OLLA Project Report

Color Rendering Index (CRI) of State-of-the-Art broadband emitters

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Executive summary

Color appearance of our natural environment in the absence of sunlight is always an important issue in lighting applications. For this purpose a color rendering index was defined additionally to the color coordinates to describe the color appearance with a unitless color rendering index (CRI). The CRI describes the appearance of the emitted light in terms of color reproduction. The value of the CRI mainly indicates how well two different white spectra (test source and “perfect” reference) are coinciding. A high color rendering is essential in settings where **natural** color appearance is important (e.g. in shops, butcher for instance, special lighting is used to have the meet even redder than in normal day light) In office and factory applications, high color rendering can increase visual clarity and create a more pleasing and productive work environment.

The scope of this report is to investigate whether the current state- of- the- art broadband emitting polymers are matching the CRI properties of usual light bulbs or other illumination sources. So far the polymers were developed for display applications, for which only the visual color coordinates are essential.

In the first part of this report the basics - definition and measurement – of the CRI are described. The second chapter deals with the limitations of the CRI measurement. In the last section CRI measurements of current polymeric OLED emitters are shown and are compared with other light sources with which they have to compete in future applications.

1. Introduction

The color rendering index (CRI) was investigated to render the quality of (white) light in one unitless index. It specifies how well the color of an object appears under illumination by a light source compared to a reference light source (e.g. daylight). A detailed description of the measurement is given in Section 3.

The CRI was introduced by the International Commission on Illumination (CIE, [1]) in 1975 and ranges from 0 to 100 having no unit. Low CRI values indicate that the quality of the tested light is low in comparison to the “perfect” (white light) reference source, while high values denote that the spectra of the reference and the tested light match each other closely. Thus, low CRI values result in colors appearing washed out and perhaps even take on a different hue. high CRIs on the contrary make all colors look natural and saturated (Figure 1). A CRI of at least 70 is believed to be required for illumination purposes. Typical CRI values for different light sources are given in Table 1.

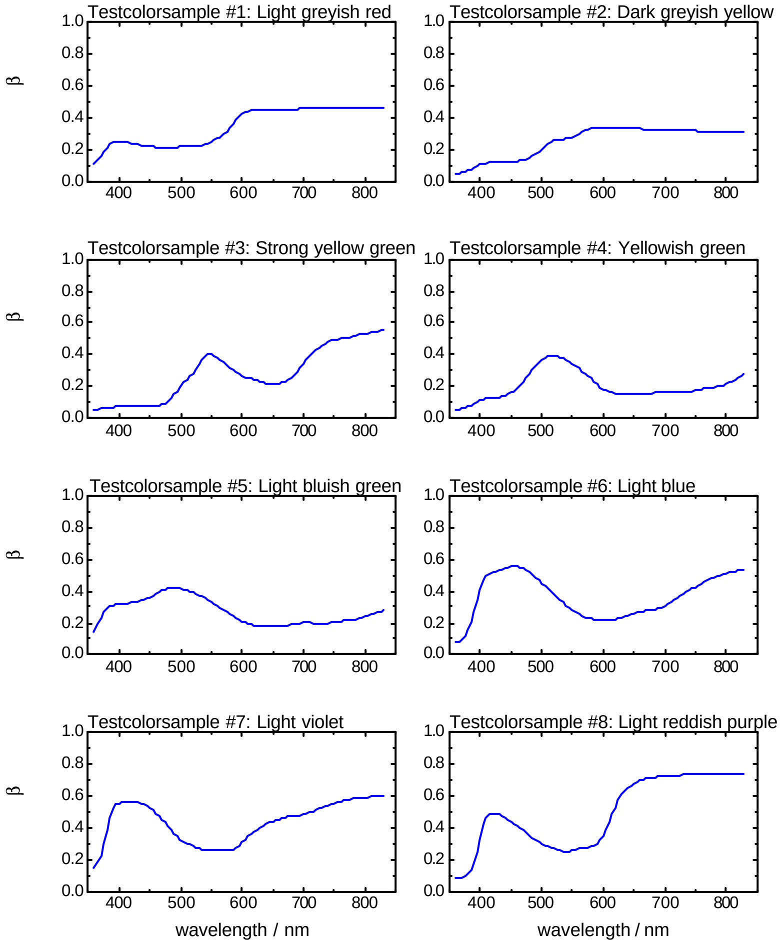
Figure 1: *Left: Illumination by a light with a CRI of 62; Right: Illumination by a light with a CRI of 90; [2]*

