Fluorescence errors in integrating sphere measurements of remote phosphor type LED light sources

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problem

integrating sphere

à self-absorption

à second-order fluorescence from phosphor type LEDs

à flux error

during auxiliary and LED source measurement

theory

spectral irradiance at receiver:

$$E_{e,\lambda}(\lambda, a_r, b_r) = \frac{1}{4\pi R^2}\left[\frac{r_s(\lambda)}{1-\bar{r}(\lambda)}\right] F^{0}_{e,\lambda}(\lambda) + \rho R_p \int_{\lambda'} \frac{f_\lambda(\lambda,\lambda')}{1-\bar{r}(\lambda')} F^{0}_{e,\lambda}(\lambda')\, d\lambda'$$

common sphere theory

error term

spectral fluorescence coefficient (matrix)

theory

spectral relative error on radiant flux:

$$e_{e,r,\lambda}(\lambda) = \frac{\rho R_p}{F^0_{e,\lambda}(\lambda)} \int \frac{f_\lambda(\lambda,\lambda')}{1-\bar{r}(\lambda')} F^0_{e,\lambda}(\lambda') d\lambda'$$

relative error on luminous flux:

$$e_r = \frac{\int \left[\int \frac{\rho R_p f_\lambda(\lambda,\lambda')}{1-\bar{r}(\lambda')} F^0_{e,\lambda}(\lambda') d\lambda' \right] V(\lambda) d\lambda}{\int F^0_{e,\lambda}(\lambda) V(\lambda) d\lambda}$$

theory

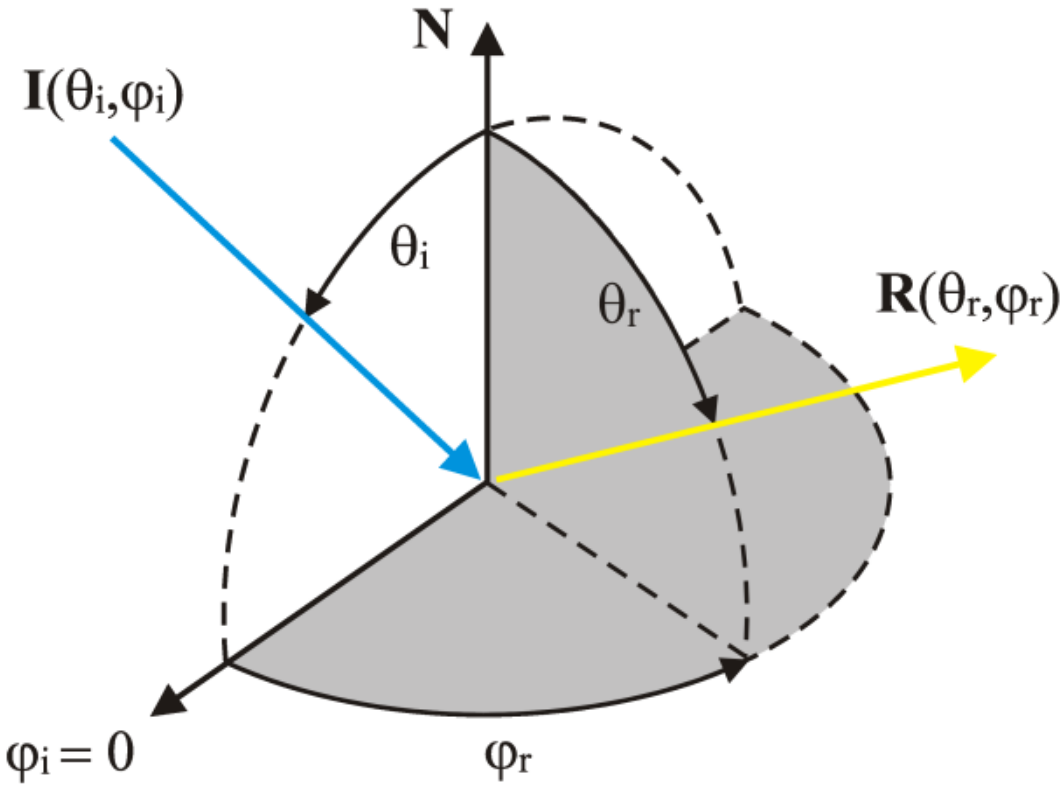
error depends on

- source spectrum
- average reflectance
- phosphor to sphere surface ratio
- spectral fluorescence coefficient

