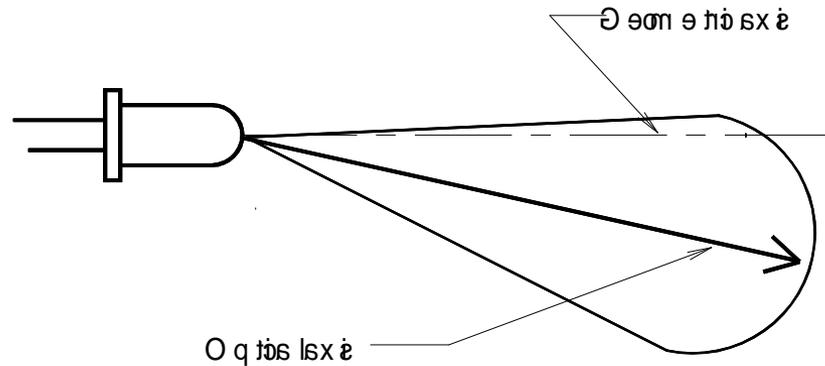
Spatial distributions of the radiation emitted by LEDs



Spectral distributions of LEDs



An LED where the geometric and optical axes point into different directions



MEASUREMENT DISCREPANCIES

- Large differences in measurement results occurred at different laboratories
- As more efficient LEDs were available, more applications developed
- It became very important to be able to characterize them by photometric and (or) radiometric quantities by a reproducible manner

RECOMMENDATIONS FROM CIE

- CIE Technical Report 127:1997
 - First recommendations how to measure the most important quantities:
 - Luminous/radiant intensity
 - Total flux
 - Spectral power distribution

LED measurement categories

- Laboratory measurements
 - Creating high accuracy data for individual LEDs, which can be used as working standards
- Bulk measurements
 - Has to deal with large number of measurements with high speed; utilizes working standards created in the Lab
 - The report considers only Laboratory measurements

Reference Standards

- Best measurement technique can be performed only with good standards
- Easiest way: use substitution method if standards are available
- Needed: Standard LEDs with spectral and spatial power distribution identical to the test LEDs

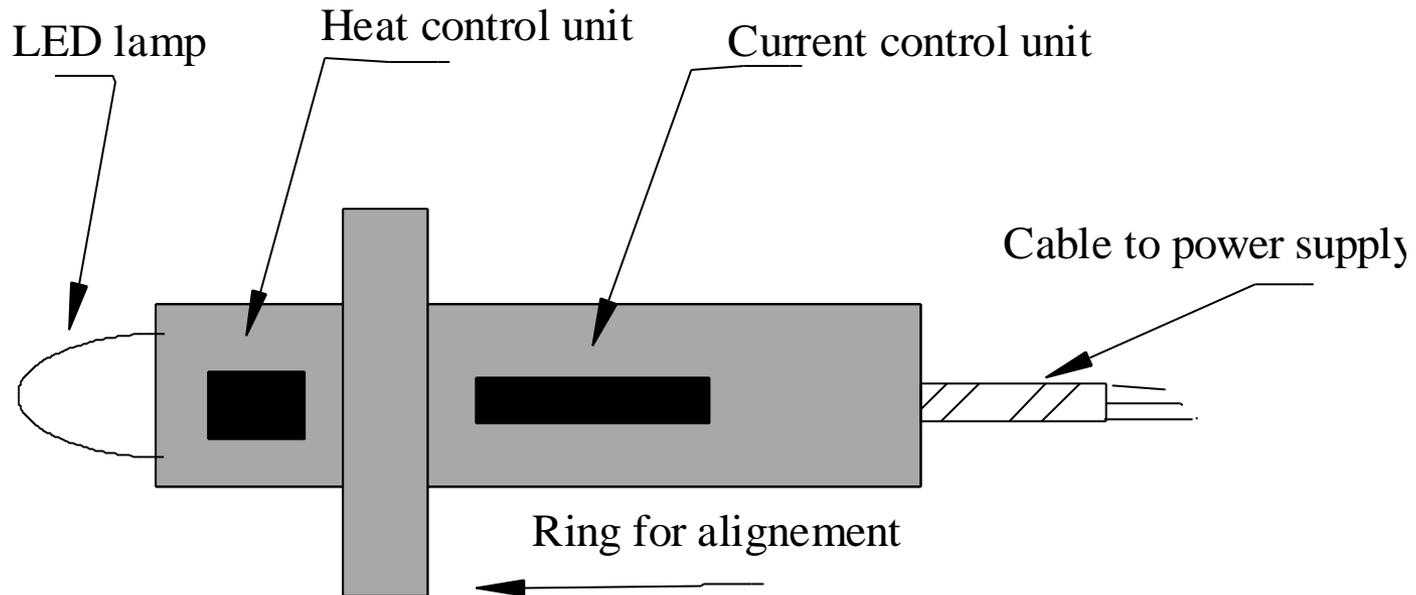
Reference Standards

- Light output is proportional to the forward current
- Light output and spectrum depends on junction temperature