Table 1: *Typical CRI values of different light sources*

incandescent light bulb, daylight	100
metal halide 4200K	85
cool white fluorescent lamp	62
high pressure sodium lamp	25
clear mercury lamp	17

2. Measuring the CRI of a light source

The CRI is defined as follows: A reference source, e.g. an incandescent lamp, is defined as having a CRI of 100 and the source to be tested is compared with this. Both sources are used to illuminate standard color samples. In total there are 14 color samples available but usually only samples #1-8 are taken into account for the evaluation of the CRI (=Ra8). The nineth sample represents a deep red and the samples #9-14 represent pastel colors especially for a better testing of skin color. The reflection coefficients of the eight color samples are shown in fig. 2. The perceived colors under the reference and test illumination (measured in CIE 1931 form) are compared – namely the difference in u, v color coordinates values - using a standard formula, and averaged over the eight samples to get the final CRI. For the exact formula and calculation see Ref. [1, 3].



Testcolorsample #1: Light greyish red

Testcolorsample #2: Dark greyish yellow

Testcolorsample #3: Strong yellow green

Testcolorsample #4: Yellowish green

Testcolorsample #5: Light bluish green

Testcolorsample #6: Light blue

Testcolorsample #7: Light violet

Testcolorsample #8: Light reddish purple

Figure 2: *Spectral reflection coefficients beta and color impression of the 8 testcolor samples [4].*

The CRI can only be used to compare two light sources that have the same color temperature. Color rendering index and color temperature are independent of each other. It is possible for two different lamps to have the same temperature and have quite a different color rendering index and vice versa.

For test sources with a color temperature CT < 5000K usually a blackbody radiator (illuminant A, [5]) is used as reference source. If CT is higher than 5000K, the daylight illuminant standard D65 [5] is used as a reference [4]. The spectra of illuminant A and D65 are shown in Figure 3.

