VARIATIONS OF COLOR CORRELATED TEMPERATURE OF WHITE LED LIGHT

Mitja Prelovšek, Grega Bizjak

Univerza v Ljubljani, Fakulteta za elektrotehniko, Ljubljana, Slovenia

Key words: Light-emitting diodes, white LED, correlated color temperature CCT, CCT consistency, color rendering index, illumination, solid state lighting sources

Abstract: Correlated color temperature (CCT) variations and low color rendering index (CRI) present many reasons for not using white light-emitting diodes (LEDs) in lighting. In this research color characteristics of light emitted by LEDs were measured on 29 (In)GaN LEDs of 6 different kinds.We found that color characteristics, notably CCT, are significantly dependent on distance from geometrical axis of the LED, of which the ones that do not use light-diffusion layer were more susceptible to CCT variations. Furthermore, variations of color characteristics of LEDs belonging to the same type were significantly higher than the minimum color difference that human eye can notice. The obtained data suggest, that in order to achieve sufficient light quality and color consistency between different white LEDs, diffusion layer use is highly recommended, due to its smoothing effect.

Razlike v najpodobnejši barvni temperaturi svetlobe belih LED

Kjučne besede: svetleče diode, bele LED, najpodobnejša barvna temperatura CCT, konsistentnost CCT, indeks barvnega videza, razsvetljava, polprevodniški svetlobni viri

Izvleček: Razlike v najpodobnejši barvni temperaturi in indeksu barvnega videza predstavljajo danes glavno oviro pri uporabi belih svetlečih diod (LED) v razsvetljavi. V opisani raziskavi smo izmerili osnovne značilnosti barve svetlobe pri skupaj 29 (In)GaN belih svetlečih diodah šestih različnih tipov. Ugotovili smo, da je najpodobnejša barvna temperatura (CCT) svetlobe LED zelo odvisna od kota opazovanja glede na geometrično os LED. Pojav je najbolj izražen pri LED, ki nimajo nanesenega difuzijskega sloja za razprševanje svetlobe. Ugotovili smo tudi, da so razlike v najpodobnejši barvni temperaturi svetlobe pri LED istega tipa večje, kot je meja zaznavnosti pri človeku. Pridobljeni podatki kažejo, da je za uporabo v razsvetljavi priporočljiva edino uporaba belih LED z difuzijskim slojem, če želimo doseči ustrezno kakovost barve svetlobe.

1 Introduction

Color temperature is a way of describing the hue of white light. The term color temperature originates from the correlation between temperature of planckian black body and its emission spectrum. For example, planckian body heated to 3000 K radiates white light with reddish hue, while at 6000 K the light adopts a bluish hue. The hues and corresponding temperatures are shown on Fig 1, which presents a CIExy color space, while the Table 1 presents the exact CCT values with corresponding x,y coordinates.

The term correlated color temperature (CCT) is used with light sources, that do not function as black body radiators and therefore, the color of the emitted light does not follow the planckian curve plotted on Fig 1. CCT can be obtained by an algorythm, which moves the color of light source on the planckian curve with a minimum visual change in hue. Obviously this procedure can lead to significant mistakes in color representation, especially if there exists a significant offset of the color of the emitted light from the planckian curve.

The CIExy color space, which is shown on Fig 1, is a much more accurate way of specifying color of light. This method of color representation is therefore the prefered one