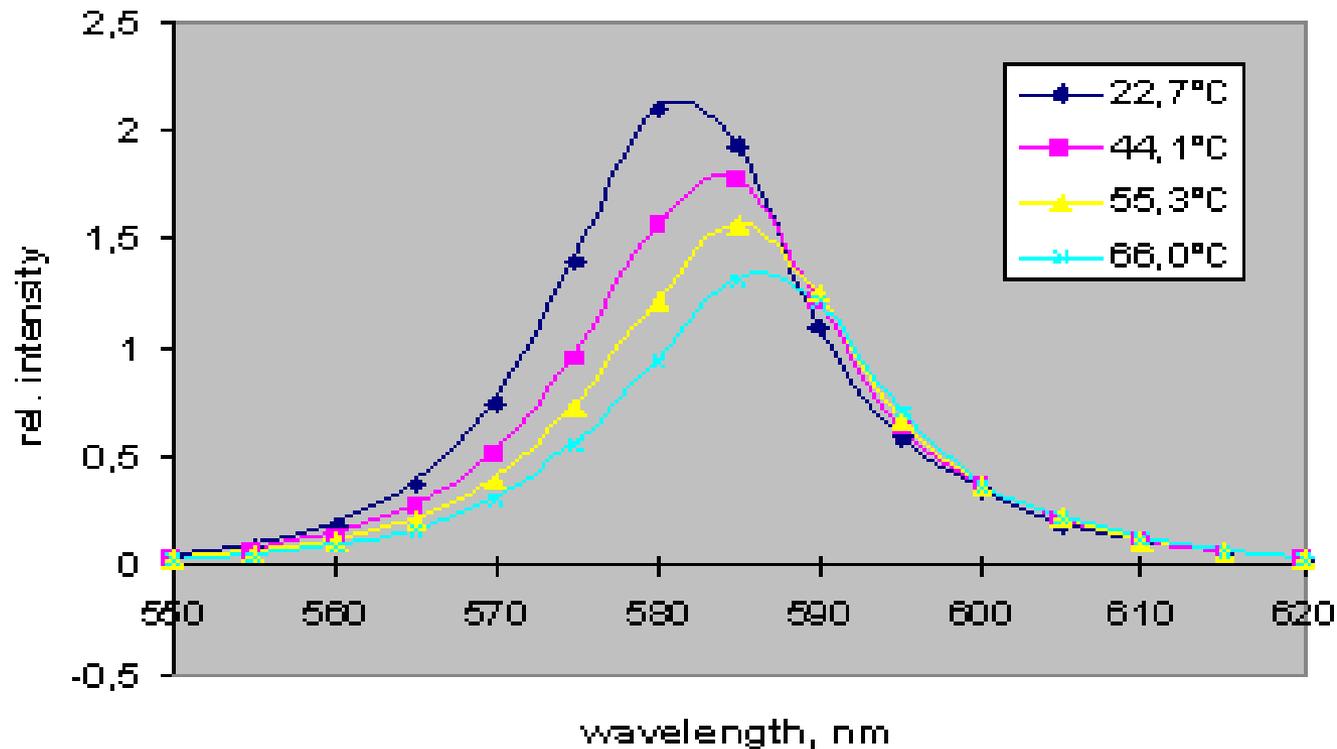
$$\frac{\partial \lambda_p}{\partial T_c} \approx (0.1 \text{ to } 0.3) \text{ nm/K}$$

- Important to keep junction temperature stable

Reference Standard



Example: Spectrum of a green LED at different temperatures



Reference Standard LEDs

- Pre-selection of LEDs:
 - Select those lamps which show best alignment of their optical axis to the geometrical axis
 - Few hundred hours of “burn-in”
 - Periodic checking and recording their light output
 - Select only those lamps where light-output stays constant after about 200 hours

Reference Standard LEDs

- They need to be operated with constant current (e.g. 20.00 mA)
- Their junction temperature need to be kept constant (preferably above room temperature)
- The housing has to be easily applicable to holding fixtures for proper alignment

Photometers

- Simplest LED measurements are performed with Silicon detector-filter type photometers
- For accurate photometric measurement results it is very important to choose detectors with spectral response very closely matched to the $V(\lambda)$ function

Photometers

- Spectral responsivity of photometers and photo-current:

$$s(\lambda) = s_0 \cdot s_r(\lambda)$$

$$i = X_0 s_0 \int_0^{\infty} s_r(\lambda) S(\lambda) d\lambda$$

Here $X(\lambda) = X_0 \cdot S(\lambda)$, where X_0 is the incident light normalisation factor and $S(\lambda)$ is the relative spectral distribution. $X(\lambda)$ represents whichever photometric or radiometric quantity is to be measured.

Photometers

- Photometers are normally calibrated using a tungsten filament lamp set to the CCT temperature of CIE Standard Illuminant A.
- f_1' can safely be used for qualifying detectors in the case of white LEDs
- The new CIE LED measurement Technical committee (CIE TC2-45) examined the validity of using f_1' for qualifying detectors in the case of blue and red LED measurements

Photometers

- It was found that f_1' will not give the right answer for goodness of the fit when LEDs of different color are measured
- At this time no easy way was found to use one single number similar to f_1' for all the different colored LEDs
- An other technical committee will consider this problem in the near future

Photometers

- For white LED measurements:
- The goodness of the match to the $V(\lambda)$ function can be judged by the f_1' number:

$$f_1' = \frac{\int |s^*(\lambda)_{\text{rel}} - V(\lambda)| d\lambda}{\int V(\lambda) d\lambda}$$

Photometers

- $s^*(\lambda)_{\text{rel}}$ is the normalised detector sensitivity using the equation

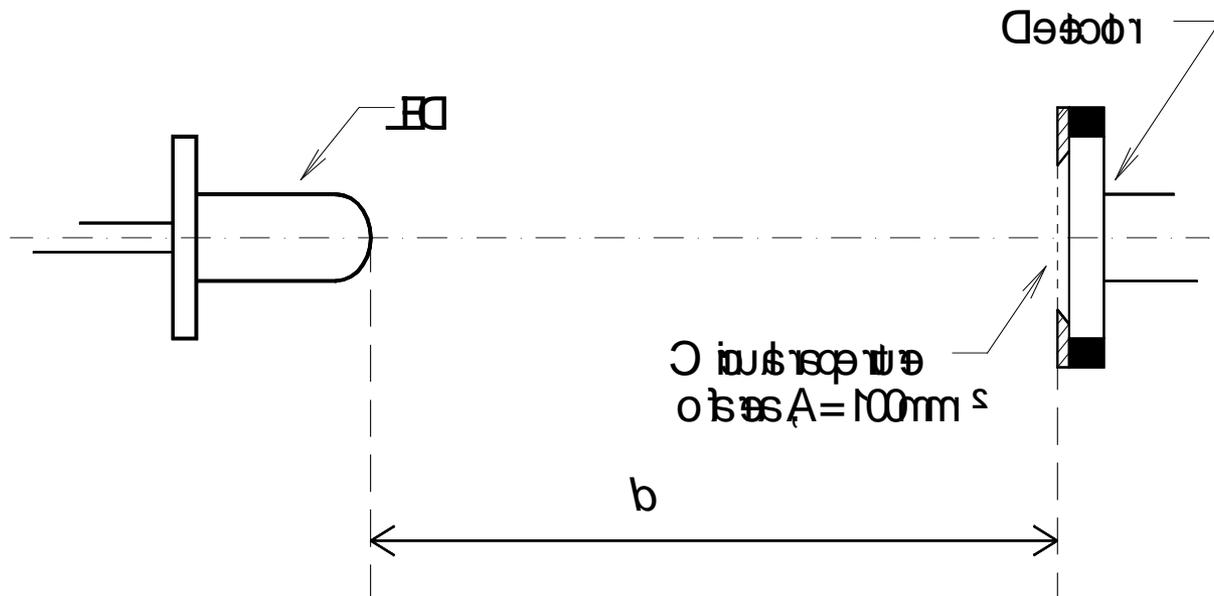
$$s^*(\lambda)_{\text{rel}} = s(\lambda)_{\text{rel}} \cdot \frac{\int S(\lambda)_A \cdot V(\lambda) d\lambda}{\int S(\lambda)_A \cdot s(\lambda)_{\text{rel}} d\lambda}$$

$S(\lambda)_A$ is the relative spectral distribution of Standard Illuminant A

Measuring single color LEDs even if f_1 ' value is very small, does not guarantee high accuracy results. It is important to determine spectra of the LEDs.

