Measuring Forward Fluorescence in Remote Phosphors Used in LED Luminaries: A Path to Reproducible Measurements?

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Outline

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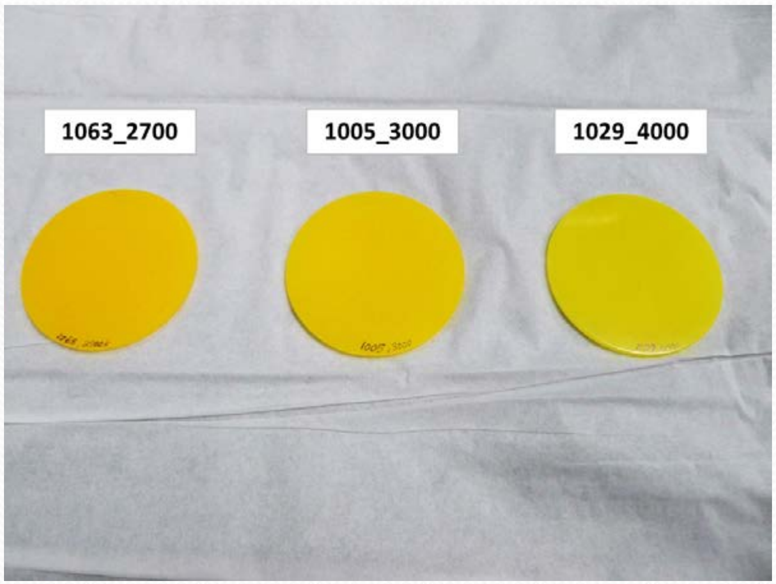
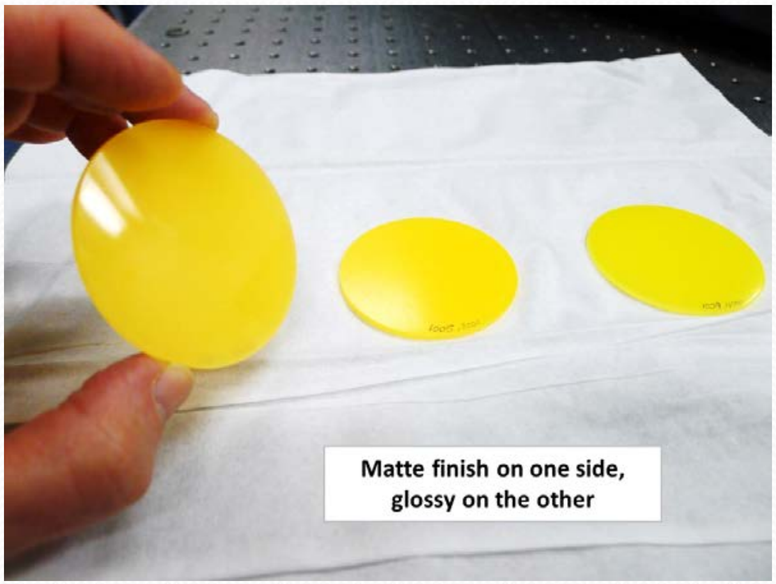
- Motivation
- Measurements and Geometries Used: directional-hemispherical (integrating sphere) and directional-directional (goniometer)
- Data
- A simple relationship to link results for quantum efficiency between measurement geometries
- Summary

Motivation

- A robust method for measuring quantum efficiency in remote phosphors used in luminaires, and for transferring calibration, is desired
  - Not only for overall characterization of samples but also for manufacturing and process control
  - Results are found to vary depending on measurement geometry, for example, when using integrating spheres of different sizes and wall reflectance
    - Why? Feedback of the pump by the sphere alters the source irradiance, and the fluorescence also contributes to the overall illumination
    - Is there are a way to remove the feedback?
      - Sure…try a goniometer which more represents the geometry in a luminaire, and then relate the goniometer measurements to those obtained using a sphere(s). Can a relationship be found?