à remote phosphor type LED light sources

experiments: goniophotometer

determine spectral fluorescence coefficient of phosphor (2)



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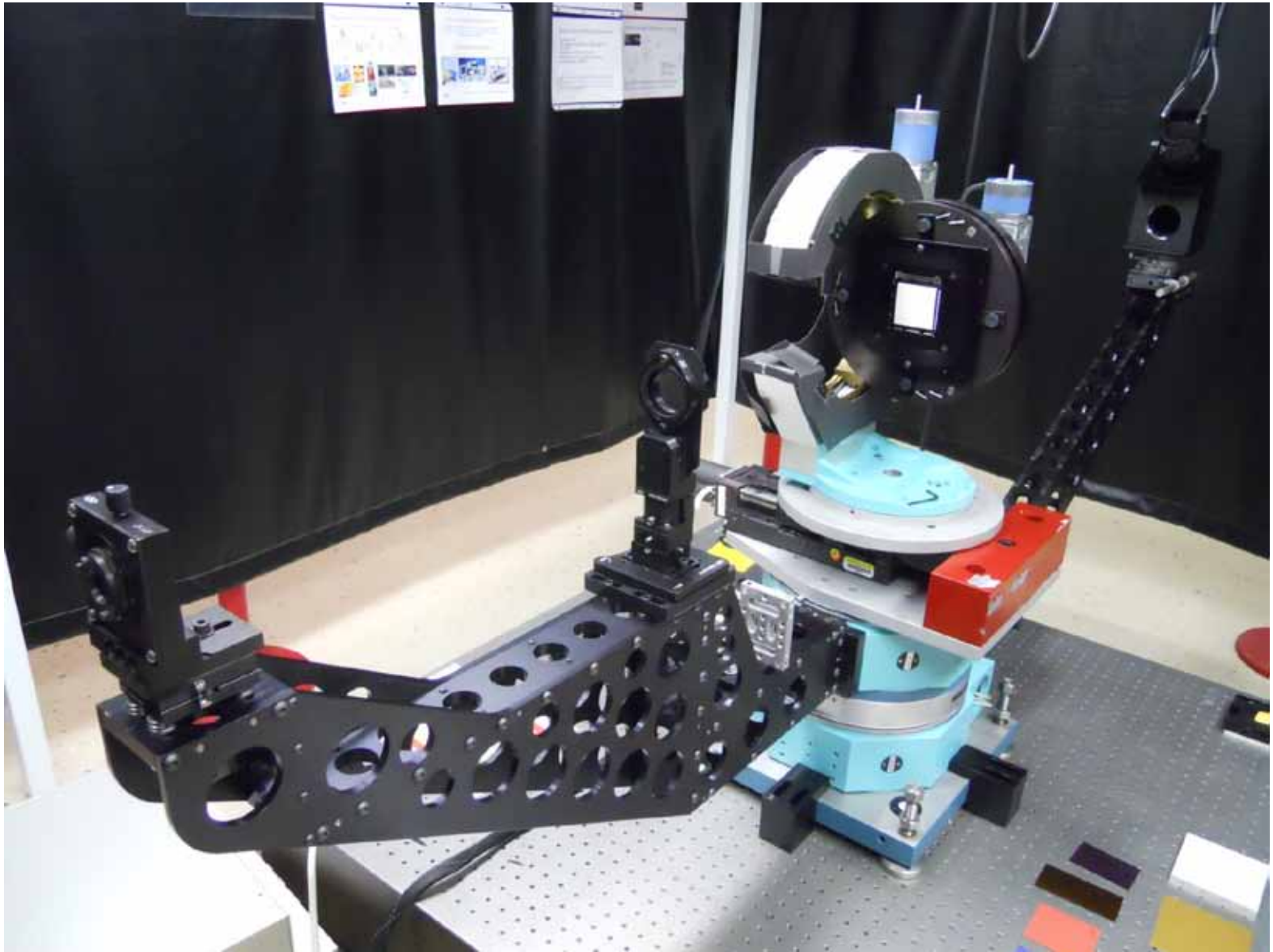
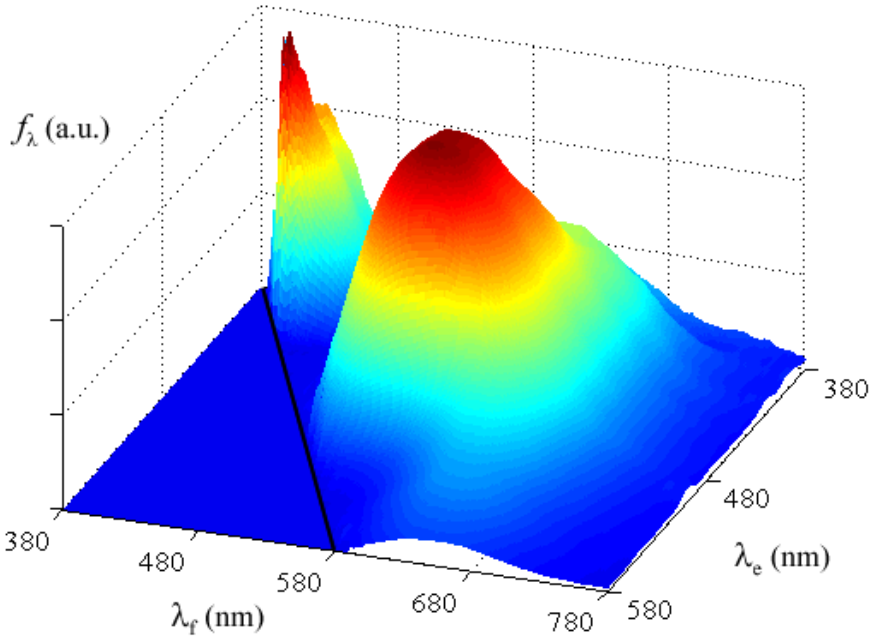
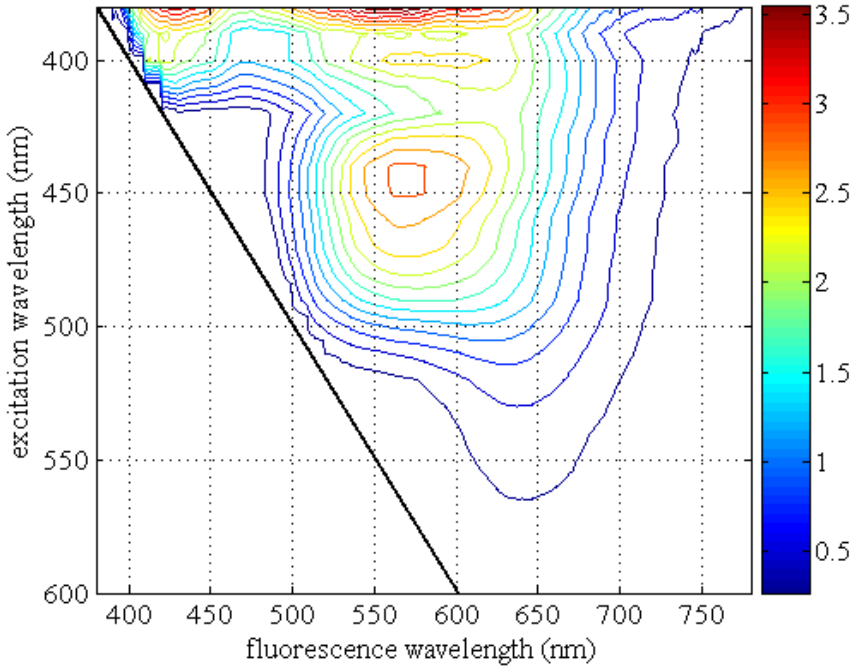
experiments: goniophotometer