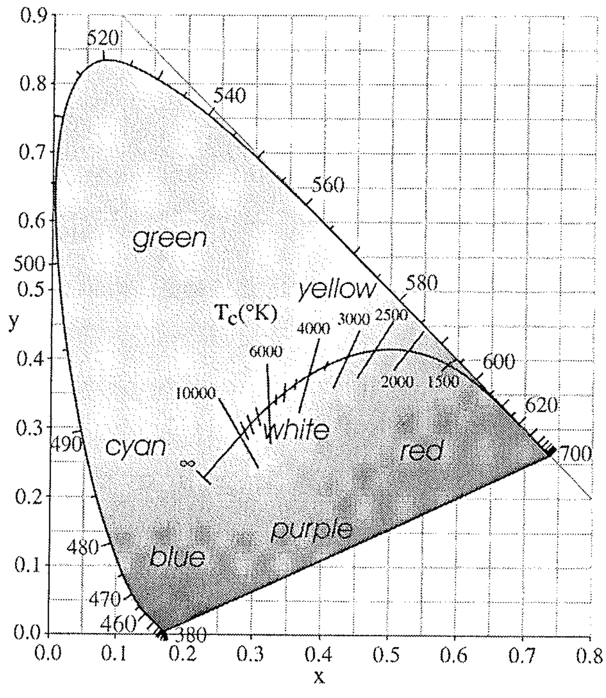

Fig 1: CIExy diagram with planckian curve

Table 1: CCT and CIExy coordinates equivalents

T/K	x	y
2000	0,52669	0,41331
2353	0,49059	0,41498
2500	0,47701	0,41368
3077	0,43156	0,40216
3333	0,41502	0,39535
3636	0,39792	0,3869
4000	0,38045	0,37676
4444	0,36276	0,36496
5000	0,3451	0,35162
5714	0,32775	0,3369
6667	0,31101	0,32116
8000	0,29518	0,30477
10000	0,28063	0,28828
12500	0,27011	0,27547
14286	0,26526	0,2693
16667	0,2607	0,26333
20000	0,25645	0,25763
25000	0,25251	0,25222

when measuring LEDs. The biggest advantage of CIExy color space, however, is accurate representation of the perceived color of light containing various distinct peaks in its spectrum. For example, if there are only red and blue components in the spectrum of incident light, then the perceived color of light will be on the line connecting the red point and blue point in CIExy space. Similarly, when there are three or more components in the spectrum, then the perceived color of light is somewhere inside the geometrical shape, which connects all the points in CIExy space.

The CIExy space has 2 coordinates, which allow representation of every color detectable by human eyes. Coordinate x is roughly proportionate to the amount of red color, while y represents the amount of green.

2 White LEDs

There are three different technologies of producing white light by using LEDs. First and perhaps the most known way of achieving white light is by mixing light of red, green and blue LEDs with appropriate luminances. This mixture of wavelengths is interpreted as white light by our visual system. The advantage of this principle is, that any color in the triangle in CIExy color space, which connects those three primary colors, can be achieved. However, the costs of the installation are often too high, especially when dynamic color changes are not required.

The second principle is based on luminiscence of red, green and blue phosphor coatings, which are placed over near-UV LED chip. The UV light excites the phosphors, which consequently down-shift UV light into three broad peaks in red, green and blue interval of the spectrum. The n-UV LED chip + RGB phosphors is a technology which is still in its infancy, where the efficiency of such n-UV LED chip and wavelength conversion is too low for illumination applications.

The most widely used white LED technology uses blue LED GaN chips coated with yellow phosphor, which down-shifts part of emitted blue light to yellow wavelengths. The right mixture of yellow and blue spectral components is perceived as white light, which can be seen from Fig 2.

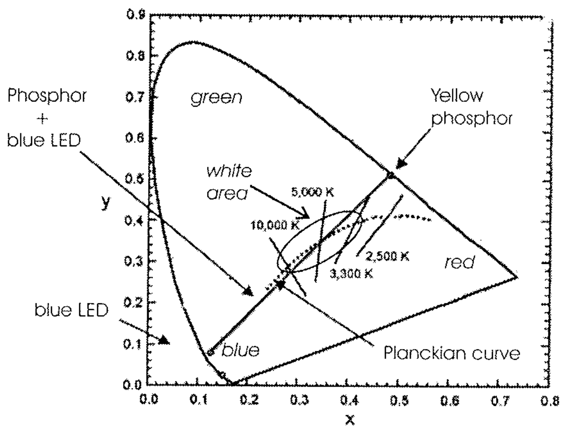

Fig 2: CIExy diagram with line connecting color coordinates of blue LED and yellow phosphor

This kind of white LED has only 2 peaks in its spectrum, as shown on Fig 3, and consequently very low color rendering index (CRI).