RESULTS

- Most successful of the first recommendations was the measurement technique of luminous/radiant intensity of LEDs
- The recommended method required introduction of new quantity:
Averaged LED Intensity: I_{LEDA} , and I_{LEDB}



Schematic diagram of CIE Standard Conditions for the measurement of Averaged LED Intensity. Distance $d = 0,316\text{ m}$ for Condition A, $d = 0,100\text{ m}$ for Condition B.

RESULTS

- It is very important to set the measurement geometry as recommended.
- If followed precisely, agreement between different laboratories has been improved significantly

RESULTS

- Best measurement technique can be performed only with good standards
- Easiest way for accurate measurements is to use substitution method
- Needed: Standard LEDs with spectral and spatial power distribution identical to the test LEDs

Measurement of I_{LED}

- For the simple case:
- If $X_1(\lambda)_{rel} = X_2(\lambda)_{rel}$
- Substitution measurement is simply reduced to
- $$X_{10}(\lambda) / X_{20}(\lambda) = v_1 / v_2$$

Photometers

- At present best photometers made have $f_1' < 1.5\%$ values (Quite expensive)
- $f_1' < (3-5)\%$ are commonly available;
- May not be good enough for precision LED measurements when different colors are tested

Standard LEDs

- In case of lower precision photometers standard LEDs of same colors are needed as the test LEDs.
- Substitution method would still allow high precision measurements.
- Particularly important for blue and red LEDs

Standard LEDs

- If fewer color Standard LEDs are available then test LEDs, color correction can be applied:

$$I_{\text{LED,test}} = F \cdot \frac{y_{\text{test}}}{y_{\text{ref}}} \cdot I_{\text{LED,ref}}$$

Standard LEDs

$$F = \frac{\int S_t(\lambda) V(\lambda) d\lambda}{\int S_r(\lambda) V(\lambda) d\lambda} \cdot \frac{\int S_r(\lambda) s_{\text{rel}}(\lambda) d\lambda}{\int S_t(\lambda) s_{\text{rel}}(\lambda) d\lambda}$$

$S_t(\lambda)$ is the relative spectral distribution of the test LED;
 $S_r(\lambda)$ is the relative spectral distribution of the reference LED;
 $s_{\text{rel}}(\lambda)$ is the relative spectral responsivity of the photometer head, and
 $V(\lambda)$ is the CIE spectral luminous efficiency function of the photopic vision

Spatial Distribution

- In general, the luminous intensity $I(\theta, \phi)$ depends on the direction (θ, ϕ) and this dependence is called the spatial intensity distribution
- If the absolute value of the intensity $I(\theta, \phi)$ is measured in a specified reference direction corresponding to $\theta = \theta_0$ and $\phi = \phi_0$ and denoted by $I_{00} = I(\theta, \phi)$, then this can be used as a normalising factor

Spatial Distribution

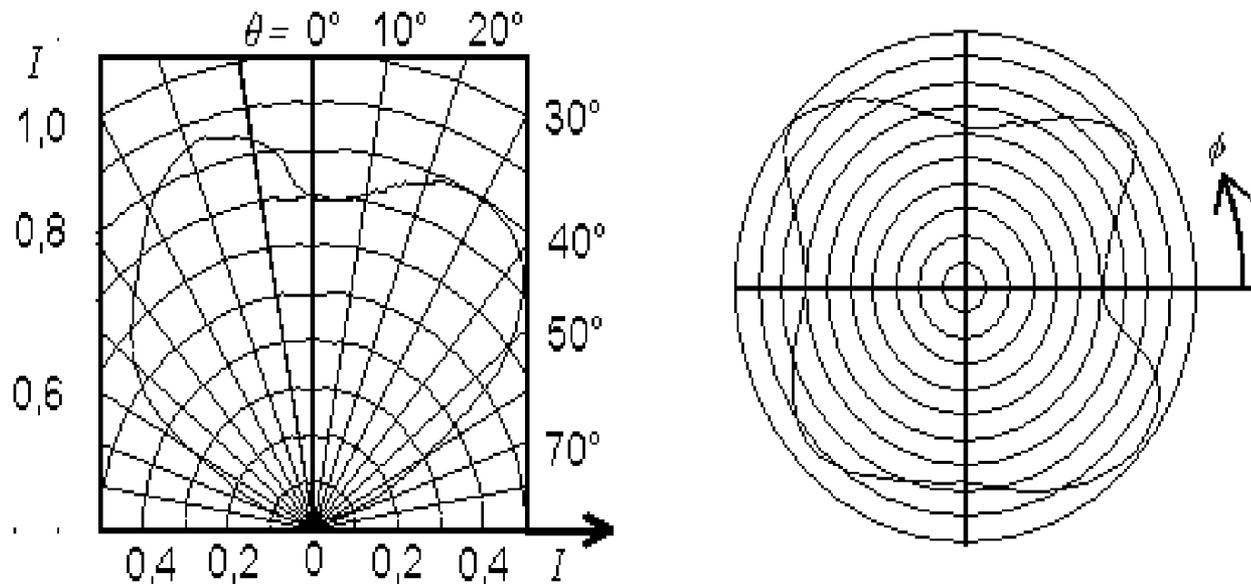
- A relative spatial distribution $G(\theta, \phi)$ can be defined. The spatial intensity distribution $I(\theta, \phi)$

$$I(\theta, \phi) = I_{00} \cdot G(\theta, \phi)$$

Spatial Distribution

- In case of LEDs $G(\theta, \Phi)$ varies greatly for different type of LEDs
- Measurement of total flux therefore can be very challenging
- Sphere photometers designed for other light sources usually cannot be used for LED total flux measurements