experiments: goniophotometer

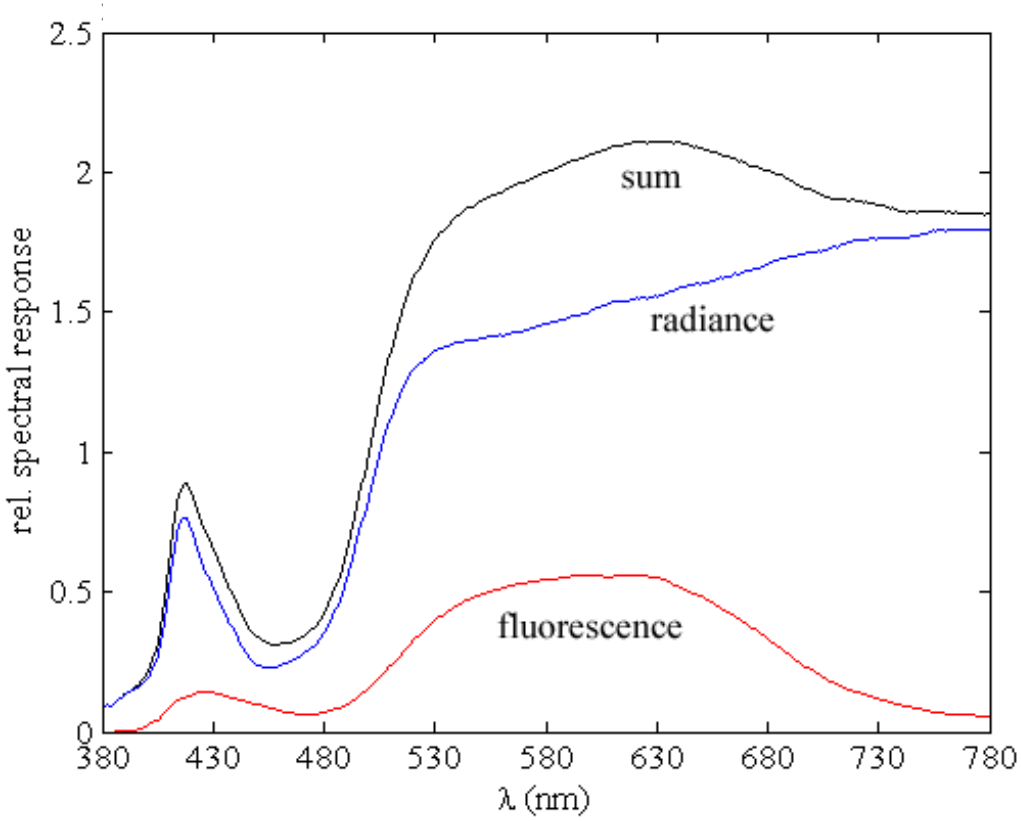
determine spectral fluorescence coefficient of phosphor





experiments: goniophotometer

calculated phosphor respons for flat spectrum



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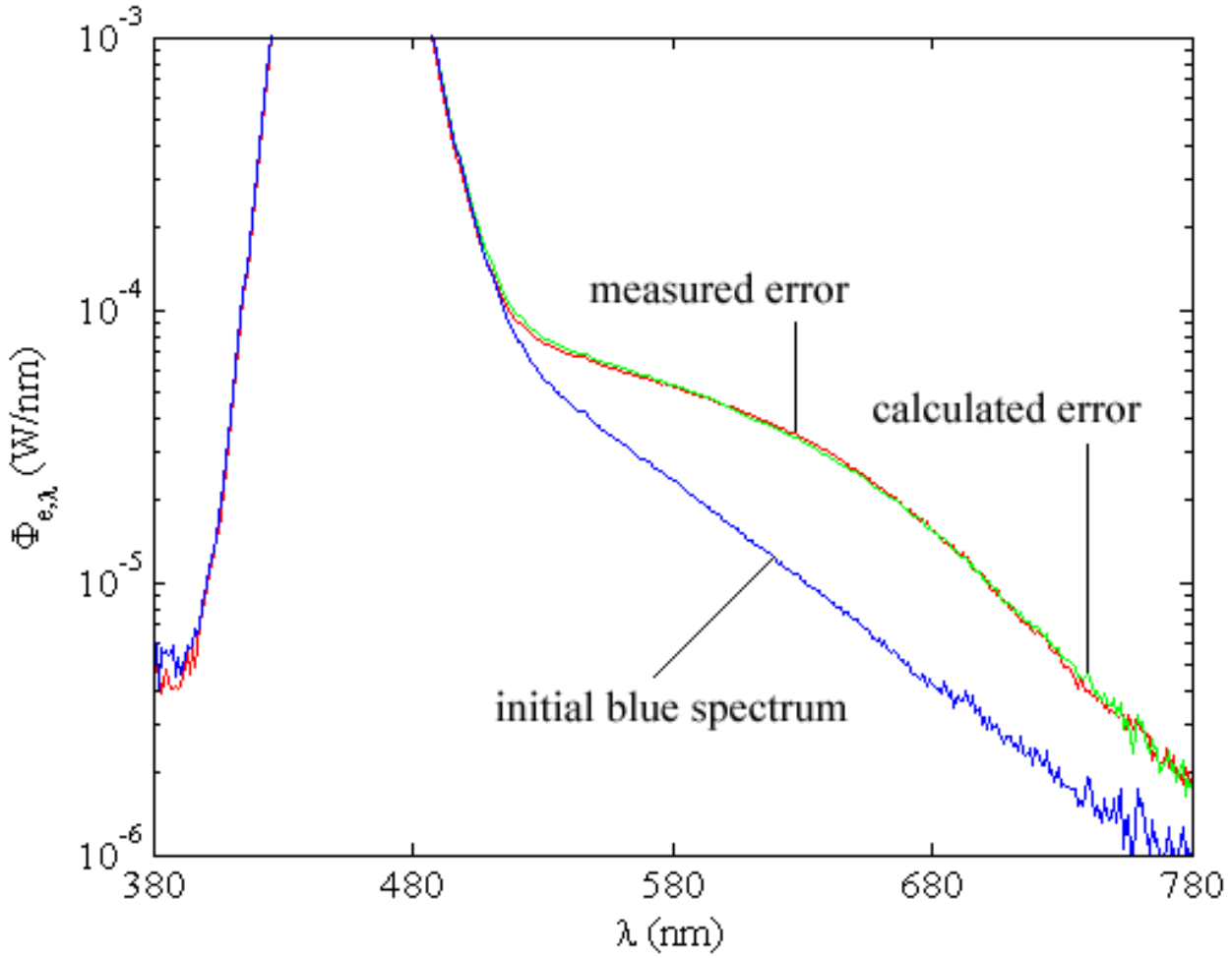
experiments: integrating sphere