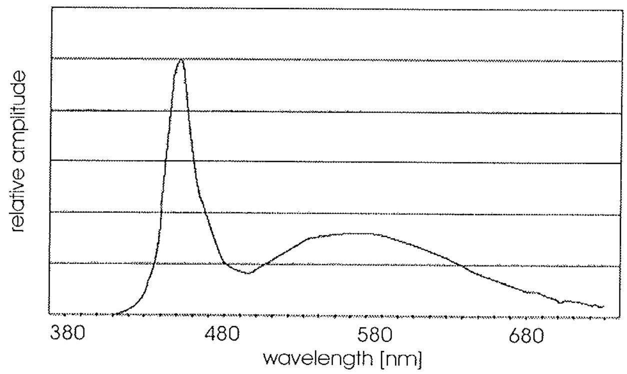

Fig 3: Spectrum of GaN white LED

However, low CRI is not the only weakness of this type of white LEDs. The other major disadvantage originates from the fact, that the amount of yellow, which is represented in the spectrum, is directly proportionate to the distance through yellow phosphor, that has to be traversed by the emitted light. Furthermore, since that distance is bigger at larger angles of observation, CCT depends not only on the thickness of the phosphor coating, but also on the angle of observation as shown on the following figure. Here d_1 and d_2 label distances through phosphor at an arbitrary angle and on the geometrical axis.

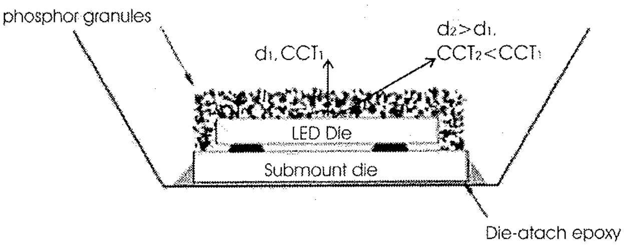

Fig 4: GaN white LED structure

CCT variations and dependancies of GaN white LEDs, that are mentioned above, were measured on 3 types of through-hole LEDs, 2 types of high-output LEDs with diffusion layer and 1 type of high-output LED without diffusion layer. The corresponding viewing angles or maximum radiation angles are presented in Table 2, where diodes have been labeled according to their type with TH, HOD or HO, meaning through-hole, high-output diffusion and high-output respectively.

Table 2: measured LEDs

Label	Viewing angle	Number of LEDs
TH1	10°	5
TH2	15°	5
TH3	15°	5
HOD1	110°	5
HOD2	110°	4
HO	>90°	5

A typical through-hole, high-output diffusion and high-output LED can be seen on Fig 5, Fig 6 and Fig 7 respectively.