Three Remote Phosphor Samples Measured

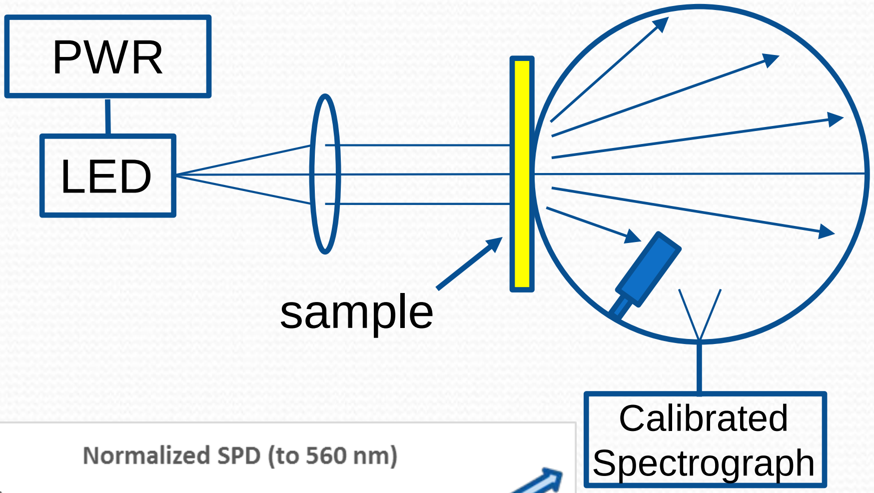


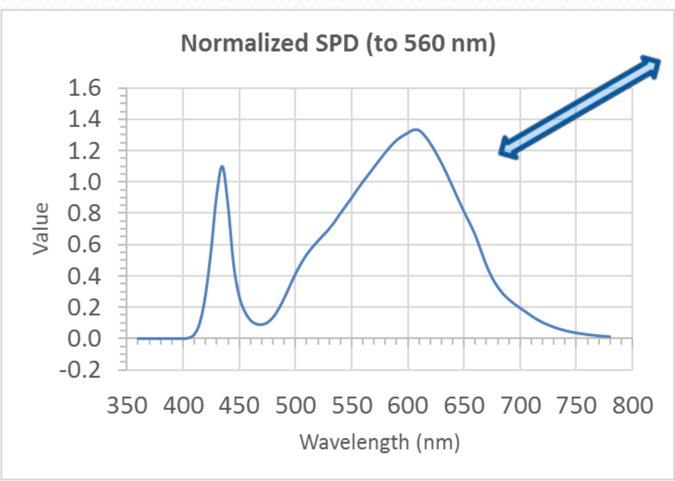


Glossy side oriented away from LED in all cases

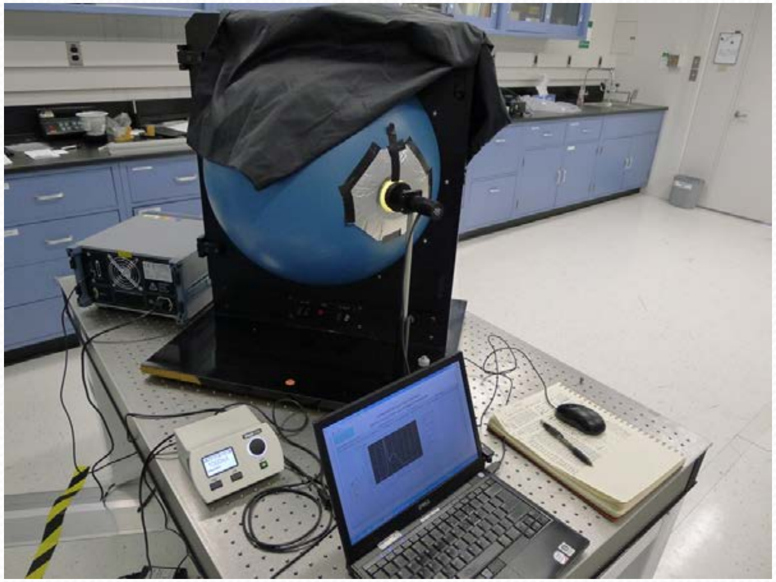
Measurement System A:

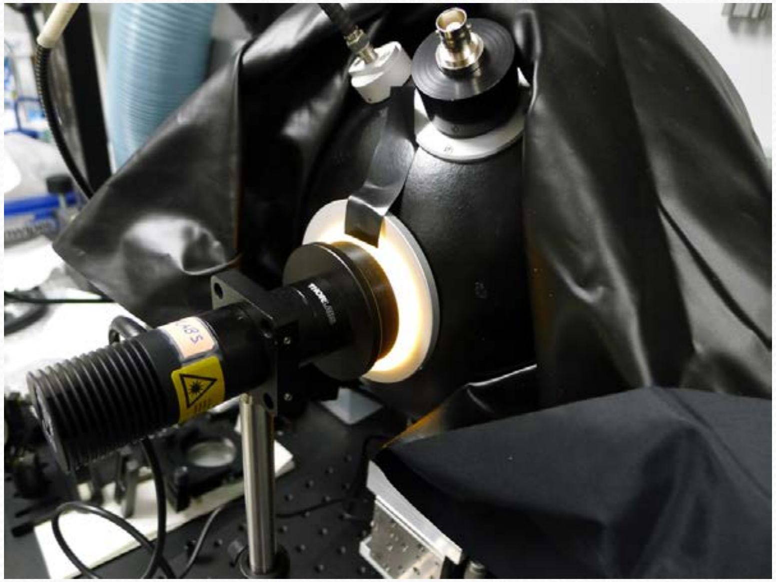
Two Spheres, Two Different Diameters: 500 mm and 186 mm