Spatial Distribution



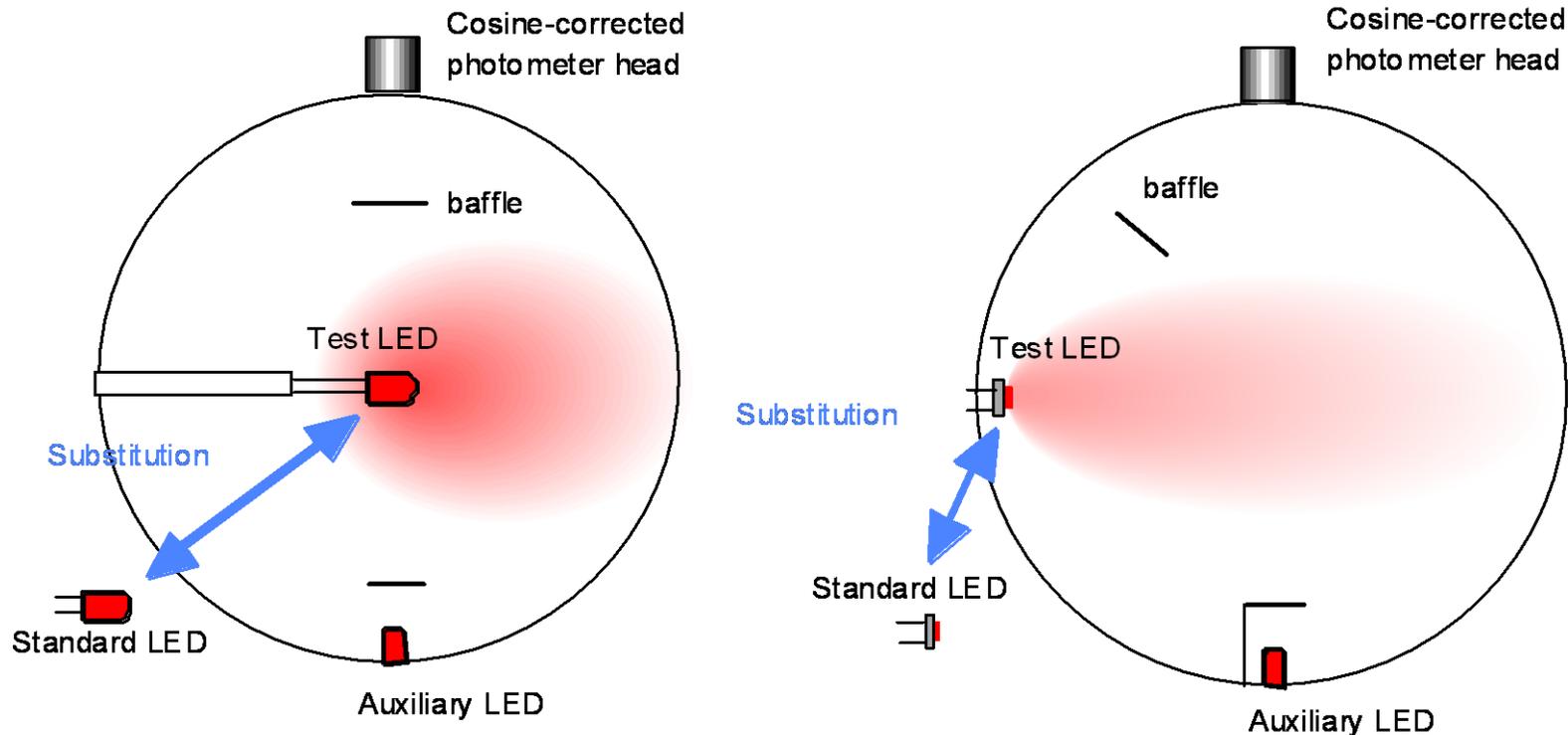
Two frequently occurring non-symmetrical intensity distributions: the optical axis is off the geometric one, the spatial intensity distribution is non axial symmetric

Flux Measurement

- CIE 127:2007 is recommending how to measure LED Total Flux; new requirements made necessary to introduce an additional quantity:
- “Partial Flux”; it’s exact definition and measurement condition is recommended as well as specific sphere designs