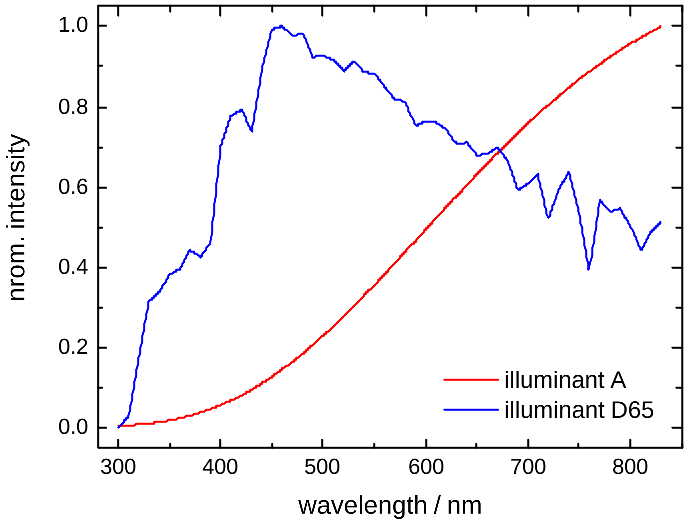


***Figure 3:** Spectrum of the standard illuminants A and D65*

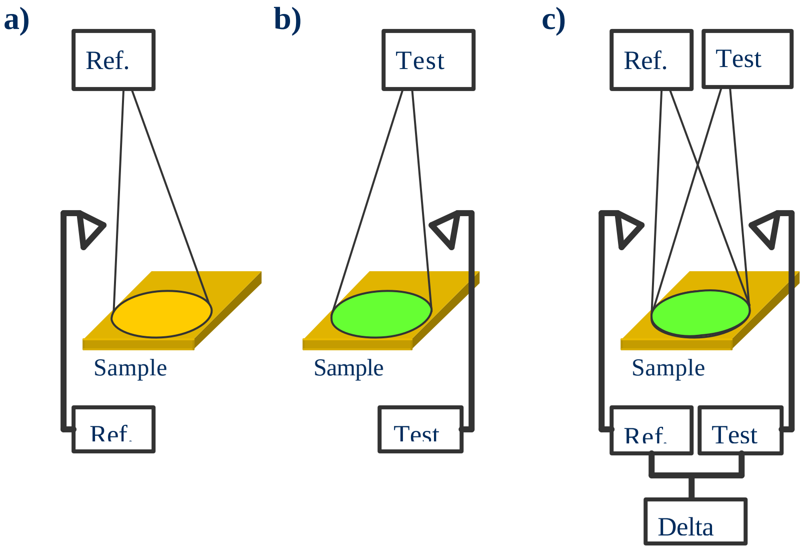


***Figure 4a:** Workflow for measuring the CRI, steps a) – c)*

For all eight color samples steps a) to c) have to be done.

a) Illumination of the color sample with reference source and color measurement.

b) Illumination of the color sample with test source and color measurement.

c) Calculation of color difference between reference and test source.

d) Averaging of color differences over all 8 samples and converting into a unit-less number.

Step a) is independent from the test source and thus has not to be repeated for each measurement.

d)

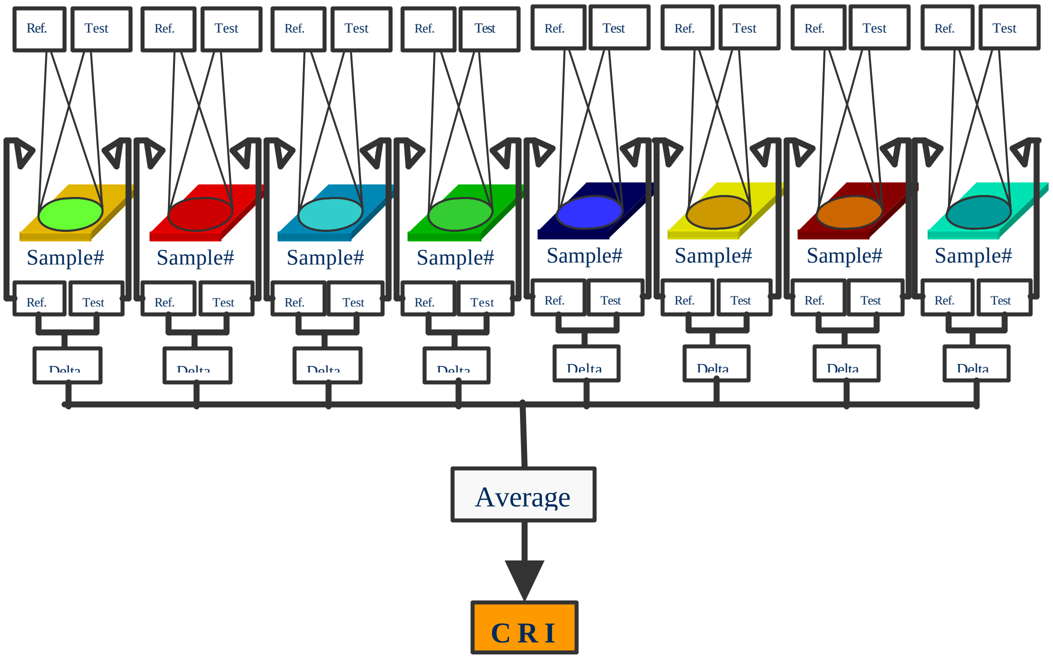


Figure 4b: *Workflow for measuring the CRI, step d)*

The scope of the definition of the CRI value was to characterize mainly incandescent light bulbs as lighting sources. Thus the color plates are somehow designed to give a high CR-Index if the emission spectra are close to these of an incandescent light bulb. In Figure 5 the sum over the first 8 color plates is shown. It is clearly visible, that the “red” part of the spectra 600 – 800 nm is overemphasized. So, a strong contribution of red in the spectra is necessary to obtain high CRI-values.

