CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF ELECTRICAL ENGINEERING

DEPARTMENT OF ELECTRICAL POWER ENGINEERING

Bachelor Thesis

Possibilities of LED quality improvement

Možnosti zvýšení kvality LED zdrojů světla

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Study Program: Electrical Engineering and Computer Science

Supervisor: Ing. Marek Bálský, Ph.D.

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BACHELOR'S THESIS ASSIGNMENT

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Guidelines:

1) Analyze common technologies of the white light generation with LEDs
2) Compare power efficiency and quality (CRI, CFI, CCT) of described white LED technologies
3) Define conditions for increasing white LED power efficacy and its quality (CRI, CFI, CCT)

Bibliography / sources:

[1] CIE 013.3-1995: METHOD OF MEASURING AND SPECIFYING COLOUR RENDERING PROPERTIES OF LIGHT SOURCES, ISBN 978 3 900734 57 2
[2] David L. DiLaura, Kevin Houser, Richard Mistrick, Gary Steffy: IES LIGHTING HANDBOOK 10th edition, ISBN: 978-0-87995-241-9

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III. Assignment receipt

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Declaration

I hereby declare that this thesis is the result of my own work and that I have clearly stated all information sources used in the thesis according to “Methodological Instructions of Ethical Principle in the Preparation of University Thesis”.

In Prague, 20.05.2019 Signature ....…………………

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Abstract

This thesis is dedicated to the investigation and comparison of the technologies for white light generating LED and possibilities to improve quality of LED sources. Color quality and power efficiency of two main technologies, namely color-mixing and phosphor-conversion method are described and compared according to the real-life examples. This thesis includes measurement of luminous efficacy and color quality of two phosphor-conversion DEN LEDs. This research also includes brief discussion about the quality improvement of LED light sources.

Keywords

LED, luminous efficacy, color quality, CRI, CCT, RGB, PC LED, phosphorus, LED chip

Abstrakt

Tato diplomová práce se zabývá analýzou technologií pro bílých LED pro všeobecné světlování a možnostmi zlepšení kvality světelných zdrojů LED. Jsou zde popsány a porovnány reálné příklady, kde se sleduje kvalita barev a energetická účinnost dvou hlavních používaných technologií, které jsou míchání barev a metoda konverze s využitím luminoforu. Součástí práce je též měření měrného výkonu a kvality barev LED diod s luminoforem. Práce také obsahuje stručnou diskuzi týkající se možnosti zlepšení kvality světelných zdrojů LED.

Klíčová slova

LED, měrný výkon, kvalita barev, CRI, CCT, RGB, PC LED, luminofor, LED čip

List of Abbreviations

SPD - Spectral Power Distribution

LED - Light Emitting Diode

WLED - White Light Emitting Diode

UV - Ultra Violet

R,G,B - Red, Green, Blue

CMF - Color Matching Function

CCT - Correlated Color Temperature

CRI - Color Rendering Index

CIE 1960 UCS - Uniform Color Space

HID - High Intensity Discharge

HPS - High Pressure Sodium

MH - Metal Halide

PC LED - Phosphor-conversion Light Emitting Diode

YAG:Ce - Yttrium aluminium garnet doped with Cerium

DEN LED - Day-evening-night Light emitting diode

TLED - LED Tube

Table of Contents

1. Introduction

From the creation of the world the nature was embraced by the light. Over the centuries, humanity was doing researches and experiments about the light and as a result now lighting sources, both natural and artificial, has been implemented into the many fields of the life. Thanks to the developing technology, nowadays we have more developed light sources with low-energy cost and more “natural” color quality. First light sources, that is incandescent appeared as high color quality lamps with very low power efficiency. Later discharge lamps are introduced which has very high power efficiency, but poor color quality. Last part of lighting family, which is light emitting diode reduced this huge gap between color quality and power efficiency and already dominated market for many applications. However, this technology is still evolving and far from its planned quality and has some drawbacks.

Light emitting diodes first invented as monochromatic light source and as a result of improvements of this technology, obtaining white light from LEDs are possible with two main technologies which together with the color quality and power efficiency of LEDs will be described in the research paper.