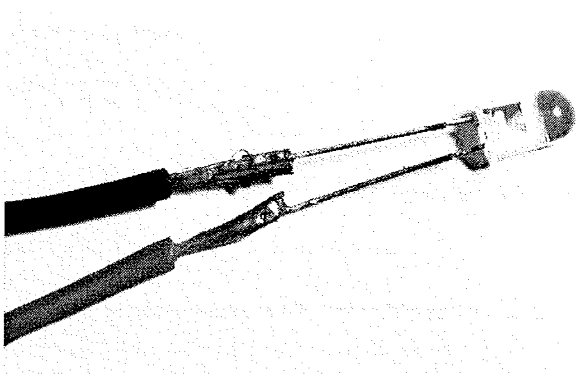

Fig 5: through hole LED

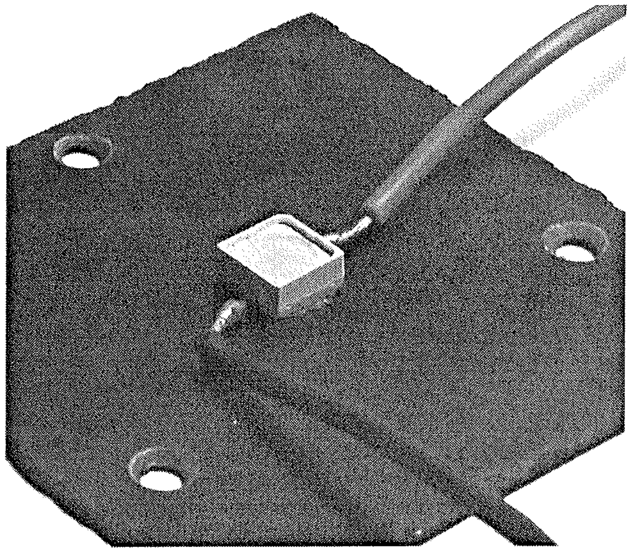

Fig 6: high output LED with diffusion layer positioned on the measurement holder

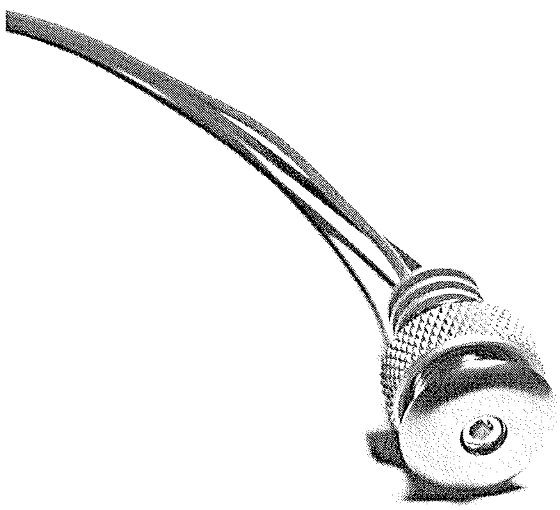

Fig 7: high output LED

3 Experimental procedures

CCT was measured by rotating the LEDs around their vertical and geometrical axis as shown on Fig 8.

LEDs were rotated on two custom-made holders, while the CCT data were measured by a spectrometer, which was positioned 10cm from the LED. Position of the instruments is shown on the following figure.

The rotation around vertical axis was in our experiment limited to 70 degrees, because 70 degrees present the angle where luminous flux is usually cut off in normal white LED applications. That is achieved either by a reflector of some sort or the LED itself includes lenses that limit the viewing angle, which is a standard practice with indicator LEDs. Therefore, we have set the angle φ either to the

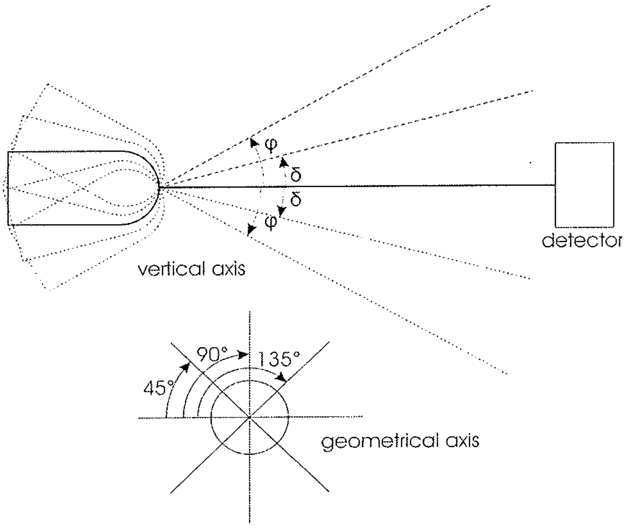

Fig 8: rotation around geometrical and vertical axes

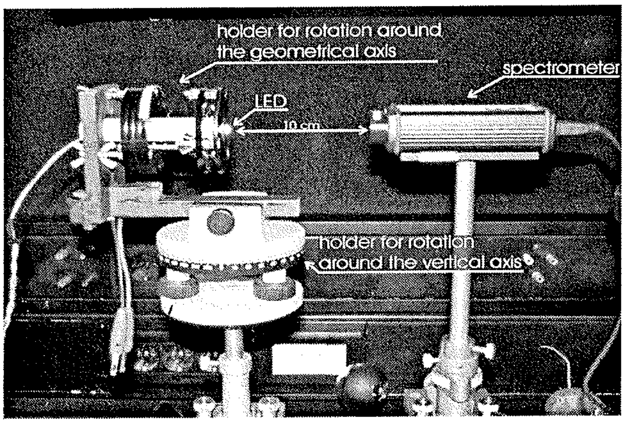

Fig 9: position of the instruments

viewing angle of the LED or to 70 degrees, if the viewing angle of the LED exceeded 70 degrees. Measurement angle δ was approximately one half of φ. Measurement angles for corresponding LEDs are shown in Table 3.