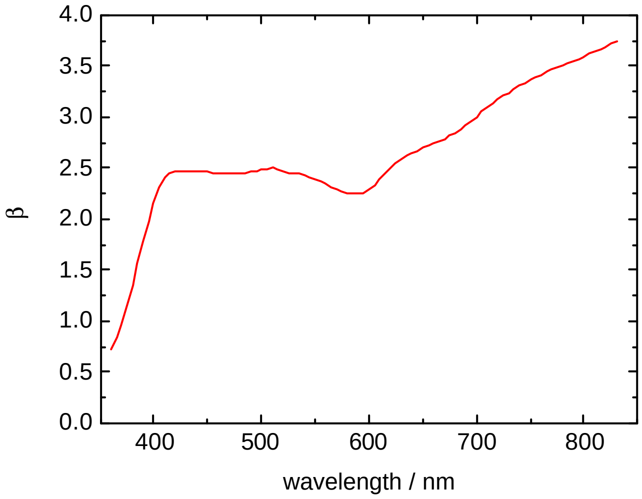


Figure 5: *Sum of the reflection coefficient of all 8 color samples*

A further aspect is that the CRI was developed to compare sources with a continuous spectrum (incandescent bulb) with the reference. Line or narrow band spectra show typically low CRI values if using the actual CRI measuring procedure. *Nevertheless such spectra can render colors in a way that would indicate for the human eye a much better color appearance as the calculated CRI.*

CRI values are typically measured using a spectrometer and an included mathematical algorithm which folds the emission spectra with the reflection curves of the color plates and calculates the CRI. Because deviations may occur when calculating/measuring the same emission spectra with different hardware, the next chapter will highlight some of the most important sources of errors.

3. Limitations

There are known influences, which can affect the measurement of the CRI:

- First of all in the CRI standard the color plates are defined using a step-width for the wavelength of 5 nm. It is also suggested to interpolate in between the steps– if needed – using a linear regression. So if spectra are used having spectral features of 5 nm or less the CRI value can be affected by the linear interpolation. Absolute deviations in the CRI of 2 can be expected.
- Second, due to the technical improvement over the last years, the "c2" value (Second Planck constant – used in the CIE standard to describe the reference sources) has changed. So using mathematical algorithms having different "c2" values the final values vary (expected deviation of 2).

Despite the more technical aspects, there is an additional aspect for measurement the CRI index: While the mathematical routine could supply a CRI value for each possible spectrum, the CRI standard demands additionally a white appearance of the emission. According to Ref. [4] the color difference between reference and test source should not be more than ?C=$5.4\cdot10^{-3}$ in CIE color coordinates (u, v CIE 1960). Thus, a light source has **no** CRI value if its color coordinates show a deviation of more than $5.4\cdot10^{-3}$ in u, v with regard to the Planck's line. To illustrate that, Fig. 6 shows the CIE color coordinate diagram with the Planck line and the Judd's lines (indicating the colors coordinates having the same color temperature). In Figure 6 the right plot shows the area in the CIE diagram covering the region for the CRI definition.