2. Photometry and colorimetry of light sources

2.1 Fundamentals of photometry

2.1.1 Spectral sensitivity of the human eye

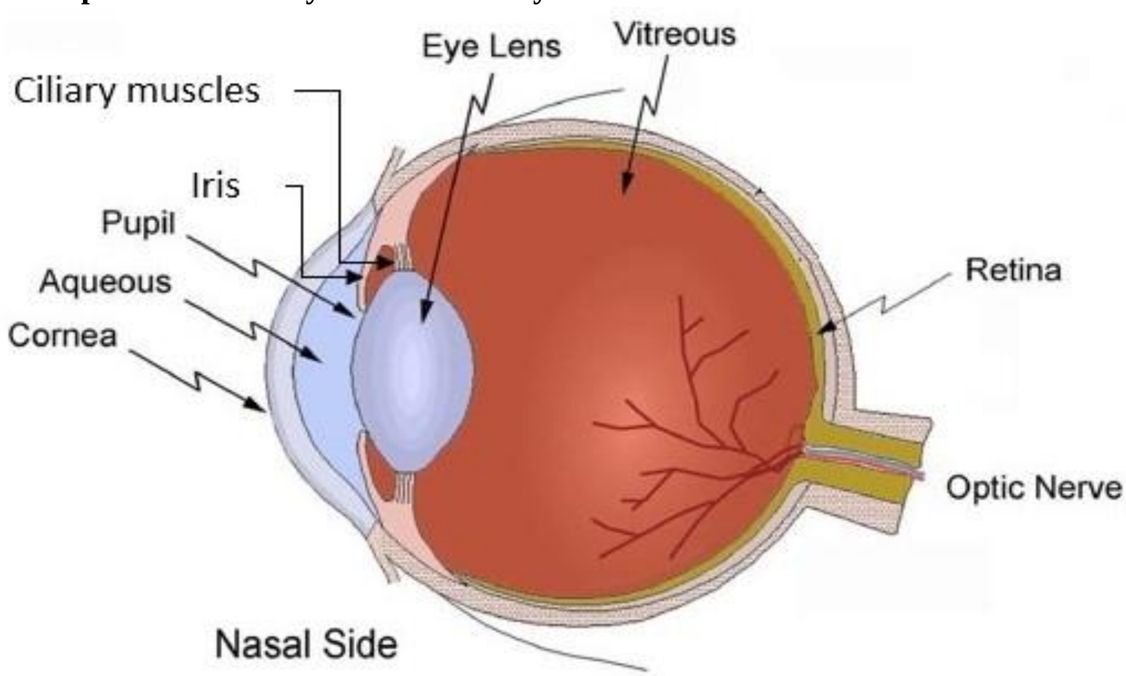

Fig.1 *Diagram of the human eye [1]*

Among the base senses of the human, vision is one of most complex sense which is the process between the human eye and brain. Our visual sensor (eye) perceive light, process it and transfer it to the brain in few milliseconds and as a result of this complex process visual representation of the things appear in our brain. Human eye consists of several components and the most vital components are: sclera, cornea, pupil, aqueous and vitreous humors, lens and retina. [2].

Above drawn diagram (Fig.1) gives us visual information about the position of the basic eye components. The definitions for these components are as followings:

The sclera is the opaque, strong and the protective part of the human eye. The sclera which is called "white part of the eye" contains blood cells. [3].

The cornea is the transparent, frontal part of the sclera. Its main role is the protection of the eye from the possible dangers. The ideal geometrical shape of the cornea is near to the sphere with approximately 40 diopters optical power. [1][3].

Aqueous humor is the transparent, thin liquid which is made up mostly from the water and locate between cornea and the eye lens. It usually controls intraocular pressure. [3].

The pupil is the rounded and one of the frontal parts of the eye which is surrounded by the iris. The pupil determines the amount of the light entering to the eye while increasing or decreasing the its diameter. The variation in the diameter of the pupil is being controlled by the iris. [1].

The lens is the transparent, elastic layer which is located on the back of the iris and the pupil and helps eye to focus object or light onto the retina. For the close or distant vision, the shape of the lens changes as the relaxation (for distant vision) or the contract (for close vision) of the ciliary muscles. The eye lens has approximately 20-25 diopter of power for the ideal case and it is getting lower while aging. [1].

Vitreous humor is the transparent gel-like liquid which fills the huge part of the eyeball between lens and the retina. [3].

Retina is the nervous tissue layer which is light-sensitive and located on the back part of the eyeball. It can be called the 'end-process' of the light perception and 'beginning process' for the visual system. The reason for this is retina is usually referred as the extension of the brain and it is connected to the brain by the optic nerve. The function of the retina is the perception of the light and converting into electrical signal and sending it to the brain. [3][4].

There are two main types of the light-sensitive receptors in the retina, namely rods and cons which contains photopigments. Photoreceptors absorb optical radiation and convert photons (light) into the neural signals. Rod cells are functioning in the relatively dark environment which is called scotopic (night) vision. Shape, brightness and size perception of the images are the responsibility of the rod cells. However, they don't perceive color of the image because it is perceived by cones which is more sensitive in the brighter environment in contrast with rods and it is called for photopic (daylight) vision. There exist three types of the cones for perceiving different lengths of the wavelengths, L-cones for long wavelengths, M-cones for medium wavelengths and S-cones for short wavelengths. They are approximately perceiving red, green and blue colors. Light absorbance of the photopigments of the cones and rods defines spectral response of the photoreceptors for photopic and scotopic vision. [1][3].

After new investigations about visual system, scientists were interested in the quantities of the light and human eye response to the different wavelength. For dealing with the measurement of electromagnetic radiation within the frequency range between $3 \times 10^{11}$and $3 \times 10^{16}\, Hz$ there is the science called radiometry. This range includes several forms of electromagnetic radiation including ultraviolet, infrared and visible. However, visual system of human is quite complex and only sensitive to the special spectral range of the electromagnetic radiation (light) which is from 380 nm to 760 nm according to the nature of the eye. According to this knowledge, the photometry - special branch of radiometry is doing the measurement of the light which is perceptible by human eyes. [3][5].

In former times, measurements for luminous quantities was based on the visual comparison of individuals and the name of this technique was called visual photometry. However, this method was quite error-prone because it was based on the individual measurement of observer and there were other factors may affect the precise result. [6].

According to the previously mentioned troubles about techniques, the Commission Internationale de l'Eclairage (CIE) has decided to make measurement for the light-adapted eyes of the representative group of people. As a result of this experiment, CIE Standard Luminosity Function, which depicts spectral response of human eye to different wavelengths has been plotted (Fig. 2).The measurement was conducted for two cases: photopic - for day time vision and scotopic - for night time vision. For photopic vision, maximum value for efficiency is in the 555 nm wavelength and for scotopic it is in the 507 nm wavelength. Modern photometry methods - physical photometry only uses this function as a reference because spectral range for visual photometry measurements was defined by this function. Although luminosity function is not ideal because it is based on the individual decision of the participant of the measurement it is still more precise function than previously used methods. [3][7].