Table 3: Measurement angles

Label	δ	φ
TH1	5°	10°
TH2	7°	15°
TH3	7°	15°
HOD1	35°	70°
HOD2	35°	70°
HO	35°	70°

With this procedure we obtained 17 different measurement points, which are shown as black dots in the following figure:

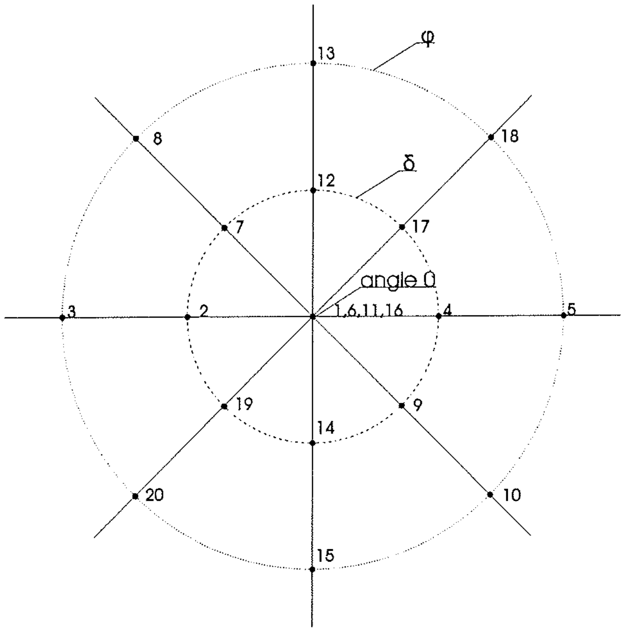

Fig 10: Measurement points

Since all of the measured LEDs showed significant CCT dependance on the measurement angle, it was decided, that we will calculate 3 CCT averages for every type of LED - one for every measurement angle (0, δ, φ). Thus we could evaluate the dependance of CCT on the angle of observation.

As for CCT variance calculations, we wanted to be able to evaluate CCT variations, which can be noticed, when an observer looks at a luminaire which employs a cluster of LEDs. The observer is in this very typical LED application able to notice the maximum and minimum CCT variations of separate LEDs compared to an average CCT of the whole cluster at that specific angle of observation. Therefore we calculated the variances separately for every measurement point (Fig 10). The average used for variance calculation was the average of measurements of the same measurement angle, that the measurement point belonged to. For example: to calculate a variance in point 4 (Fig 10), we used 5 CCT measurements of the point 4 (one for every LED in the group) along with the average of 40 CCT measurements (5-times 8, for 5 LEDs in a group and 8 measurement points at the measurement angle δ).

4 Results and discussion

As mentioned above, CCT data of all of the measured LEDs have shown significant dependance on the measurement angle, that is whether the measurement point belonged to 0, δ or φ. All of the LEDs without light diffusion layer have shown significant decrease in CCT with increasing measurement angle, while the CCT of LEDs with diffusion layer was slightly higher at angle φ compared to values at angles 0 or δ, as can be seen from Table 4 and Fig 11

Table 4: dependance of CCT from measurement angle

CCT[K]	angle 0	angle δ	angle φ
TH1	7427	7174	6487
TH2	15840	11358	7137
TH3	16100	8062	7756
HOD1	5787	5805	5850
HOD2	6118	6132	6140
HO	5509	5408	5226