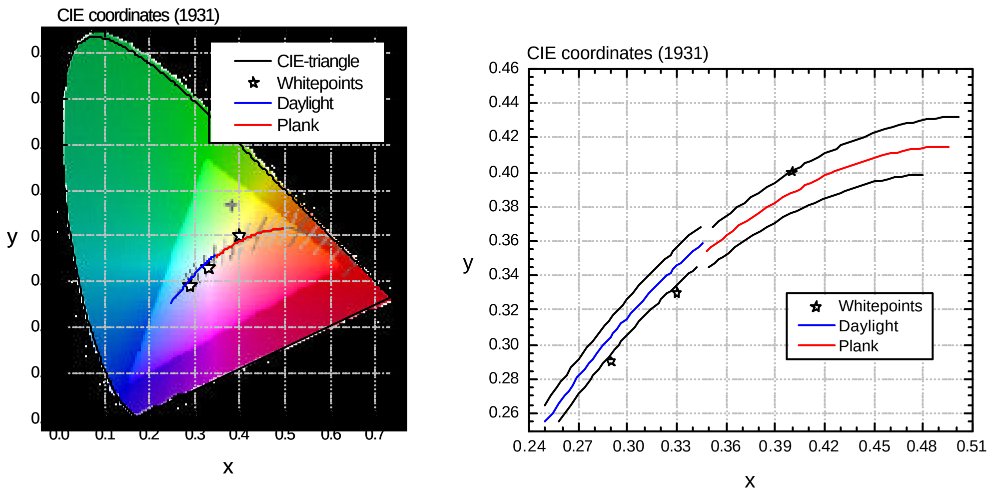


***Figure 6:** CIE color coordinate graph with the Planck's line and some of the Judd's lines. The length of the distance marked in the right plot shows the maximum distance ?C which covers the area in the CIE diagram for definition of the CRI.*

4. CRI of current state- of- the- art broadband emitting polymers

Today copolymers containing structural elements for blue, green and red emission in appropriate concentrations are the most promising way for white emitting polymers as compared to polymer blends. In this work COVIONs experimental copolymers based on a polyspiro backbone have been evaluated in the past focusing on the requirements for displays.

To achieve broadband emission minor concentrations of the green and red emitting comonomers are copolymerized using Suzuki polymerization together with hole transporting units and the blue emitting spirobifluorene unit as depicted below [Buchhauser et al., 2004].

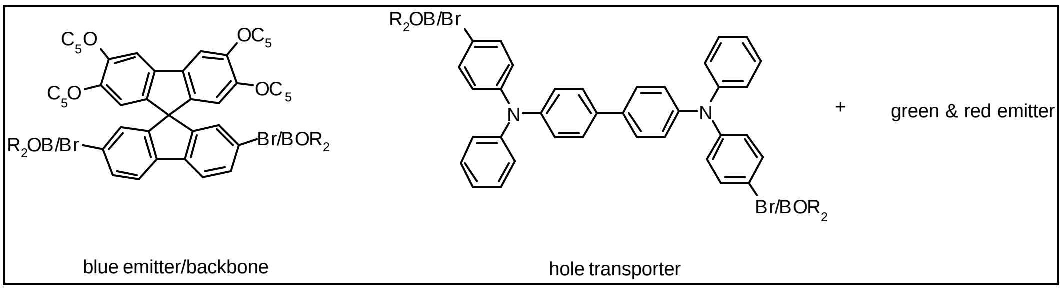


Figure 7: *Composition of white emitting copolymers*

During the development of a broadband emitter for lighting applications the concentration and the type of emitters could be optimized. The broadband emitter, evaluated during the first 6 month within OLLA, are shown below.