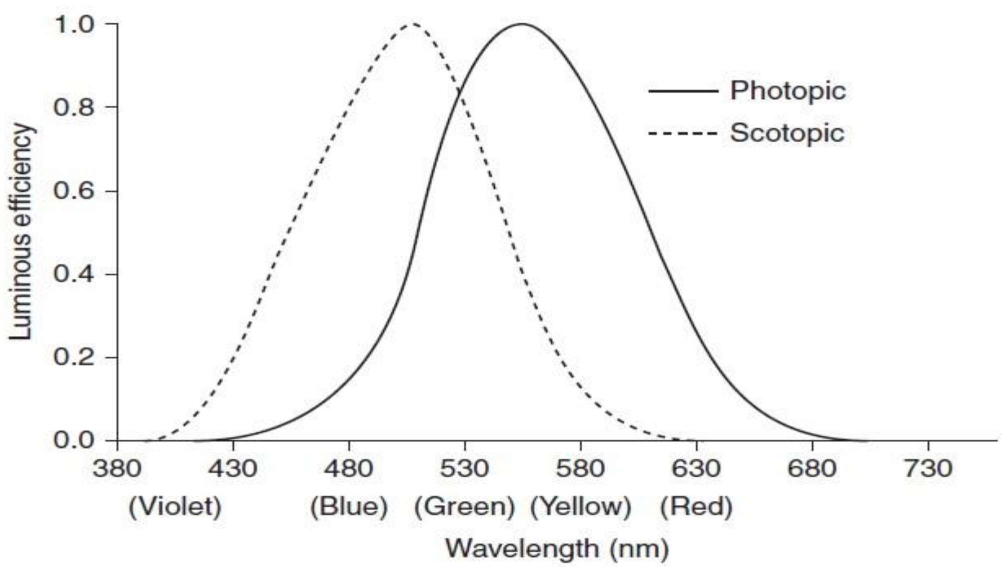

Fig. 2 *CIE photopic luminosity function [6]*

To understand basics of photometry, we will describe photometric quantities briefly in the following chapters.

2.1.2 Solid angle

While discussing about photometry, we should have recalled our knowledge from geometry about solid angle. Solid angle (Ω) is the two-dimensional angle in three-dimensional space that is subtended by any object. The formula for expressing solid angle is as following [8]:

$$\Omega = \frac{A}{r^2} \ (steradian[sr]) \quad (1)$$

$$A - area\ on\ the\ surface\ of\ the\ sphere$$

$$r - radius\ of\ the\ sphere$$

The diagram below will give us better visual explanation of expressed variables of the formula. (Fig 3.)

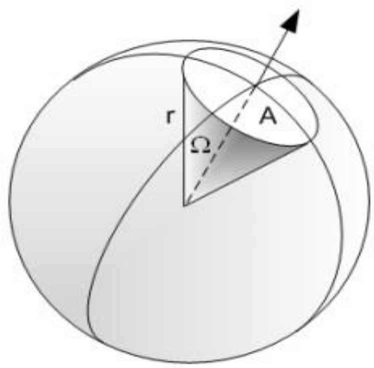

Fig.3 *Diagram of solid angle in 3D system [9]*

When the surface is sphere, the area on the surface of sphere (A) is equal to the $4\pi r^2$, so according to the formula, solid angle is equal to the 4π $[sr]$.

2.1.3 Luminous Intensity

The luminous intensity of the light sources represents the light intensity which is perceived by the human eyes. Unit of the intensity is candela (cd) which is one of the base units of The International System of Units (SI). Physical explanation of the candela according to the standards is as following: "The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz (Hz) and that has a radiant intensity in that direction of 1/683 watt per steradian." (540×10^{12} $[Hz] = 555\ nm$). The luminous intensity (I_v) is defined as following [7] [10]:

$$I_V = \frac{\Delta\phi_V}{\Delta\Omega}\ [cd] \qquad (2)$$

$$\Delta\phi_V - luminous\ flux\ directed\ into\ the\ solid\ angle$$

$$\Delta\Omega - solid\ angle\ of\ the\ object$$

The root of the name "candela" is coming from the candle which has the luminous intensity close to one candela.

2.1.4 Luminous Flux

In Photometry, luminous flux (Φ_V) is the measurement of the total amount of the light which is dissipated from the source. (Fig. 4). It is different from the radiant flux because of the operational spectral range, which is only on visible wavelengths for the human eye. The calculation of the luminous flux can be done using the CIE Standard Luminosity Function (Fig.2) where weighting sum of the power at all wavelengths corresponds to luminous flux. [7].

The unit of the luminous flux is the lumen (lm). The lumen is the emitted 1 candela of luminous intensity of the light sources over the solid angle of 1 steradian. This definition can be expressed as [6]:

$$\phi_V = I_V \cdot \Omega \ (\mathrm{lm} = \mathrm{cd} * \mathrm{sr}) \qquad (3)$$

$$I_V - Luminous\ intensity$$

2.1.5 Luminance and Illuminance

Last two main quantities of photometry, luminance and illuminance are directly related to the luminous flux and luminous intensity. These two quantities are usually confused by people because of the similarity of the names, however they are two different quantities.

Luminance is the ratio of luminous intensity of the source by the area of the surface (such as a display or LED) where light was emitted. The unit of Luminance is cd/m^2 which is derived from the main SI units or $Nit(nt)$ which is non-SI unit. [6][7]

Illuminance term stands for the incident of luminous flux on the surface divided by the unit area ($1\ m^2$). The unit of illuminance is lm/m^2 or lux (lx) which is derived SI unit [11].