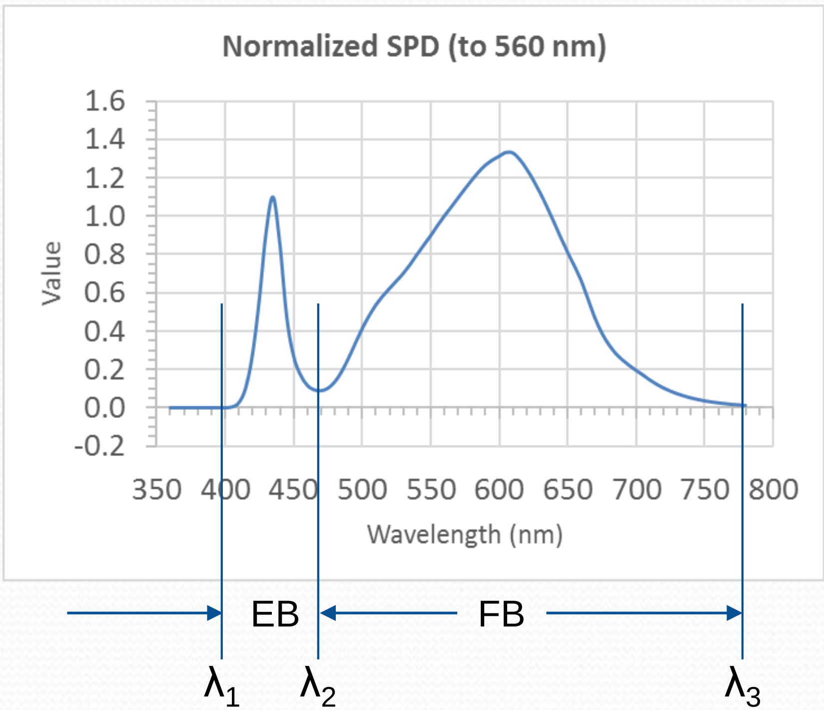


1 nm data from spectrograph is used





Calculating Quantum Efficiency from Spectral Power Distribution (SPD) Data



Measure first w/o sample to determine initial pump value; then measure with sample at port to determine f_{PFB} and f_{PEB}. Integrals replaced by summations using 1 nm spectral data.

Effective Quantum Efficiency

$$\eta_{eff} = \frac{\int_{\lambda_2}^{\lambda_3} \Phi_{conv} \lambda d\lambda}{\int_{\lambda_1}^{\lambda_2} \Phi_{init} \lambda d\lambda - \int_{\lambda_1}^{\lambda_2} \Phi_{trans} \lambda d\lambda}$$

Where:

Φ_{conv} = phosphor-converted flux spectrum
Φ_{init} = initial pump flux spectrum
Φ_{trans} = transmitted pump flux spectrum

Limits of integration depend on source

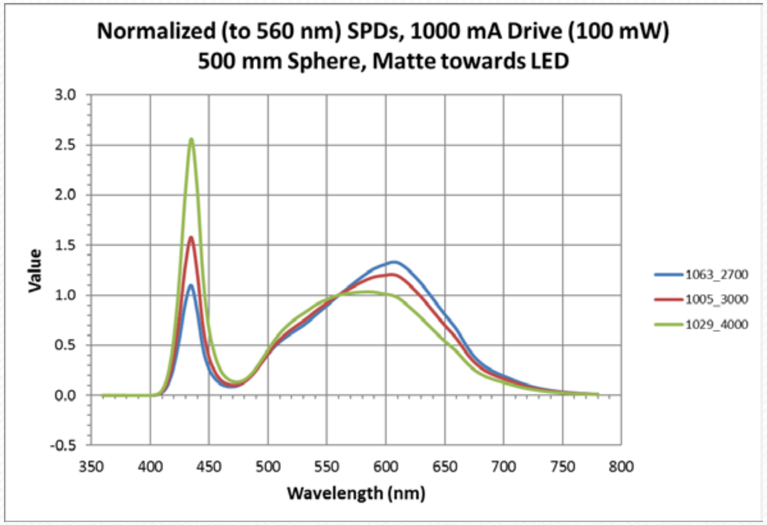
From *Keppens et. al., "Determining Phosphors' Effective Quantum Efficiency For Remote Phosphor Type LED Modules", CIE Expert Symposium on Spectral and Imaging Methods for Photometry and Radiometry, CIE x036:2010.*

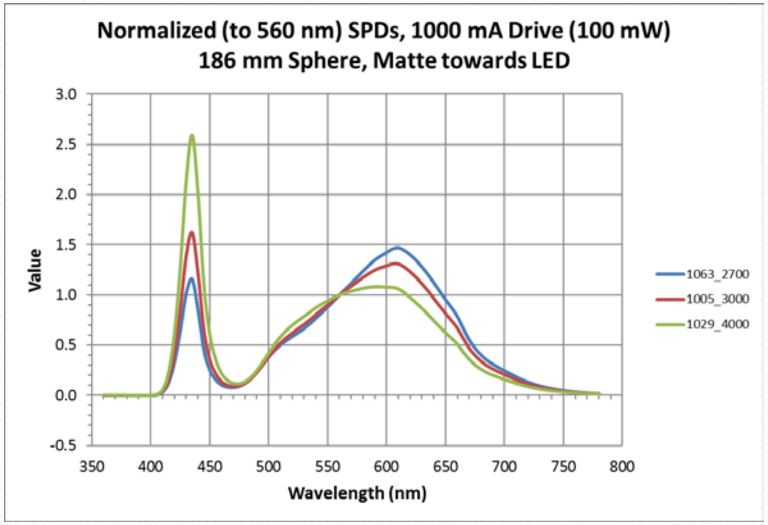
$$\eta_{eff} = \frac{\int_{\lambda_2}^{\lambda_3} \Phi_{conv} \lambda d\lambda \,/\, \int_{\lambda_1}^{\lambda_2} \Phi_{init} \lambda d\lambda}{1 - \int_{\lambda_1}^{\lambda_2} \Phi_{trans} \lambda d\lambda / \int_{\lambda_1}^{\lambda_2} \Phi_{init} \lambda d\lambda}$$

$$\eta_{eff} = \frac{f_{PFB}}{1 - f_{PEB}}$$

f_{PFB} = fraction of pump in fluorescence band
f_{PEB} = fraction of pump in excitation band