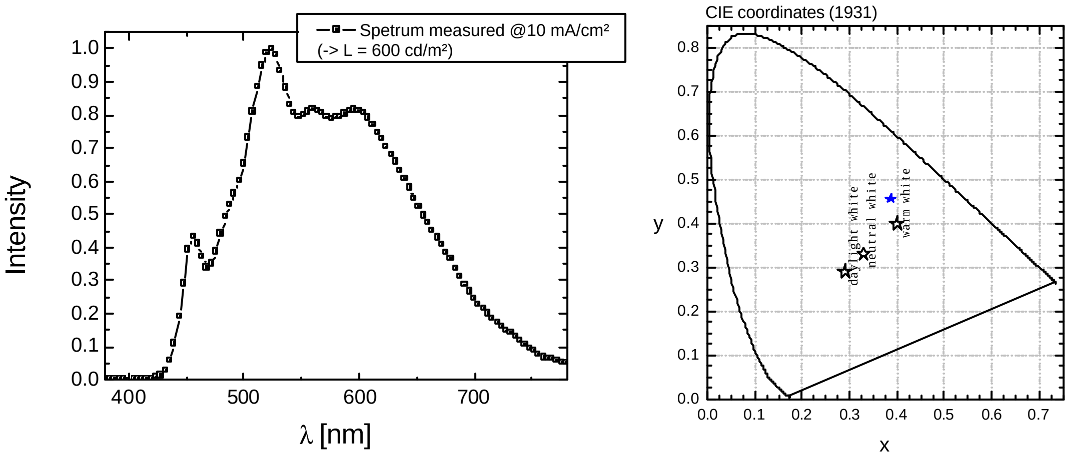


Figure 8: *left hand side: Typical "white OLED (W030)" spectrum measured within WP3 with a state- of- the- art emitting polymer from WP1. Right hand side: corresponding color coordinates (CIE 1931)*

The color coordinates of the emission spectrum shown in Figure 8 left hand side are x = 0.387 and y = 0.457 (Figure 8 right hand side), thus far away from the maximum allowed distance to the Planck’s. Thus, in this case no CRI could be defined.

The existing state-of-the-art polymers were developed in the past for display application together with color filter technology and are optimized for lifetime and for the color filter transmission. Resulting from this fact none of the evaluated polymers W012 and W030 show color coordinates within the exact white range to state a CRI value. Nevertheless we tested the obtained spectra in order to get an idea which CRI values are achievable if the color coordinates are shifted towards white.

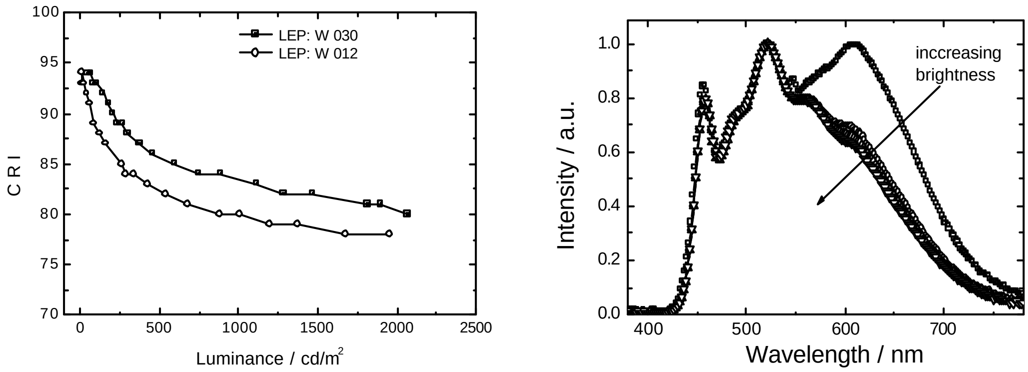


Figure 9: *left hand side: “CRI” values of tested polymeric emitters. The CRI values decrease with increasing brightness but do not fall below 75 in the interesting range (up to 1000 cd/m²). right hand side: The decreasing CRI is a consequence of the relatively declining intensity in the red spectrum region.*

In Figure 9 the “CRI” values of the two state- of- the- art emitters tested within WP3 are plotted versus the brightness. Within the range of interest 500 – 1000 cd/m² both emitters show values of CRI > 75. Both emitters have decreasing CRI values with increasing brightness. This can be attributed to shifts in the emission spectra, as plotted in the right hand plot of Figure 9.

Further work is underway to optimize the electroluminescence spectra of the broadband emitter from the synthetic approach by changing the chromophore concentrations as well as from the device architecture approach by modifying the device stack resulting in a shift of the emission by cavity effects for example. The simulations in Figure 10 represent the emission spectra by incorporating the existing chromophores but changing the concentrations to reach three different white-lighting points in the CIE diagram. Concerning the CRI measurement procedures these spectra are resulting in CRI indices of 84, 88, 95, 96 respectively (for 0.29/0.29, 0.33/0.33, 0.38/0.38, 0.4/0.4 in Figure 10).