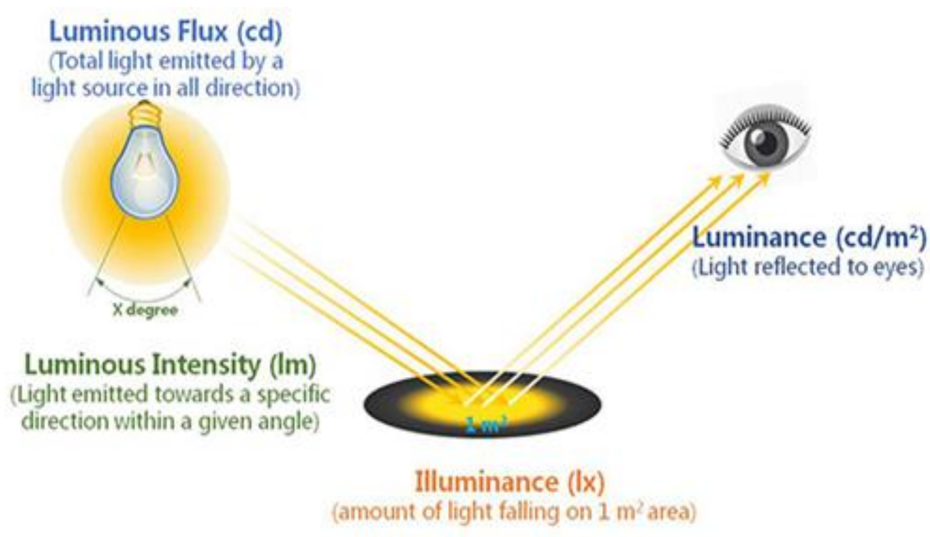

Fig. 4 *Diagram of the four basic quantities of photometry [12]*

The above diagram gives better explanation for the all basic quantities of the photometry while light is emitted from the source and reflected from the surface. (Fig. 4).

2.1.6 Luminous efficacy of the light sources

The physical definition of the luminous efficacy (η) is the ratio of the luminous flux of the source to the power which is required for emitting radiation. The unit of the luminous efficacy is lumens per watt $[lm/watt]$. Mathematical definition is as following [3]:

$$\eta = \frac{\phi_V}{P} \qquad (4)$$

$$\phi_V - Luminous\ flux$$

$$P - Input\ power\ of\ the\ light\ source$$

The calculation of the luminous efficacy for non-monochromatic sources are derived from the general formula and is:

$$\eta = \frac{683 \cdot \int_{\lambda=380}^{\lambda=780} V(\lambda) \cdot P(\lambda)\, d\lambda}{P} \qquad (5)$$

$$V(\lambda) - luminosity\ function$$

$$P(\lambda) - Spectral\ Power\ distribution\ of\ the\ light\ source$$

Luminous flux of the light source can be computed from the multiplication of the luminosity function and SPD of the source which is the luminous intensity of the light source. Calculated result will be multiplied with the steps of wavelength, solid angle and 683 to find total luminous flux. Power of the light sources can be either obtained from the data sheet of the source or with simple experiment with the help of power analyzer. After dividing calculated flux by the power of the source we get numerical result for the luminous efficacy. This calculations method is applied to the all type of the light sources.

To calculate luminous flux without SPD, integrating sphere can be used which will be explained more detailed in the measurement part of the thesis.

2.2 Fundamentals of the Colorimetry

Colour is the property of the object which is accepted by human eye and processed by the cons of human eye because of the absorbed or reflected light from the object. While discussing the quality of the light sources, colour properties are one of the basics along with the luminous efficacy. [3].

As it is described above, eyes have three different types of cones for light perception and color determination. From this statement, we understand that human colour vision system is trichromatic and for human applications usually three primary colours are used. Secondary colours can be obtained from the proper mix of those primary colours. For lighting purposes and displays red, green and blue are the primary colours. [3][6].

To start with, we will describe color matching experiment by the CIE to understand the basics of colorimetry. Following diagram describes (Fig.5) the setup for the measurement.

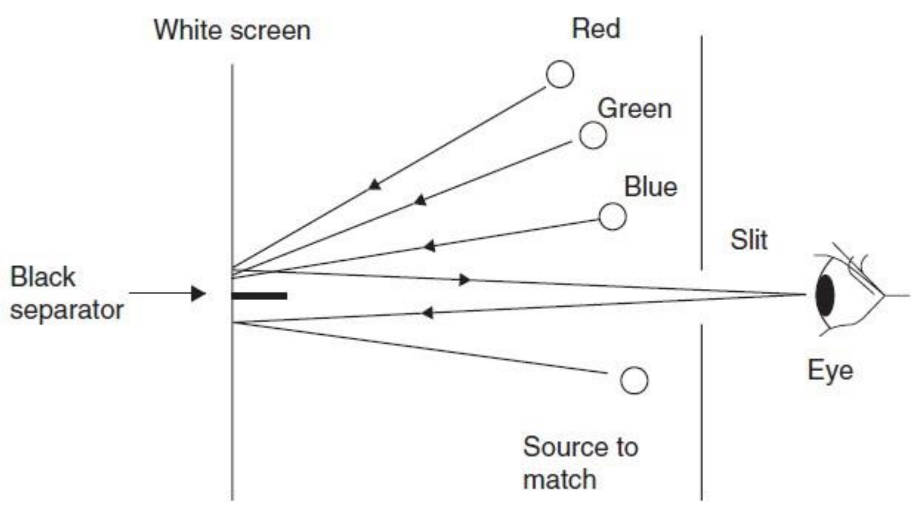

Fig. 5 *Setup for color matching experiment [6]*

As it is drawn, observer looks to the white screen from the narrow slit at an angle of the 2°. The screen was separated to the two parts by the black separator. Upper part of the screen was illuminated by the three separated monochromatic radiation with 700 nm wavelength for red, 546 nm for green and 436 nm for blue colors and down part by the reference color stimulus. When reference field was illuminated with the color different than the primary colors, observers were adjusting the intensity of each primary until it was matching exactly with the reference color. According to the obtained tristimulus values for different wavelength color matching function was plotted (Fig. 6). However, matching was not successful for all wavelengths despite the amount of the R,G or B added to the screen. In such case, one of the primary colors was moved to the reference field for identical matching and which result as a negative color coefficient for some part of the graph. [3][6].