Flux Measurement

Design of the integrating sphere for Total Flux measurement

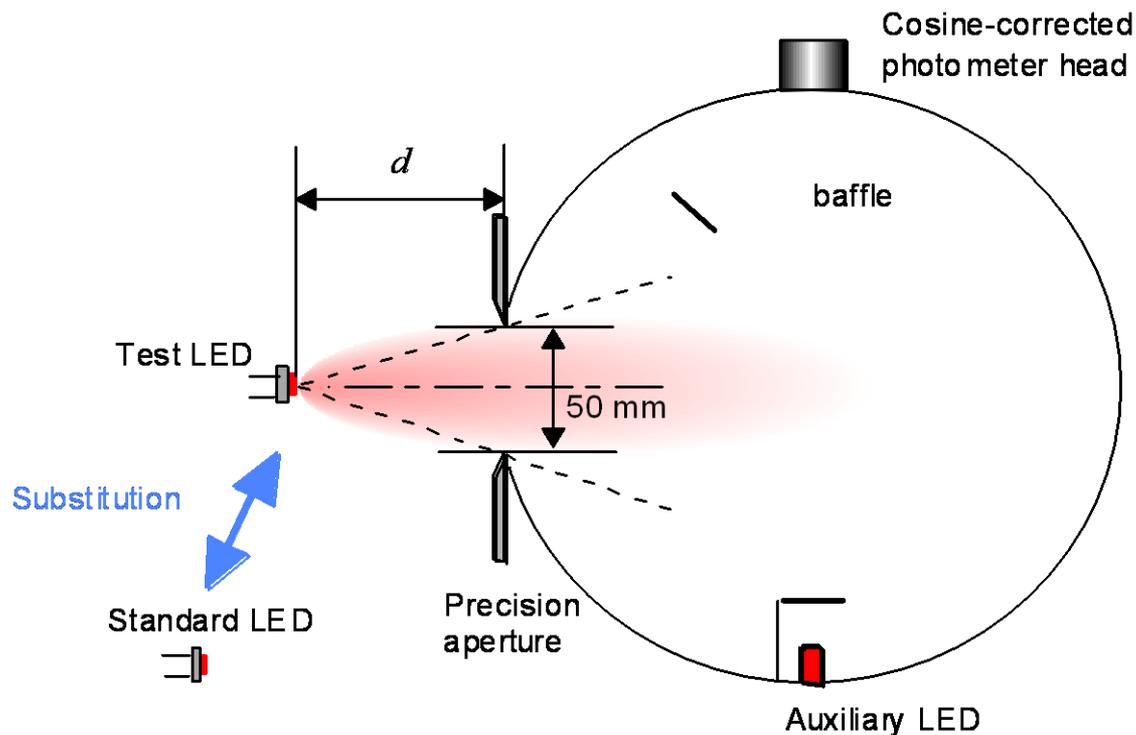


Flux Measurement

- Integrating sphere size should be 20 cm diameter or more
- White interior coating reflectance should be 90% or higher (reducing errors due to different spatial power distributions)
- Photometer head should have a cosine response

Flux Measurement

Designing integrating spheres for Partial Flux measurements



High Power LEDs

- Measurement of high power LEDs with currents over 100 mA is more challenging
- Calibration standards need to have sufficient thermal conducting elements added to the chip
- For very high currents, and DC operation, additional cooling has to be provided.

Calibrating the Integrating Sphere

- Calibration should be performed by a standard LED, having the same spectral and spatial power distribution as the test LEDS
- Most importantly the spatial power distributions should be similar

Calibrating the Integrating Sphere

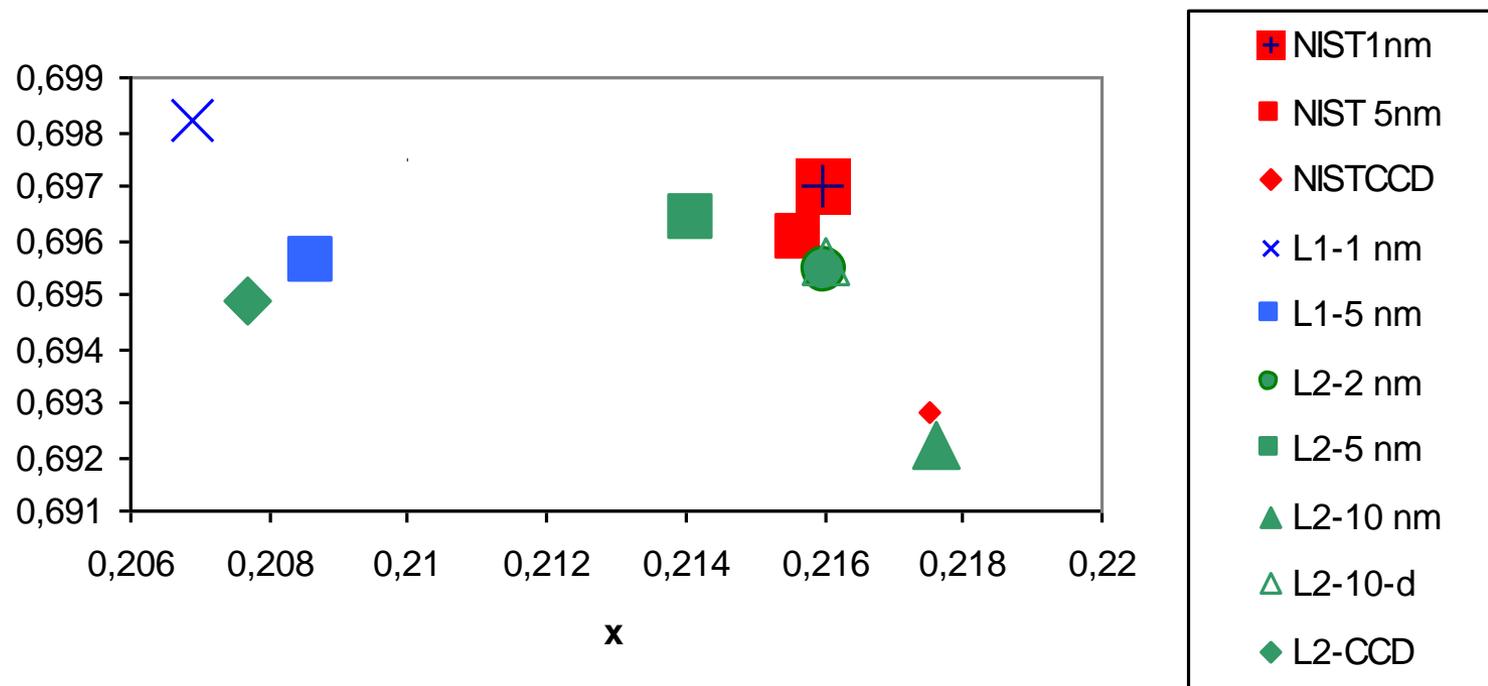
- If the spectral distribution of standard and test LEDs are different, a correction formula can be applied to the simple substitution formula

Spectral Power Distribution

- Measurement results depend on the spectroradiometer and measurement conditions applied
- Comparison between several different systems with NIST data as standard are shown