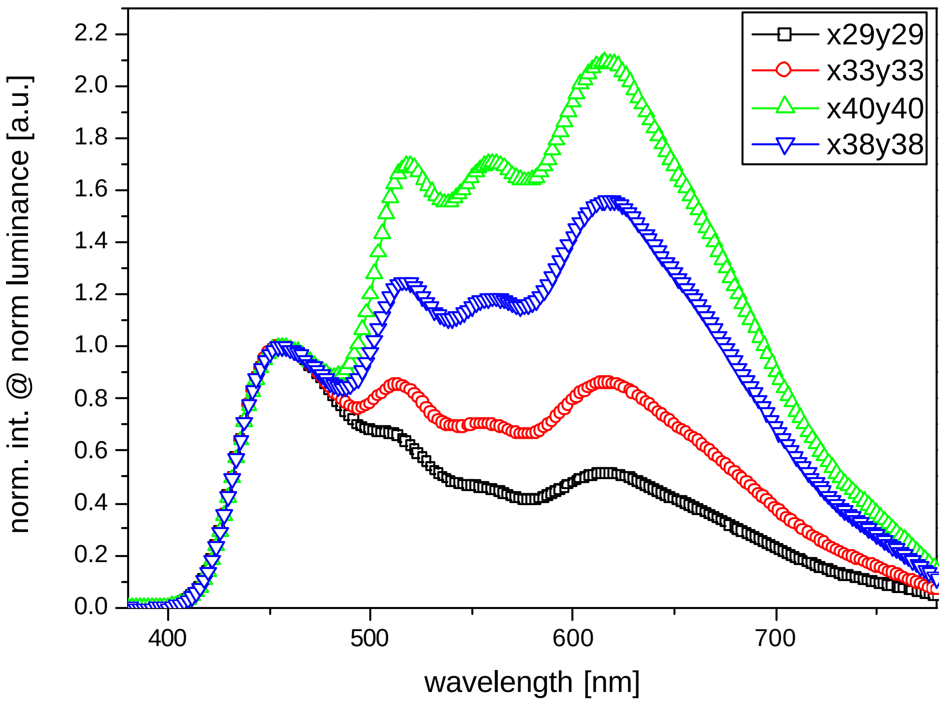


Figure 10: *Simulations of the EL spectra incorporating the red, green and blue emission of the single chromophores to achieve typical white color points. This could be realized by modifications of the chromophore concentrations within the copolymer.*

6. Color rendering comparison of broadband emitter with other light sources

The results above show that polymer LEDs have good potential to be light sources with high CRI as the emission spectra are tunable and broad. Current status is that the studied polymers are not all reaching the black body radiation in terms of x- and y- coordinates. The comparison of the spectra in figure 10 represents typical EL spectra of different light sources in comparison to the simulation of the polymer LED. The simulated OLED spectrum with CIE coordinates of (0.38, 0.38) out of the three chromophores in the copolymer would yield to a CRI value of 95.

Table 2: *Comparision of different lighting technologies regarding their color properties. Data of fluorescent lamp, light bulb and inorganic LED as measured. The polymer LED's performance is taken from the simulations shown above.*

Coords	fluorescent lamp	white inorganic LED	light bulb	Polymer LED (optimized color)
X	0.3803	0.3145	0.4428	0.3809
Y	0.3826	0.3296	0.4078	0.3768
Tc	4046 K	6407 K	2934 K	3988 K
dC	6.51E-05	6.11E-04	6.99E-04	1.15E-04
Ra	69.06	80.00	99.19	95.86

At the end the required CRI relies on the application and the spectra itself has to be optimized comparable to the “competing existing application”, if OLEDs could substitute today lighting applications.