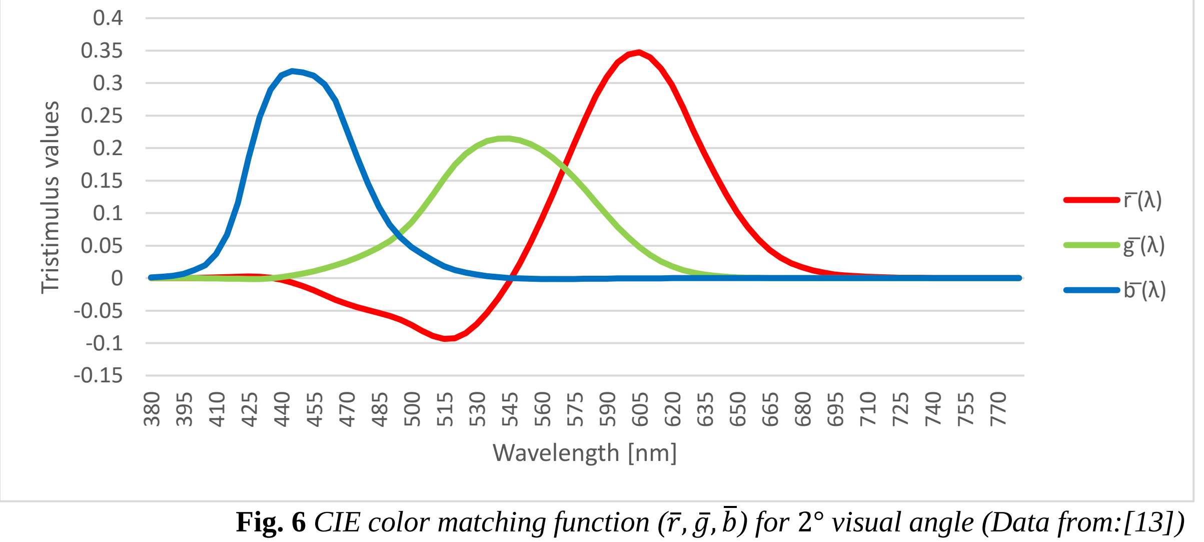

Fig. 6 *CIE color matching function* ($\bar{r}, \bar{g}, \bar{b}$) *for* 2° *visual angle (Data from:[13])*

Tristimulus value on the y-axis of the graph is the intensity of the primary color functions for matching the different wavelengths of the visible light (color) and denoted as R,G and B. Multiplying intensities by corresponding function and summing them will give the matching formulation for the exact wavelength. CIE repeated the experiment for 10° visual angle and plotted the CMF for new values because of the practical restriction caused by smaller visual angle [3][6][14].

Negative values of the CMF were causing problem for calculations, therefore RGB system is transformed to the new function which has non-negative values. One more property of the new transformed function is that the middle CMF in this function is identical to the Photopic Luminosity Function (Fig.2). The new transformed functions $(\bar{x}, \bar{y}, \bar{z})$ has X,Y and Z tristimulus values and plotted for 2° and 10° standard observer (Fig.7). CIE recommend usage of 2° standard observer CMF for the visual view between 1° and 4° and 10° standard observer CMF when the degree is more than 4° [3][15].

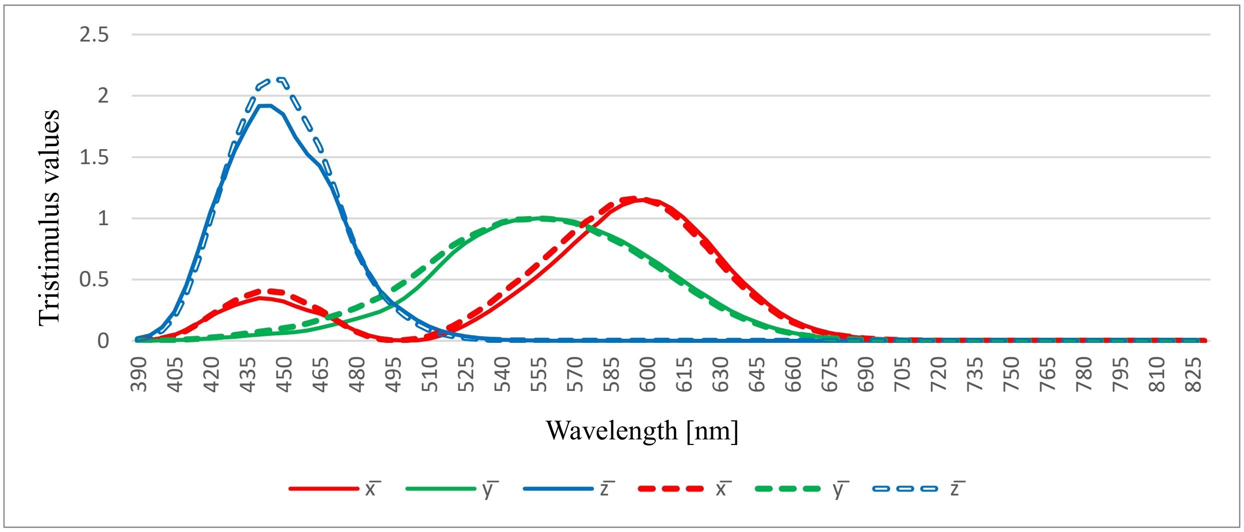

Fig. 7 *CMF transformed function* $\bar{x}, \bar{y}, \bar{z}$ *for* 2° *(straight line) and* 10° *(dashed line) standard observer (Data from:[13])*

2.2.1 Chromaticity diagram

To describe color quality from the point of view of the hue and saturation while not counting the brightness level of the light is called chromaticity. To draw chromaticity diagram for CIE standard observers, chromaticity coordinates (x, y, z) have to be derived from the tristimulus values (X,Y,Z). Conversion between the values are [3][6]:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z} \tag{6}$$

Condition for these coordinates are $x + y + z = 1$, so usually only two coordinates (x, y) is used for chromaticity because third one (z) can easily be derived from other two. Chromaticity diagram demonstrate all pure hues (monochromatic light) for different wavelengths and form horseshoes-shaped curve (spectral locus). Straight line that connects two ends of the curve are called the purple boundary and formed by the mixture of the red and blue colors. This line contains coordinates for non-spectral purple colors. [1][3][6].