Sphere Results: SPDs, η_{eff} and Appx. CCT





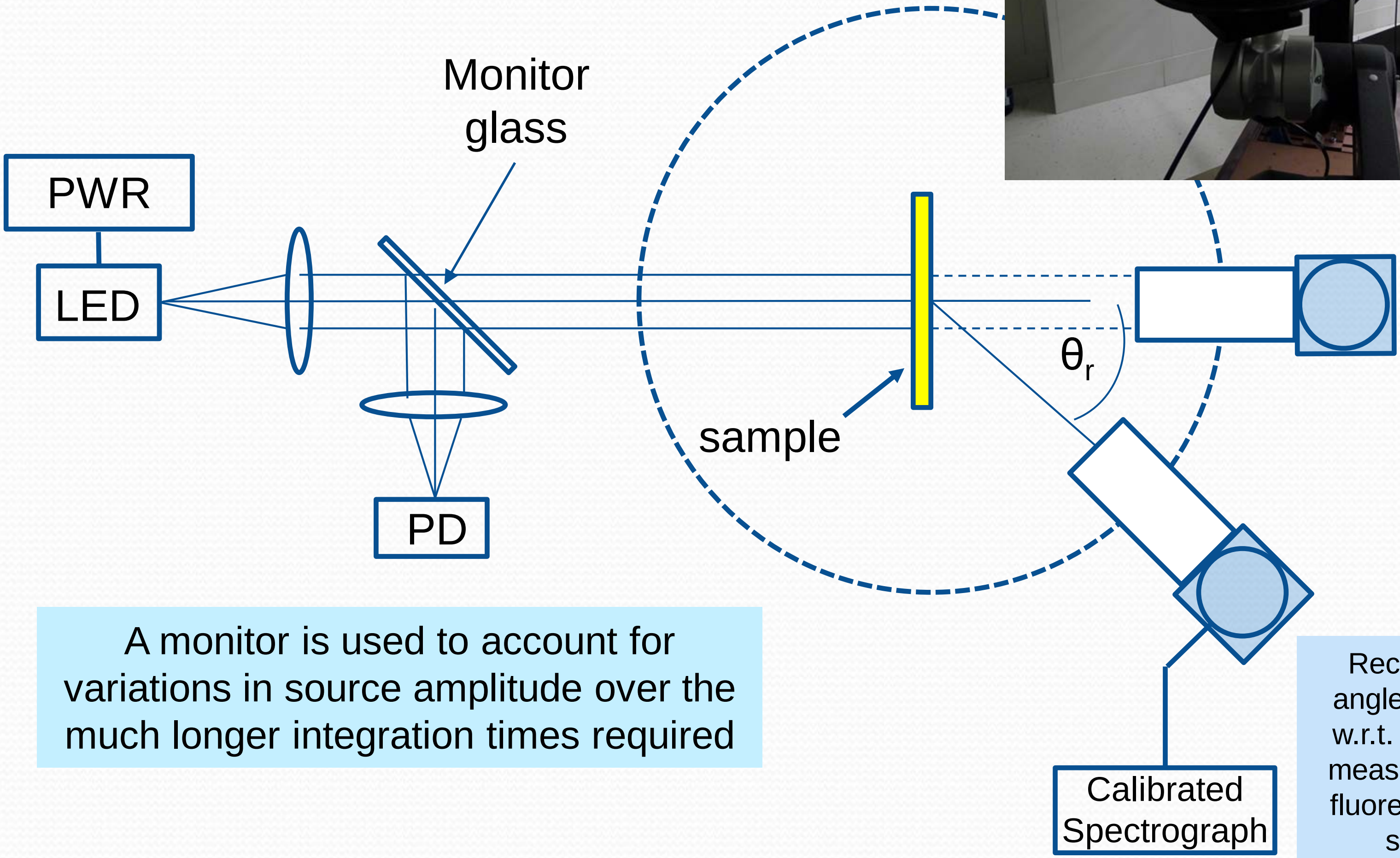
100 mW pump flux	Sample	η_{eff}	CCT
Large (500 mm) Sphere	1063_2700	0.47	3042
	1005_3000	0.46	3457
	1029_4000	0.48	4776
Small (186 mm) Sphere	1063_2700	0.52	2795
	1005_3000	0.52	3181
	1029_4000	0.55	4370

η_{eff} is found to vary with sphere size. Also note CCT results for small sphere are more consistent with label.