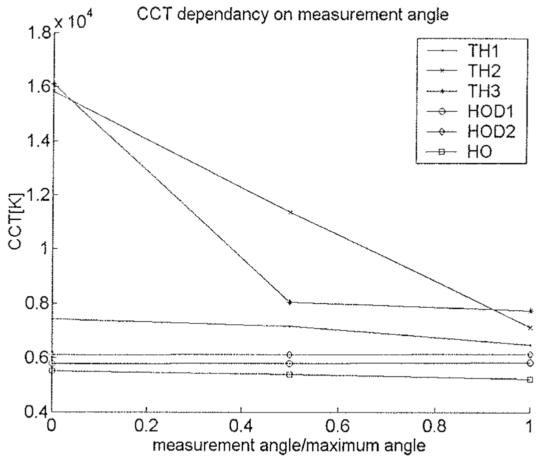

Fig 11: CCT variation

These data suggest that unevenly spread diffusion layer on LEDs HOD1 and HOD2 caused the reverse dependance of CCT, which can be seen in Fig 11

To better evaluate the perceived differences in color of light, however, it is more precise to use the distance between two points in CIExy space as a representation. Table 5 and Fig 12 show distances of CCT averages at δ and φ to CCT average on geometrical axis. Minimum difference in color, that human visual system can detect, is approximately 50K to 100K [2] in range of daylight variations, which span from 2000K to 6000K. 100K equals approximately 0.007, which is also shown on Fig 12. For an observer it presents a boundary, when he/she notices the change of color of the emitted light.

Table 5: Distances from central average in CIExy space

Distance in CIExy space	angle δ	angle φ
TH1	$4.98\cdot10^{-3}$	$2.3\cdot10^{-2}$
TH2	$2.59\cdot10^{-2}$	$6.38\cdot10^{-2}$
TH3	$6.87\cdot10^{-2}$	$6.5\cdot10^{-2}$
HOD1	$6.13\cdot10^{-4}$	$2.79\cdot10^{-3}$
HOD2	$2.95\cdot10^{-4}$	$4.75\cdot10^{-4}$
HO	$5.96\cdot10^{-3}$	$1.68\cdot10^{-2}$

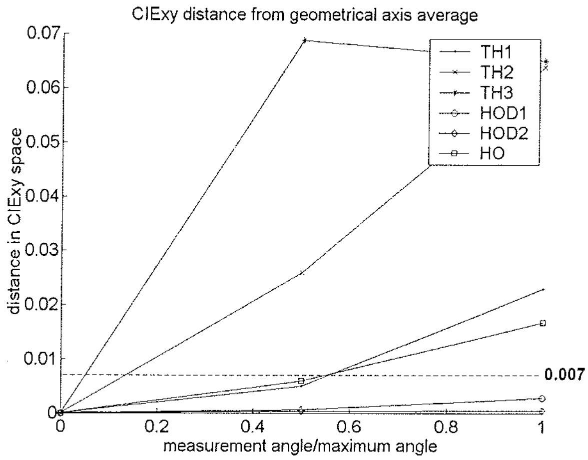

Fig 12: CCT variation shown as distance in CIExy space

It can be observed, that LEDs, which use diffusion layer show the best performance in terms of angular stability of CCT. Furthermore, these types of LEDs are the only ones, that remain below the minimum noticeable distance in CIExy space, regardless of the measurement angle. It is thought, that use of diffusion layer with GaN+yellow phosphor white LEDs has positive effect on angular stability of CCT.

There is, however, another obstacle, which must be dealt with, when using white LEDs and these are differences in light color between different LEDs. We calculated 17 variances, one for every measurement point, for each type of LEDs, as explained in chapter 3. The maximum variances at each angle are shown in Table 6 and Fig 13.