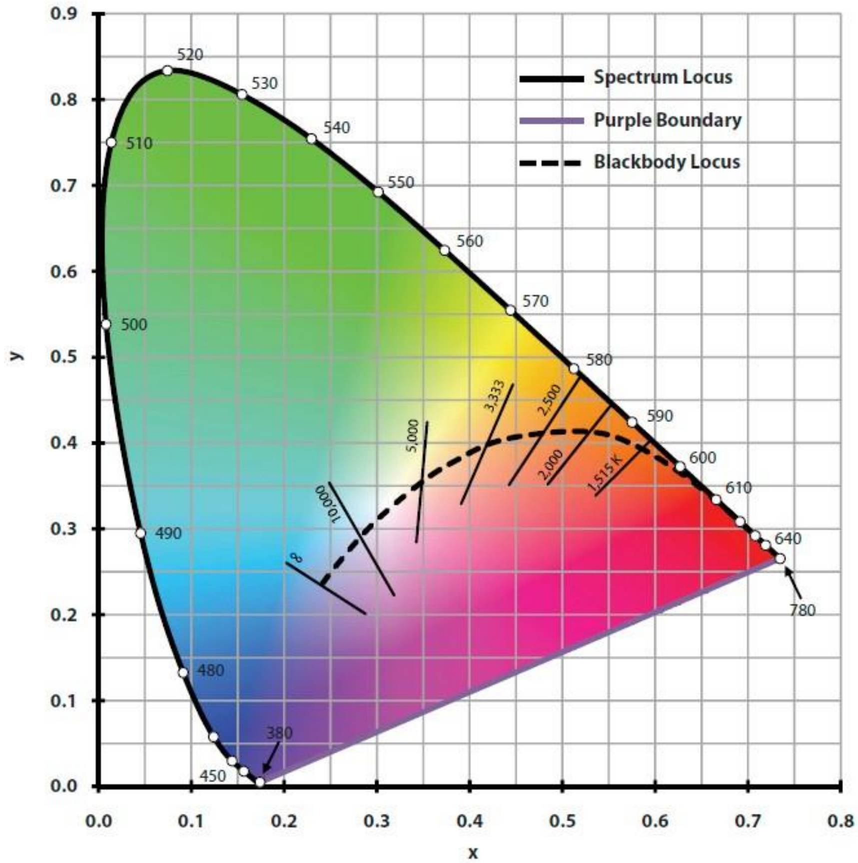

Fig. 8 *Chromaticity diagram (x-y) [3]*

Despite being one of the characteristic for colorimetry, chromaticity diagram was still not useful in practice because of non-uniformity. Simply, in chromaticity diagram, colors are not distributed evenly around the diagram (Fig. 8). Therefore, CIE 1960 UCS diagram was introduced and coordinates can be calculated from the either chromaticity coordinates or directly from tristimulus values [15][16]:

$$u = \frac{4x}{-2x+12y+3} = \frac{4X}{X+15Y+3Z} \qquad (7)$$

$$v = \frac{6y}{-2x+12y+3} = \frac{6Y}{X+15Y+3Z} \qquad (8)$$

This diagram is only recommended to use for calculation of color rendering index and correlated color temperature by CIE.

In 1976, CIE introduced new diagram which is called CIE 1976 UCS chromaticity diagram with a few improvements on diagram and new coordinates (u', v'), such as following [1][15]:

$$u' = u \qquad (9)$$

$$v' = \frac{3}{2} * v \qquad (10)$$

2.2.2 Correlated Color Temperature

Blackbody is the type of material that absorbs all of the lights which is hitting its surface. When the temperature of the blackbody is 0 K, it is not emitting any light and appears as black. When the temperature of the blackbody increase, it starts emitting light in a different colors depending on the temperature. [1][3].

Chromaticity of the blackbody can be obtained from the blackbody locus curve drawn on the chromaticity diagram. Color temperature for the light source can be defined only when chromaticity coordinate of the source is exactly on the blackbody locus curve which shows that light source emits light same as the blackbody on the same temperature. However, for most of the light sources, chromaticity coordinate doesn't exactly locate on the blackbody locus but close to it, hence we describe the **correlated color temperature** quantity for these sources. It must be denoted that, CCT has no connection with the actual surface temperature of the source. Increasing in the CCT leads to the change from warm-white (yellow or orange tone) color to the cool white (bright, blue-white). CCT of modern the light sources vary approximately between 2600 K and 6500 K. [1][3].

Fig. 9 *Illustration for the changing of the color while increasing CCT [17]*

CCT for the light sources can be derived in several ways, and here we will discuss two method for calculations. To determine CCT of the light source, we need to have the coordinates of the Planckian locus for different temperatures. Then we determine the point where minimum chromaticity difference (shortest geometrical distance) between the coordinates of the test source and Planckian locus on the (u', v') chromaticity diagram is minimum. The temperature of the blackbody on the determined coordinate of the Planckian locus corresponds the correlated color temperature of the light source. [18].

Direct calculation of the CCT can be performed with the help of formula which is proposed by McCamy and needs chromaticity coordinates (x, y) to calculate temperature [19]:

$$CCT = 449 * n^3 + 3525.0 * n^2 + 6823.3 * n + 5520.33 \quad (11)$$

$$n = \frac{(x - 0.3320)}{(0.1858 - y)} \quad (12)$$

This method has less than 2°K absolute error for the CCT range between 2,856 and 6,500° K which indicates that, we can use this method for most of the light sources. [19].