Example: Spectral Power Distribution

Distribution

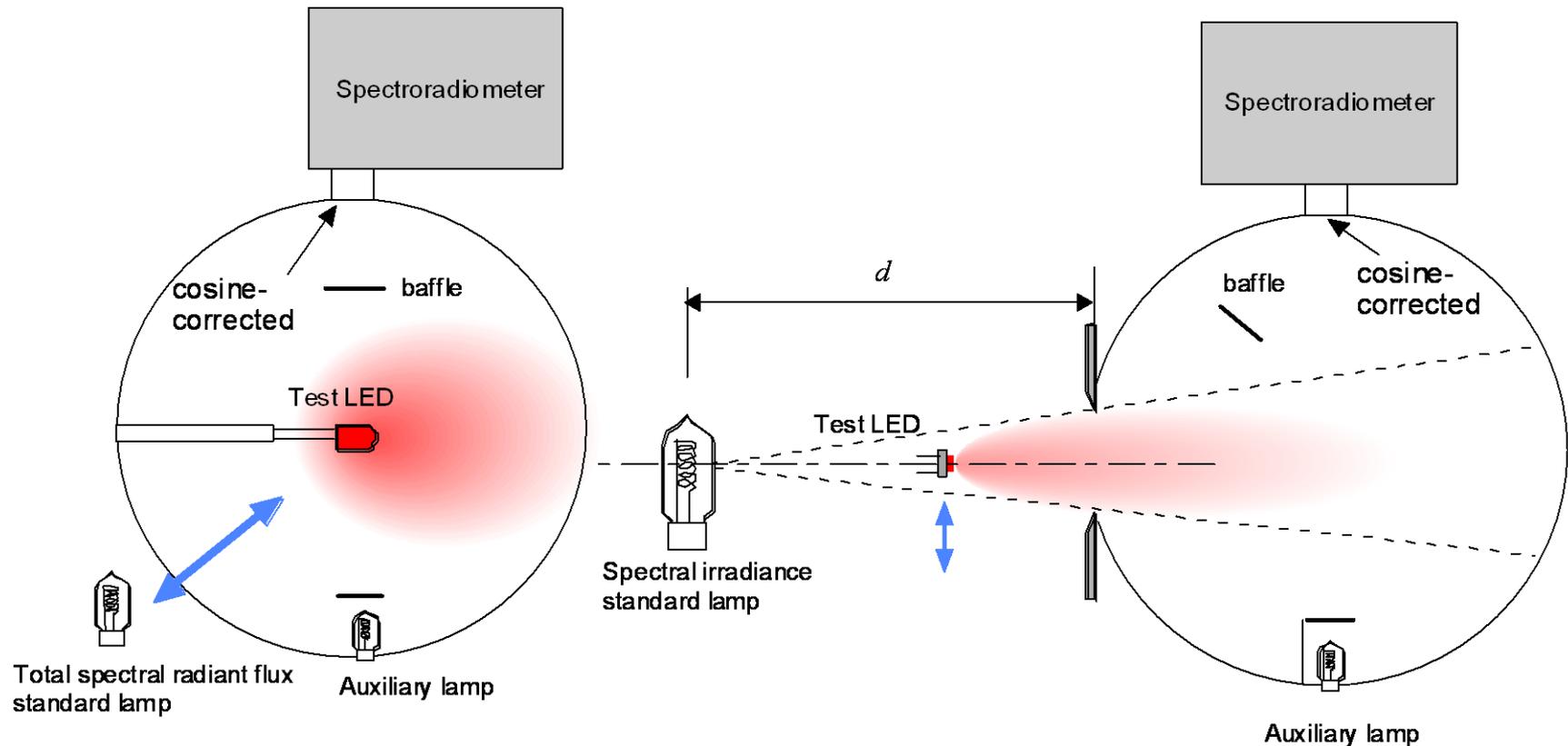


Chromaticity of a green emitting LED measured using different spectroradiometers

Spectral Power Distribution

- Measurement geometry can influence the results
- Serious discrepancy might occur if geometry is not specified
- CIE 127:2007 recommends specific measurement geometries

Geometry for total and partial flux mode spectroradiometer



Spectral Power Distribution

- Errors can occur due to wrong bandwidth selection (LEDs have very narrow emission bands)
- Bandwidth of 5nm or less is recommended for LED spectral measurements
- Scanning interval for accurate spectral measurement should be less than 2.5 nm

Examples: Unique Properties of White LEDs

- White LEDs developed after High Intensity blue LEDs became available
- Two different possibilities exist to create “white” LED light
 - Adding a blue, a green and red chip and mix the output light
 - Or: A./ Using a blue LED chip and cover it with phosphor layers
 - B./ Using an UV LED chip and cover it with phosphor layers

Unique Properties of White LEDs

- Mixing the three colors gives the flexibility to create a range of CCT-s and color rendering
- Using blue LEDs with Phosphor coating results in high CCT and less than perfect color rendering
 - CCT and Color rendering will depend on the kind of phosphor(s) used; new phosphor coatings show improvement

Mixing three colors

- There is a great deal of difference in spectra of the 3 chip/3 lamp type of “white LEDs” along different spatial directions.
- It is very difficult to mix the colors uniformly
- This arrangement is costly, creates more difficulties for temperature control
- The three different color LEDs age differently, causing a change in CCT with time

Blue LED with Phosphor

- Some example of white LED lamps
 - (PAL conference 2003)