Table 6: Maximum variances at measurement angles

Maximum variances	angle 0	angle δ	angle φ
TH1	$9.5\cdot10^{-3}$	$1.26\cdot10^{-2}$	$1.99\cdot10^{-2}$
TH2	$2.35\cdot10^{-2}$	$2.7\cdot10^{-2}$	$1\cdot10^{-2}$
TH3	$1.73\cdot10$	$2.8\cdot10^{-2}$	$2.28\cdot10^{-2}$
HOD1	$4.9\cdot10^{-3}$	$5\cdot10^{-3}$	$5.8\cdot10^{-3}$
HOD2	$2.4\cdot10^{-3}$	$2.99\cdot10^{-3}$	$9\cdot10^{-3}$
HO	$7.98\cdot10^{-3}$	$7.9\cdot10^{-3}$	$8.18\cdot10^{-3}$

Again it can be seen, that HOD1 and HOD2 show the best performance, as they are in general always below the noticeable distance in CIExy space. This can be explained with luminance distribution of GaN white LEDs. The point of the highest luminance, which is called the optical axis of the LED, corresponds with the point of the highest CCT. This is because yellow phosphor can down-shift only a limited amount of light. However, optical axis does not, in general, correspond with geometrical axis of the LED and therefore the point of highest CCT is very rarely positioned on the geometrical axis of the LED itself. As the positioning of the LEDs in our experiment did not reflect the direc-

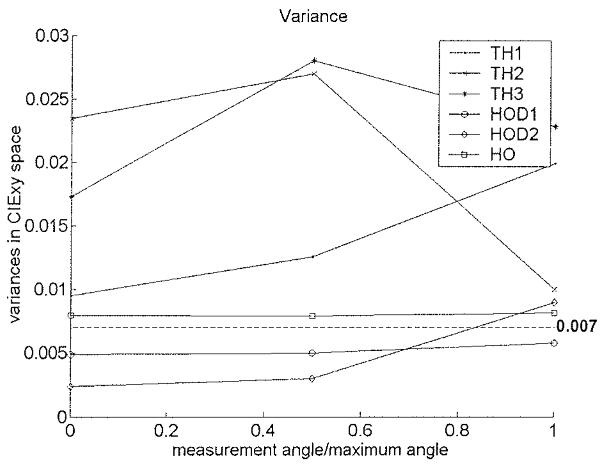

Fig 13: Maximum variances shown as distance in CIExy space

tion of the optical axes in any way, it is suggested, that these position variations of the optical axes are the origin of the variances of LEDs without diffusion layer shown in Fig 13. The advantage of using diffusion layers regarding the optical axes problem mentioned above is, that it smooths out the CCT gradient of the LED and consequently makes position variations of the optical axes less noticeable.

5 Conclusion

Considering the fact, that LEDs without diffusion layer showed poor performance in terms of CCT variations, it is thought, that the prevailent technology of manufacturing white LEDs today is not capable of enabling a widespread use of white LEDs in illumination. However, use of diffusion layers on LEDs can greatly improve their characteristics, especially in terms of angular stability of CCT.

6 References

/1./ M. Prelovšek, Barvne značilnosti svetlobe belih svetlečih diod, FERLJ, 2006

/2./ D. A. Steigerwald, Illumination with solid state lighting technology, IEEE, Vol. 8, No. 2, str. 310-320, Marec/April 2002

/3./ D. A. Kerr, Color temperature, PE, Vol. 4, November 2005

/4./ http://www.fho-emden.de/~hoffmann/coltemp18102003.pdf

/5./ J. Furlan, Osnove polprevodniških elementov, Tehniška založba Slovenije, 2002

/6./ F. Smole, Fotonski polprevodniški elementi, Založba FE in FRI, 2001

/7./ E. F. Schubert, Light-emitting diodes, Cambridge, 2003

/8./ J.K.Sheu, White-light emission from near UV InGaN-GaN LED chip precoated with blue/green/red phosphors, IEEE Photonics technology letters, Vol. 15, No. 1 , str 18-20, januar 2003

/9./ CIE technical report 127-1997, Measurement of LEDs, 1997

Mitja Prelovšek u.d.i.e.
Zarnikova 11, 1000 Ljubljana
Tel: 040298550

doc dr Grega Bizjak u.d.i.e.
Univerza v LjubljaniFakulteta za elektrotehniko
Tržaška 25, 1000 Ljubljana
Tel: 014768446
Email: grega.bizjak@fe.uni-lj.si

Prispelo (Arrived): 21. 08. 2006; Sprejeto (Accepted): 08. 09. 2006