To justify that calculated temperature are meaningful, we need to calculate the chromaticity distance between the Planckian locus coordinate and test source coordinate, since if test source coordinate is far from the locus, then defining CCT for this source is not accurate. According to the CIE 15:2004 report calculation formula is [18]:

$$\Delta C = \sqrt{\left(u'_t - u'_p\right)^2 + \frac{9}{4}\left(v'_t - v'_p\right)^2} \qquad (13)$$

$\Delta C (or\ Duv) - chromaticity\ distance \qquad u'_t, v'_t - test\ source\ coordinates$

$u'_p,\ v'_p - Planckian\ radiator\ coordinates$

2.2.3 Color Rendering Index

While characterizing the light sources, another important quantity is the **color rendering index** which indicate how accurate colors can be perceived under the light sources in comparison with a reference source. Reference source is either black-body radiator or daylight depending on the CCT of the source. If temperature of the source is less than 5000 K, black-body radiator is used as a reference source, when the temperature is more than 5000 K CIE daylight illuminant are accepted as a reference source. Value of the CRI lies within the range of 0 (worst) to 100 (best) and by convention CRI for the reference source accepted as 100. Under the high CRI sources colors appear more natural to the human eye and therefore these light sources are used on the museums, photography, cinematography and so on, where color quality is main priority. However, for outside lighting or indicating lamp CRI value is not the main issue . To determine general color rendering index, 8 test-color samples which is taken from the collection of the Munsell color system are necessary. However, nowadays many manufacturers provide data for extended CRI which is calculated for 14 or 15 samples. [1][6][7][15].

To begin calculation procedure, first we will introduce CIE 1964 UCS (or CIEUVW) system which is expressed as following, [7][15]

$$W^* = 25\, Y^{1/3} - 17 \qquad (14)$$

$$U^* = 13\, W^*(u - u_0) \qquad (15)$$

$$V^* = 13\, W^*(v - v_0) \qquad (16)$$

Where W* represent lightness, u and v are the chromaticity coordinates of the light source, u_0 and v_0 are the chromaticity coordinates of the reference stimulus that corresponds to the white light (x=1/3, y=1/3) and Y is the tristimulus value of the light source.

Fig.10 *14 test color samples for CRI calculation [20]*

Adaptation of the human eye to the different illuminated environment without losing so much color perception is called chromatic adaptation. While calculating CRI, we need to take into consideration that chromaticity coordinates of the test stimuli (quantities with "k" subscript) and reference stimuli (quantities with 'r' subscript) don't match since colors can still perceived naturally and 'correctly' under the test source because of the chromatic adaptation. To calculate chromaticity coordinates after chromatic adaptation correction [7][15]:

$$u_k' = u_r \qquad (17)$$

$$v_k' = v_r \qquad (18)$$

$$u_{k,i}{}' = \frac{(10.872 + 0.404 \times c_{k,i} \times \frac{c_r}{c_k} - 4 \times d_{k,i} \times \frac{d_r}{d_k})}{(16.518 + 1.481 \times c_{k,i} \times \frac{c_r}{c_k} - d_{k,i} \times \frac{d_r}{d_k})} \qquad (19)$$

$$v_{k,i}{}' = \frac{5.520}{(16.518 + 1.481 \times c_{k,i} \times \frac{c_r}{c_k} - d_{k,i} \times \frac{d_r}{d_k})} \qquad (20)$$

u_k' , v_k' – chromaticity coordinates of the test source after chromatic adaptation correction

u_r , v_r – chromaticity coordinates of the reference source

$u_{k,i}{}'$, $v_{k,i}{}'$ – chromaticity coordinates of each test color samples under the test source after chromatic adaptation correction

Quantities with 'i' subscript indicates that these values are obtained from the product of the SPD of the used light source and the spectrum of the used color samples. Coefficients c and d can be calculated from the following formula[15]:

$$c = \frac{4 - u - 10v}{v} \qquad (21)$$

$$d = \frac{1708v + 0.404 - 1.481u}{v} \tag{22}$$

$c_r,\ d_r -$ coefficients can be calculated from the u_r and v_r (reference source coordinates)

$c_k\ , d_k -$ coefficients can be calculated from the u_k and v_k (test source coordinates)

$c_{k,i}, d_{k,i} -$ coefficients can be calculated from the $u_{k,i}$ and $v_{k,i}$ (coordinates for each test color under the test source) [15]

As a next step, we will convert obtained values to the CIE 1964 UCS system[15]:

For reference source:

$$W_{r,i}{}^{*} = 25\,(Y_{r,i})^{1/3} - 17 \tag{23}$$

$$U_{r,i}{}^{*} = 13\,W_{r,i}{}^{*}(u_{r,i} - u_r) \tag{24}$$

$$V_{r,i}{}^{*} = 13\,W_{r,i}{}^{*}(v_{r,i} - v_r) \tag{25}$$

For test source:

$$W_{k,i}{}^{*} = 25\,(Y_{k,i})^{1/3} - 17 \tag{26}$$

$$U_{k,i}{}^{*} = 13\,W_{k,i}{}^{*}(u_{k,i}{}' - u_k{}') \tag{27}$$

$$V_{k,i}{}^{*} = 13\,W_{k,i}{}^{*}(v_{k,i}{}' - v_k{}') \tag{28}$$

$Y_{r,i}, Y_{k,i}$ are tristimulus values obtained from the product of the spectral distributions of the reference source and the test source with the spectral distribution of the test color sample spectral, respectively.

To calculate special color rendering indices for each test color sample (R_i), firstly color difference between the reference and test sources (ΔE_i) will be computed: [15]

$$\Delta E_i = \sqrt{(U_{r,i}{}^{*} - U_{k,i}{}^{*})^2 + (V_{r,i}{}^{*} - V_{k,i}{}^{*})^2 + (W_{r,i}{}^{*} - W_{k,i}{}^{*})^2} \tag{29}$$

$$R_i = 100 - 4.6\Delta E_i \tag{30}$$

After computing special color rendering indices for the n samples of the colors, finally we will calculate the average value and determine the general or extended color rendering index (R_a, R_e).

$$R = \frac{(\sum_{i=1}^{n} R_i)}{n} \tag{31}$$

$$For\ general\ CRI\ (R_a), n = 8$$

$$For\ extended\ CRI\ (R_e), n = 14\ (or\ 15\ for\ some\ applications)$$

Color rendering index value is the quality scale of the light source, however sometimes it doesn't represent the sufficient information about the source. For instance, light source can have higher CRI value which indicates that it has better color rendering ability , however R_9 (strong red) value can be quite low, which is critical for many applications, such as photography and cinematography which are mentioned before. While analyzing light sources, it is better to have individual values for specific color rendering of the source, which can help customer to choose most appropriate source for desired application.