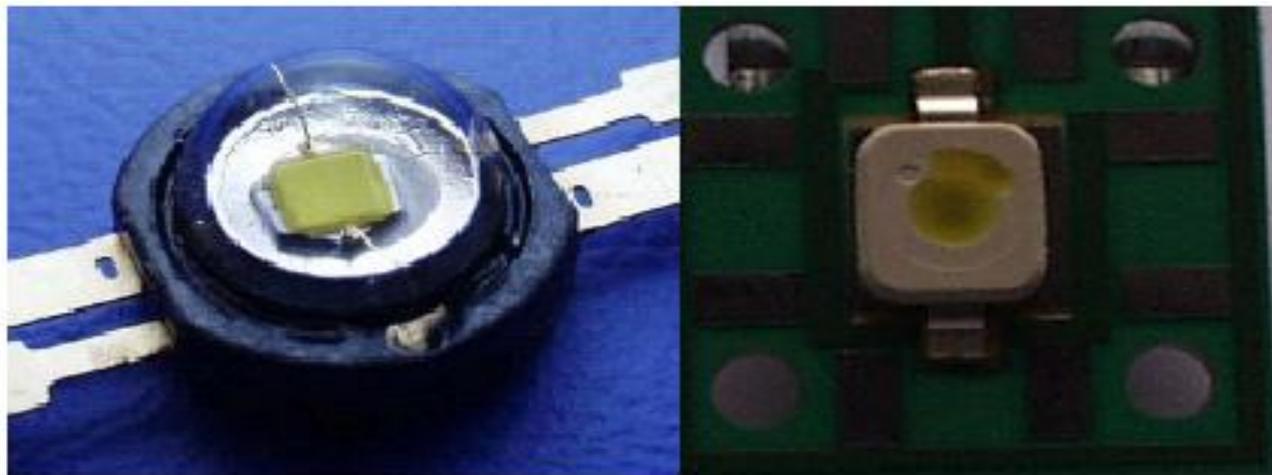
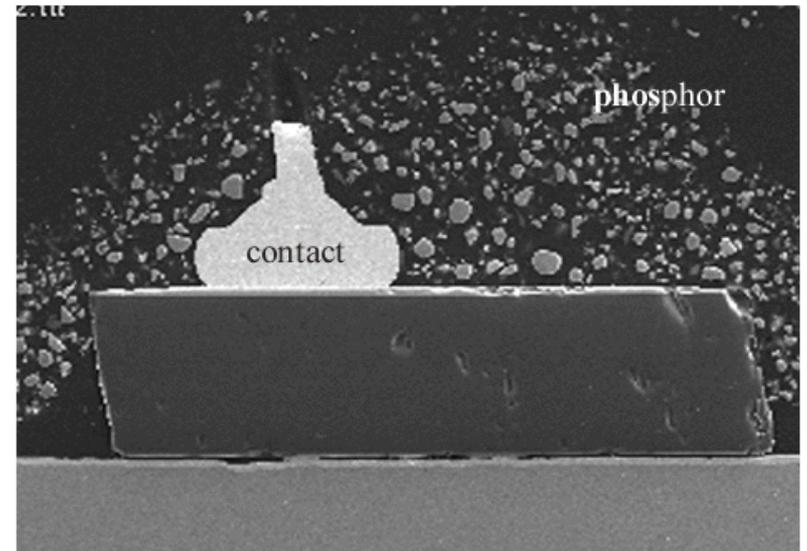
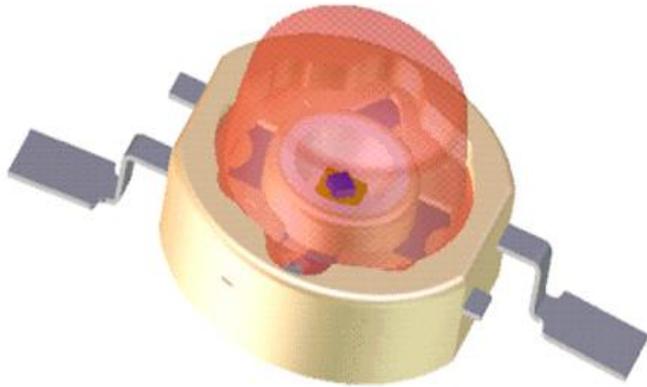


Figure 2: *Left: 1, 2 and 3 Watt Luxeon package. Size of the Chip: 1 mm x 1mm. The phosphor is added directly to the chip.*

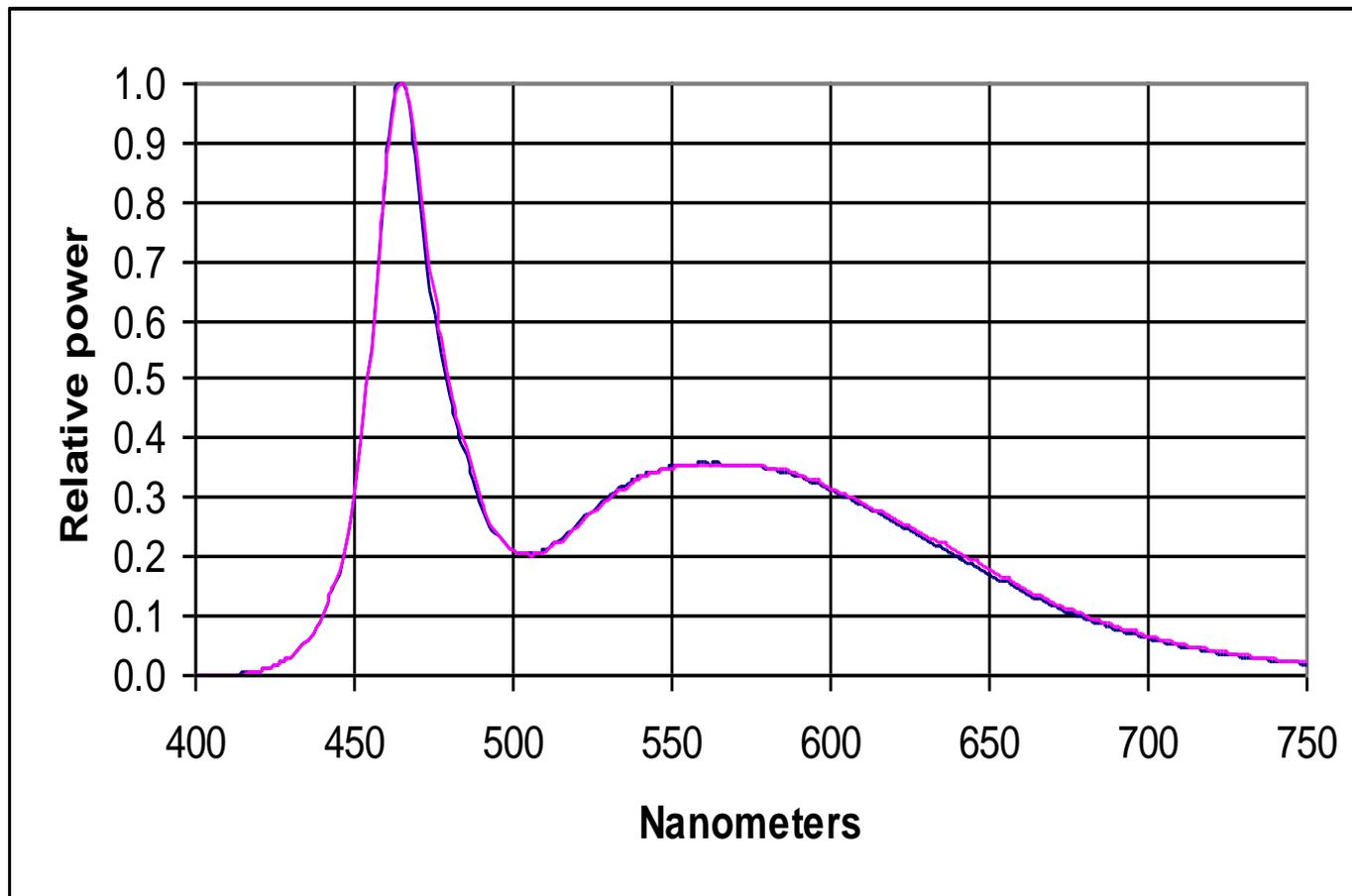
Right: 1 Watt Osram Dragon, diameter of the emitting element: 3 mm, Size of the Chip: 1 mm x 1 mm. The phosphor is added into the cavity of the lens.