spectral radiant flux measurements of

- auxiliary source, with & without remote phosphor type LED lamp
- remote phosphor type LED lamps (2)
- blue LED, with & without remote phosphor type LED lamp

experiments: integrating sphere

validation



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results

light source	error source	rad. flux error (%)	lum. flux error (%)
auxiliary	L1	0.17	0.25
L1	L1	0.17	0.17
auxiliary	L2	2.83	3.24
L2	L2	2.69	3.02

for phosphor to sphere surface ratio:

L1 (4000 K): $9.0\ 10^{-4}$

L2 (3000 K): $17.7\ 10^{-4}$

and for average sphere reflectance: 0.96

but: cancellation effect! à negligible error for industry

case study

for auxiliary with L2:

$\bar{r} \setminus T_c$	2700	3000	3300	3600	3900	4200	4500	4800	5100	5400
0.80	0.45	0.55	0.65	0.75	0.84	0.93	1.02	1.10	1.18	1.26
0.82	0.50	0.61	0.72	0.83	0.93	1.04	1.13	1.23	1.32	1.40
0.84	0.56	0.69	0.81	0.93	1.05	1.17	1.28	1.38	1.48	1.58
0.86	0.64	0.78	0.93	1.07	1.20	1.33	1.46	1.58	1.69	1.80
0.88	0.75	0.91	1.08	1.24	1.40	1.55	1.70	1.84	1.97	2.10
0.90	0.90	1.10	1.30	1.49	1.68	1.86	2.04	2.21	2.37	2.52
0.92	1.12	1.37	1.62	1.86	2.10	2.33	2.55	2.76	2.96	3.15
0.94	1.50	1.83	2.16	2.49	2.80	3.11	3.40	3.68	3.95	4.20
0.96	2.25	2.74	3.24	3.73	4.20	4.66	5.10	5.52	5.92	6.30
0.98	4.49	5.49	6.48	7.46	8.40	9.32	10.20	11.04	11.85	12.61

solutions

- goniophotometer
- partial flux

} avoid

- minimal phosphor to sphere surface ratio
- low-CCT auxiliary
- moderate sphere reflectance

} reduce

- correction method

} compensate

correction

using matrix algebra,

for known spectral fluorescence coefficient (F):

$$S^0 = \left[I + F \right]^{-1} \cdot S^M$$

$$e_r = \frac{V \cdot \left(S^M - S^0 \right)}{V \cdot S^0} = \frac{V \cdot \left(F \cdot S^0 \right)}{V \cdot S^0}$$

conclusions

- modeling of fluorescence error in integrating sphere
- remote phosphor LED light source experiments
  - goniophotometer: spectral fluorescence coefficient
  - integrating sphere: spectral radiant flux
- validation: agreement within 1 %
- fluorescence error
  - typically order of percentage
  - up to order of 10 % for extreme cases!
  - but cancellation effect!
- correction by matrix multiplication (cf. stray light)

Thank you for your attention!