CCT Approximation

- $CCT(x, y) = -449n^3 + 3525n^2 - 6823.3n + 5520.33$
  - $n = (x - x_e)/(y - y_e)$
  - $x_e = 0.3320$, $y_e = 0.1858$
  - From *McCamy, Calvin S. (April 1992). "Correlated color temperature as an explicit function of chromaticity coordinates". Color Research & Application* ***17*** *(2): 142–144. doi:10.1002/col.5080170211*

Measurement System B: In-Plane BTDF using Robot Goniometer, 0° AOI



Position for measuring pump total flux (no sample); θ_r = 0 (or 180° w.r.t. the input light axis).

Receiver having solid angle Ω_r and at angle θ_r w.r.t. the sample normal measures excitation and fluorescence bands with sample in place

A monitor is used to account for variations in source amplitude over the much longer integration times required

Goniometer: Detected Light Fraction

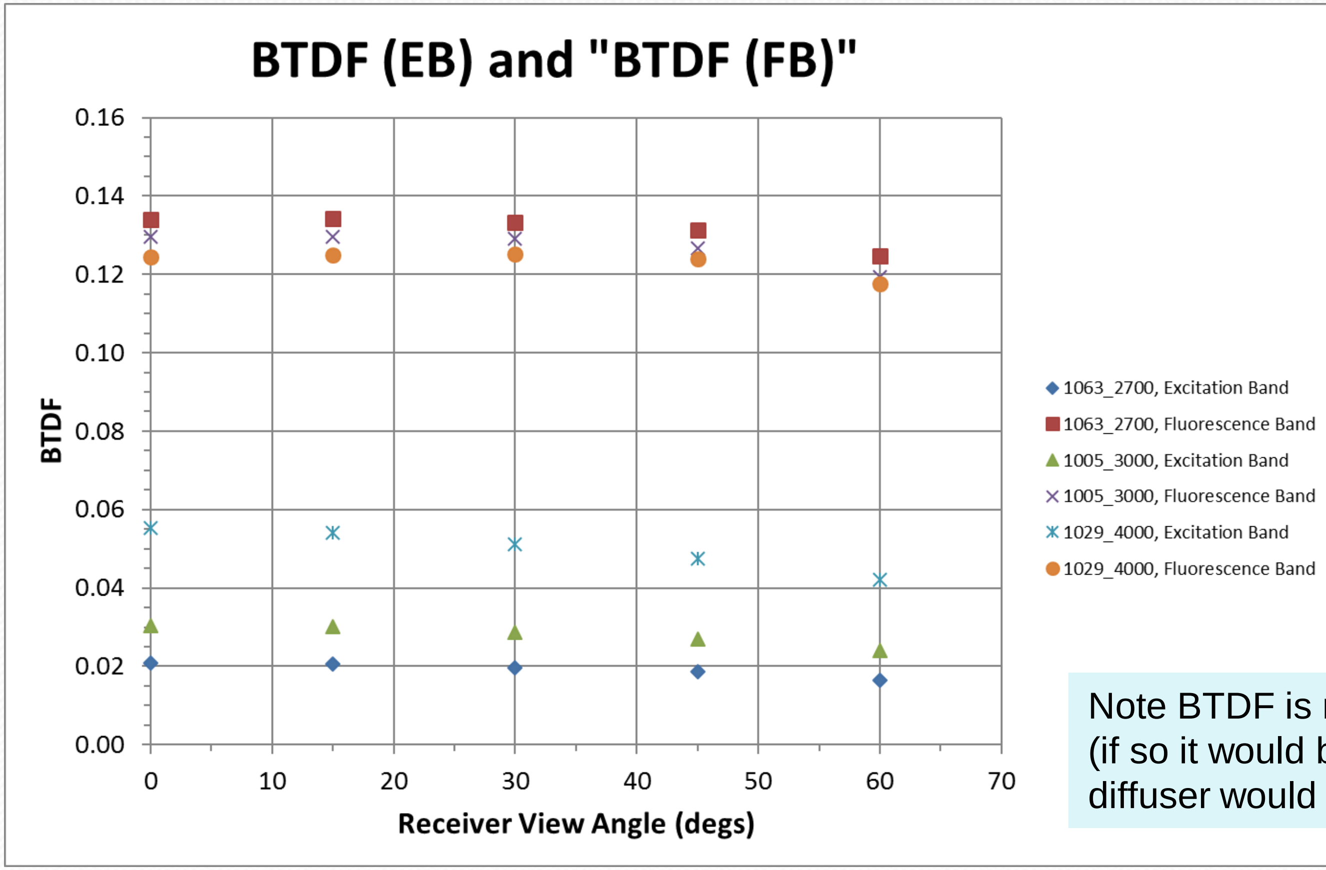
- The fraction of light collected by the goniometer on the transmitted side, P_s/P_i, will depend on the light's Angle of Incidence (AOI), the angle by which the sample is viewed (θ_r) with the receiver, and receiver solid angle, Ω_r, all related through the sample's BTDF:

$$BTDF = \frac{P_s/P_i}{\Omega_r \cos(\theta_r)}$$

Ω_r = 0.00267 sr in ROSI

- Integrated (over the appropriate λ limits) in-plane BTDFs for both the EB and FB of the three remote phosphor samples were measured for a few θ_r:

In-Plane BTDF Measurements for the Three Remote Phosphors



Procedure:

1. Measure pump w/o sample at 0° AOI, integrate over EB λ limits to form initial pump flux
2. Install sample, measure f_{PEB} and f_{PFB} with receiver at θ_r. Remember to account for much longer integration time
3. Also use monitor to account for source drift

Note BTDF is not Lambertian, but close (if so it would be constant, e.g., a perfect diffuser would be 1/π)

Now What…

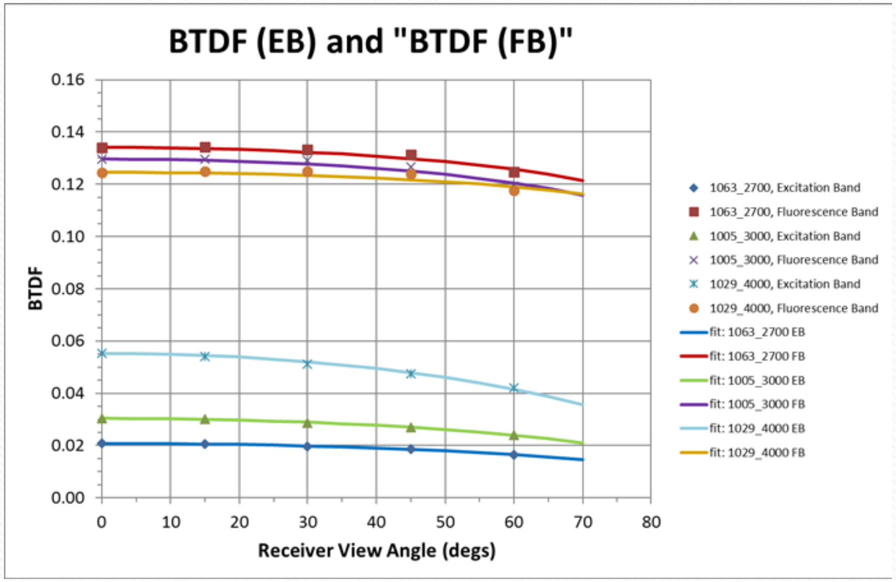
- We have an in-plane BTDF measurement at discrete θ_r using a solid angle Ω_r. SUPPOSE from this data, the expected result over a hemisphere free from feedback, $Frac_{hemi}$, is calculated:

$$Frac_{hemi}(0, 2\pi) = \int_0^{\pi/2} 2\pi BTDF(0;\theta_r)\cos(\theta_r)\sin(\theta_r)\,d\theta_r$$

Adapted from Eq. 8.28 in Germer, Zwinkels, and Tsai, eds.,"Angle-Resolved Diffuse Reflectance and Transmittance" in Spectrophotometry: Accurate Measurement of Optical Properties of Materials. Elsevier, Inc. 2014.

  - Normal incidence and an isotropic sample have been assumed

BTDF data with cosine power fit overlay



A cosine power function, $BTDF(\theta_r) = BTDF_{\theta r=0}(\cos\theta_r)^p$ was used to best-fit the data.

Other functions can be used of course.

But using a cosine power fit…

$$Frac_{hemi}(0, 2\pi) = \int_0^{\pi/2} 2\pi BTDF(0;\theta_r)\cos(\theta_r)\sin(\theta_r)\,d\theta_r$$

$$= 2\pi BTDF_{\theta_r=0}\int_0^{\pi/2} cos\theta_r{}^{p+1} sin\theta_r d\theta_r$$

$$= 2\pi\, BTDF_{\theta_{r=0}}/(p+2)$$

Note: if p = 0, $Frac_{hemi}$ reduces to Lambertian result

So?

- Calculate η_{eff} expected for hemisphere using Equations in Slide 6 and Slide 12:

Sample:	1063_2700	1005_3000	1029_4000
p, EB:	0.34	0.34	0.41
$BTDF_{\theta r=0}$, EB:	0.0208	0.0304	0.0552
$Frac_{hemi}$, EB:	0.056	0.082	0.144
p, FB:	0.09	0.11	0.07
$BTDF_{\theta r=0}$, FB:	0.1341	0.1296	0.1245
$Frac_{hemi}$, FB:	0.403	0.387	0.379
η_{eff}:	0.43	0.42	0.44

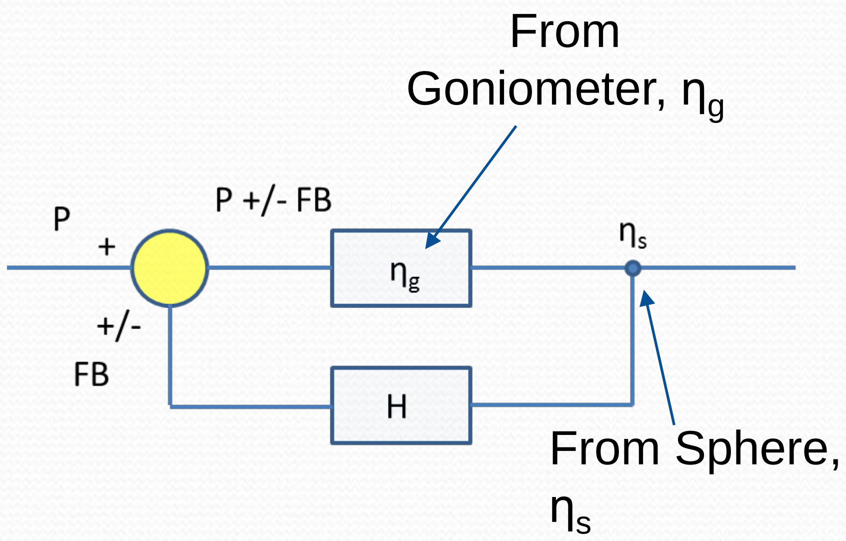
- Compare to η_{eff} from Integrating Spheres:

Sample:	1063_2700	1005_3000	1029_4000
500 mm Diam Sphere η_{eff}:	0.47	0.46	0.49
186 mm Diam Sphere η_{eff}:	0.52	0.52	0.55

Note that η_{eff} increases from value for hemisphere (no feedback) to integrating sphere value (has feedback).

Recall a simple feedback loop:

Simple Feedback Loop



- The output of the loop (η_s) depends on the feedback gain H
- If H > o and if it is required that $\eta_s > \eta_g$, the feedback must be regenerative or reinforced and

$$\eta_s = \eta_g/(1 - H\eta_g)$$

- Solving for H:

$$H = {(\eta_s - \eta_g)}\big/{\eta_s\eta_g}$$

H so calculated appears to be "constant" whose value depends on the sphere used. Encouraging result for transferring data from a gonio to a sphere, sphere to gonio, or from sphere-to-sphere!

Sample:	1063_2700	1005_3000	1029_4000
500 mm Diam Sphere η_{eff}:	0.47	0.46	0.49
186 mm Diam Sphere η_{eff}:	0.52	0.52	0.55
Gonio (hemi):	0.43	0.42	0.44
H, 500 mm Diam:	0.20	0.21	0.20
H, 186 mm Diam:	0.42	0.44	0.43

Equations and Cal Process

- $\eta_s = {}^{\eta_g}\!/_{(1 - H\eta_g)}$
- $\eta_g = {}^{\eta_s}\!/_{(1 + H\eta_s)}$
- $H = {}^{(\eta_s - \eta_g)}\!/_{\eta_s \eta_g}$

- A reference artifact is calibrated and assigned an η_g using a goniometer, a geometry much more representative of how the remote phosphor is used in a luminaire (i.e., no feedback)
- The reference artifact is supplied to the customer/manufacturer, who likely measures η_s on a sphere, then calculates H for that sphere
  - This assumes the same LED (λ centroid and bandwidth), drive current, integration limits are used when η_g was assigned (so a "standard source" is required)
- The customer then measures η_s for an arbitrary phosphor, then converts η_s to η_g using H
- In this manner, multiple spheres can be used by a customer as long as each is first characterized for H

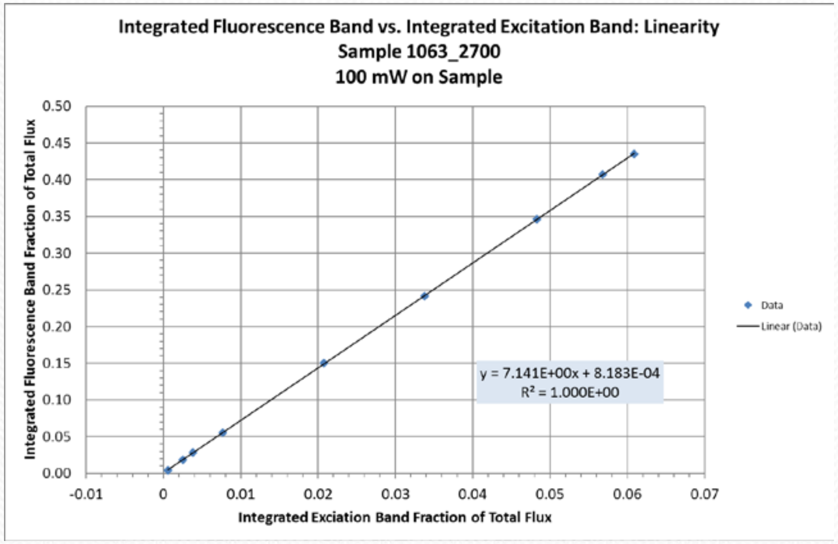
To do:

- More (dense) Goniometer data needs to be taken for remote phosphor samples
  - Will yield better cosine power fit or perhaps some other functional fit for BTDF
  - Recalculate H for as many spheres as possible
  - Just do more!
- Measure arbitrary phosphors (not used to calculate H) and predict their η_{eff} using H
  - Can measure:
    - On gonio, then predict for spheres using H calculated from reference
    - On one of known sphere, then predict for gonio and other spheres if their H is known
- Confirm idea!