Blue LED with Phosphor



White lamp and cross section of a white-light emitting diode

Spectral distribution of white LEDs



Blue LED with Phosphor

- Most common problem is the relatively low red output in the spectrum
- At present such chips and lamps are utilized in lighting applications
- With improved phosphor coating increased red output can be achieved, making it possible to use in general lighting

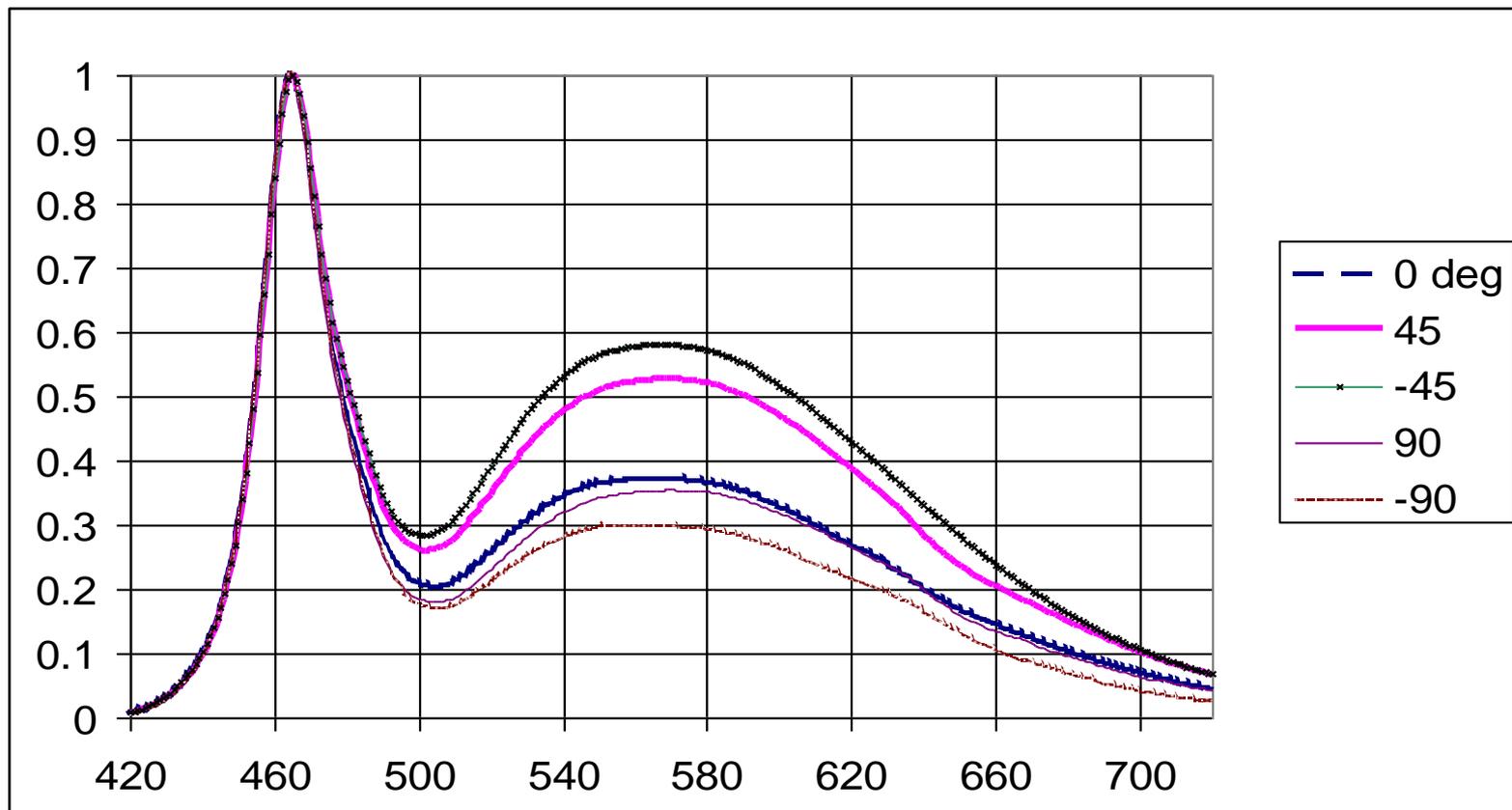
White LED testing

- Most frequently same test methods are applied to white LEDs as applied to other LEDs
- In many cases this can lead to discrepancies in measurement results

White LED testing

- White LEDs exhibit spatial distribution of their spectrum;
 - Depending on the length of optical path the blue light travels through the phosphor layer
 - Depending on the angle how the blue light enters the phosphor layer

Spectral spatial distribution



Spectral spatial distribution



Spectral spatial distribution: assimetric



White LED testing

- When spectrum of power is measured, the exact geometrical conditions of measurement are extremely important
- It is advisable to conduct this measurement under the same condition as the application will require

White LED testing

- I_{LED} measurement is no problem; here the geometrical conditions are already set
- Flux measurement: if measured in the integrating sphere, the parts of the radiation exiting from the sides of the chip will be blue or bluer than the radiation in the perpendicular direction

White LED testing

- Very important to have a perfect white-reflecting sphere paint and a very well matched photopic response to $V(\lambda)$ of the attached photometer to obtain accurate data
- Safest solution to have a standard calibrated white LED of the same kind as the test LEDs for substitution measurement

White LED testing

- Some automatic LED testers use CCD + spectrometers and a small integrating sphere as entrance optics
- From spectral data the important quantities are calculated
- If there is considerable variation in the spatial distribution of the spectrum, the results will differ from those obtained without using the integrating sphere

SUMMARY

- Recommendations by CIE for LED measurements has been discussed
 - Intensity, flux and spectral power distribution were the subject of the latest report recently completed (CIE 127:2007)

SUMMARY

- Other technical committees working on LED testing recommendations:
 - TC1-62: Color rendering of white LEDs
 - TC2-46: CIE/ISO standards on LED intensity measurements
 - TC2-50: Measurement of the optical properties of LED clusters and arrays
 - TC2-58: Measurement of LED radiance and luminance
 - R2-36: Measurement requirements for solid state light sources (in production)
 - TC6-55: Light emitting diodes (safety issues)