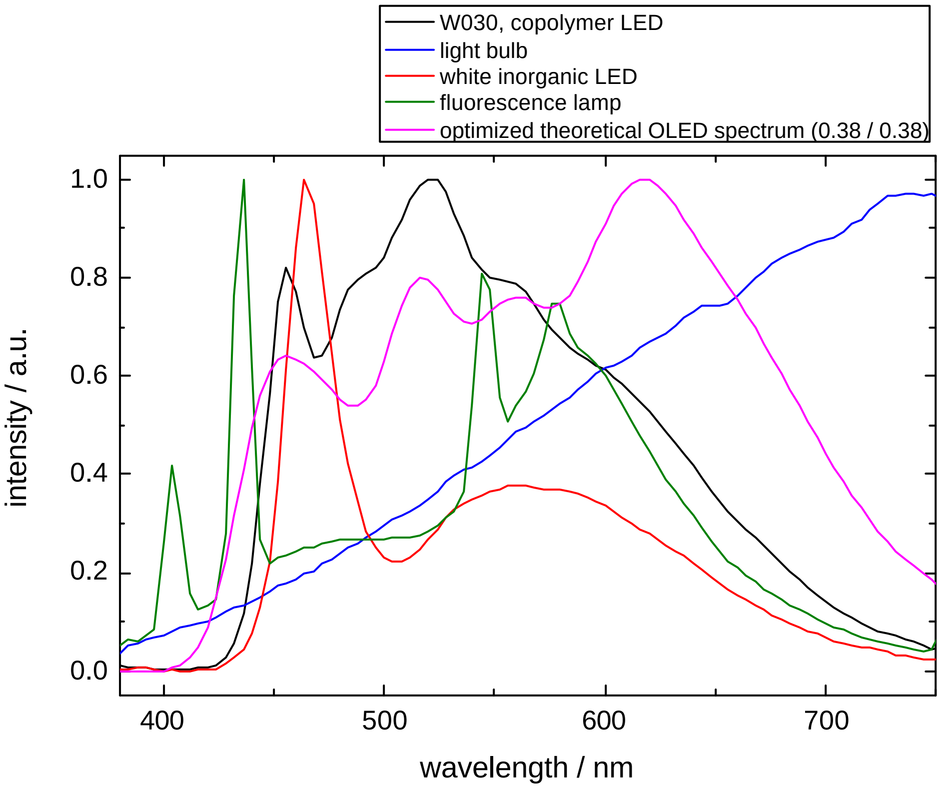


Figure 11: *Comparison of the EL spectra of typical light sources with a copolymer emission for a W030 type Covion polymer and a simulated EL spectra as required to achieve white emission.*

General conclusion:

Polyleds have good potential to be light sources with high CRI as the emission spectra are tunable and broad. Current status is that the studied polymers are not all reaching the black body radiation in terms of x- and y-coordinates. More time and effort is needed to develop white, bright polyleds which meet also the other product specifications like lifetime etc.

7. References

[1] CIE, International Commission on Illumination, www.cie.co.at

[2] http://www.goodmart.com/facts/light_bulbs/cri.aspx

[3] http://www.kruschwitz.com/cri.htm

[4] German DIN Norm 6169 part 2

[5] ISO 10526:1999, CIE S 005/E-1998

[6] Measurements at OSRAM GmbH, Munich, Central laboratory for light measurements, 2005

[7] Buchhauser et. al., Proceedings of SPIE, Vol. **5519**, pp.70-81 (2004)

8. Appendix

Additional literature:

- Y. Ohno, “Color Issues of white LEDs”, a section in "Solid State Light Emitting Diodes For General Illumination", OIDA Workshop Preliminary Report, October 26-27, 2000, also in “OLEDs for General Illumination”, OIDA Workshop Preliminary Report, Nov. 30 – Dec. 1, 2000
- J.A. Worthey, “Color Rendering – Asking the question”, COLOR research and application, Vol. 28(6), p. 403, 2003