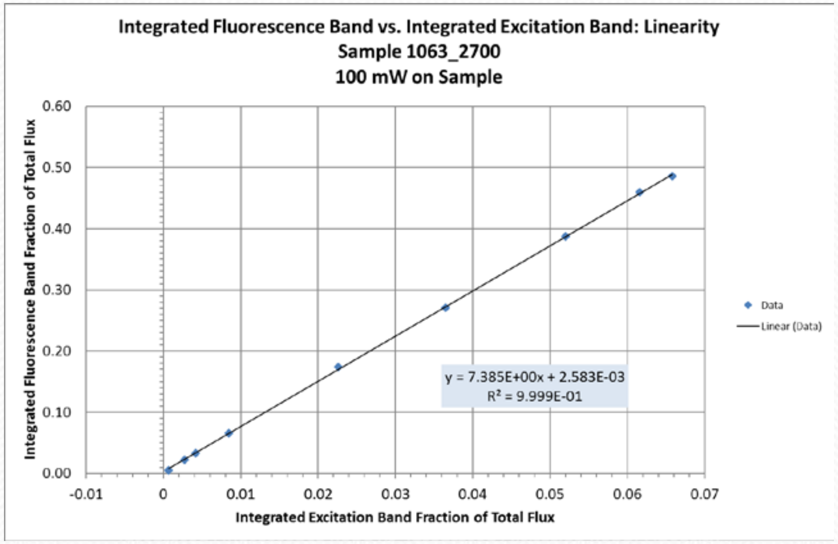
BTW…Fluorescence is linear with Excitation, but slopes are different

Neutral Density filters were installed in pump path; integrated FB fraction of total pump flux follows integrated EB fraction of a total flux in a linear manner

500 mm Sphere

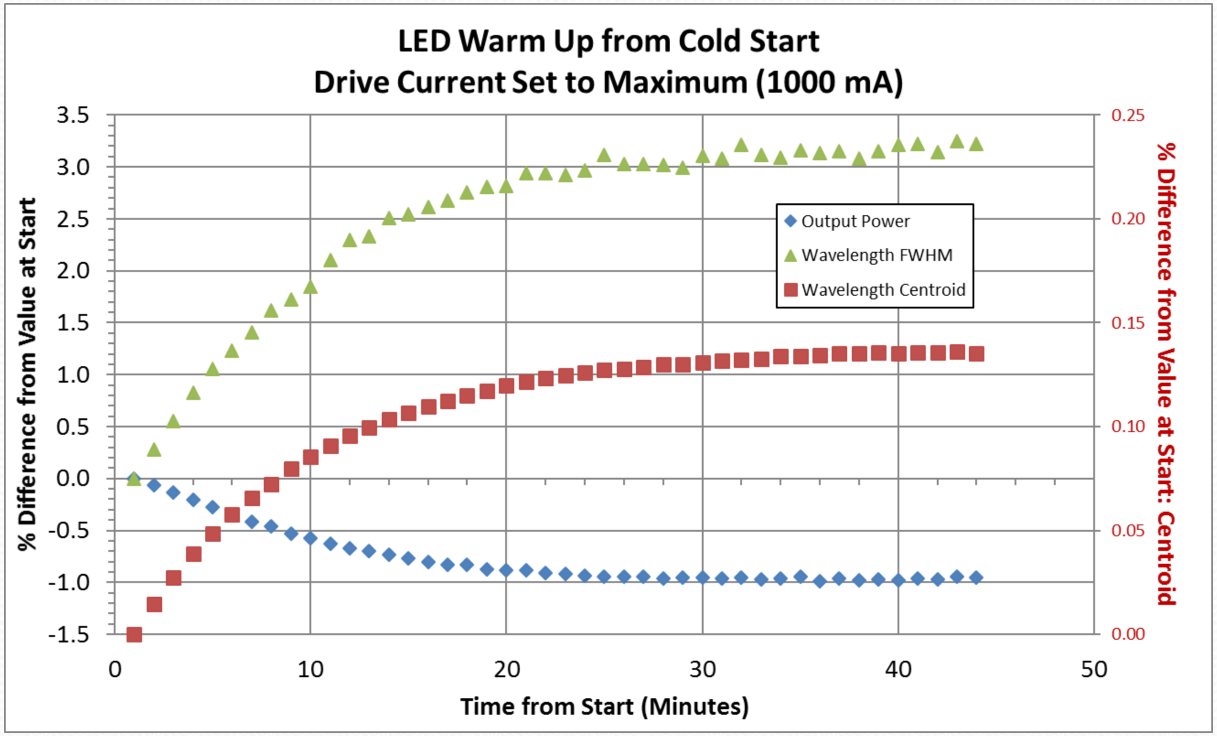


186 mm Sphere



Feedback is different so slopes are different

…and LED has warm-up period



- Wait 30 minutes for this particular LED before use

Summary

- A method to calculate quantum efficiency measured with one geometry (e.g., a goniometer) and relate it to quantum efficiency measured on a different geometry (e.g., an integrating sphere) has been proposed
  - Feedback loop gain, H, relates gonio to sphere measurements
- Remote phosphors can thus be calibrated (gonio) and then supplied to a customer who then determines H for sphere systems
  - assumes the same LED SPD is used (standard source)
- Once H is determined, use it to calculate a value of feedback-free η_{eff}, a value much more representative of that when the phosphor is used in a luminaire