2.2.4 IES TM 30-15 Standard

For evaluating color properties of the light sources CRI is the main quantity for many years. It is usually good representative for color rendering ability of light sources for 8 or 14 samples, however this amount of colors not precisely describe color quality. To solve this problem IES proposed modern approach for color measurement and while using CAM02-UCS color space, increased number of samples to the 99 and measured different quantities [21][22][23]:

a. Color fidelity
b. Color gamut
c. Gamut shape
d. Hue bin indices

As the similar method to determining CRI, TM-30 method uses 99 color samples and compare the chromaticity coordinates of the samples which is lightened by reference and test source. Calculated average change from this comparison is color fidelity index which is denoted as R_f. Range for color fidelity index is same as CRI, between 0 and 100. [21][22][23].

Color gamut measurements is for the determining the saturation level of test light source in comparison with reference source. Usually desaturated colors are not desired by many people, and even under high CRI light bulbs color can look desaturated. Gamut index calculation is also according to the 99 color samples. Firstly, chromaticity coordinates of the reference source and test source are marked on the a', b' plane of CAM02-UCS color spaces is divided into the 16 section which correspond to different colors:

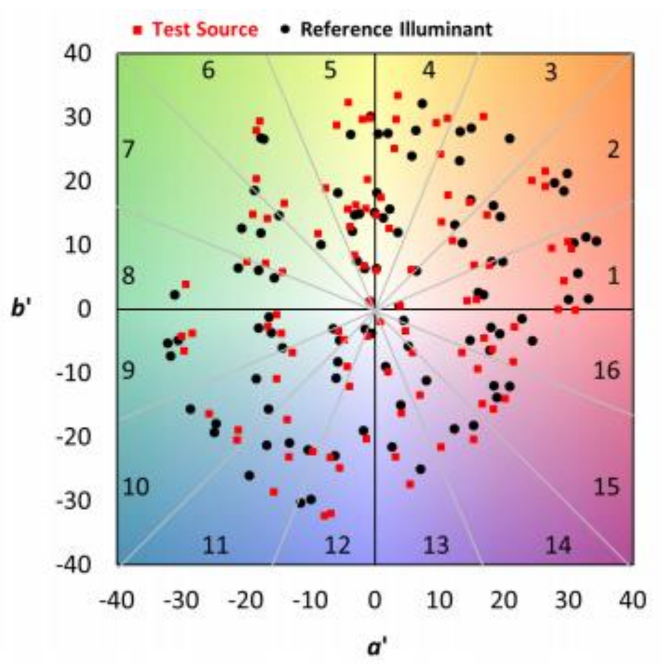

Fig. 11 *Chromaticity coordinates for 99 samples [24]*

Secondly, mean value for coordinates of each section needs to be determined, which means two coordinates for each section one for reference and one for test source. After connecting this points for each of the source, we obtain two figures and division of the area for the test source by the are for the reference source multiplied by 100 gives numerical value for color gamut index. Color gamut index , R_g, varies usually 60-140 and 100 is the value which shows that there is not any increase or decrease in the level of saturation. Gamut index below 100 means desaturation and above 100 means oversaturation. [23][24].

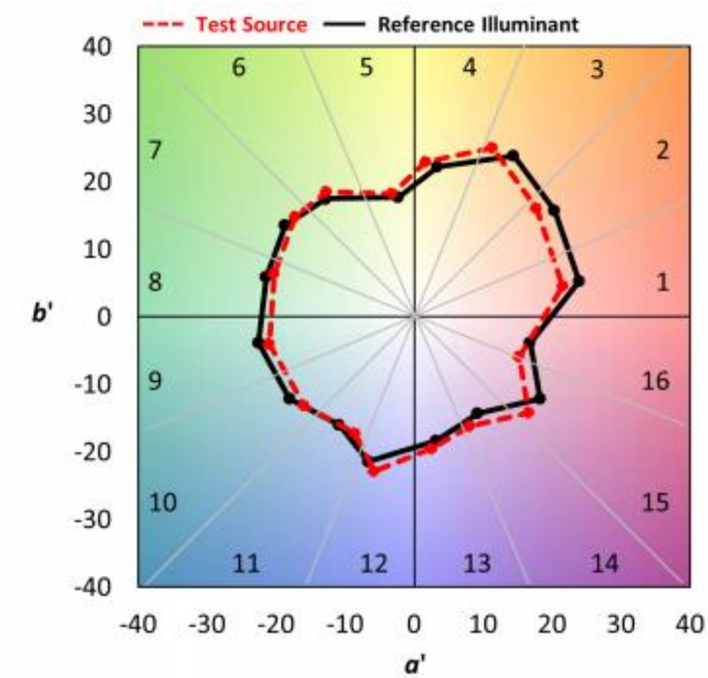

Fig. 12 *Connected average chromaticity coordinates [24]*

One should remember that, lamps with gamut index around 100 is not always rendering all color naturally, there may be desaturation or oversaturation for some types of colors, which decrease the color quality. That is why, together with these calculated values, color vector graphic which is represented as relatively uniform circle for reference source according to the average chromaticity coordinates also provides information for individual comparison of the color saturation level for each section. While observing color vector graphic, customer can get more real representation about the saturation level for each color. If test source representative line is outside of the circle of reference source, it means test source will oversaturate the colors in this range, on the other hand, if representative line is inside of the circle, it means the color in this hue range will appear desaturated. One more quantity that can be obtained from this graphic is the hue shift and arrows which is not perpendicular to the reference circle is the representative of this. To have perfectly matching graphics both representative circle for the test source should be over the line of reference source. [23][25].

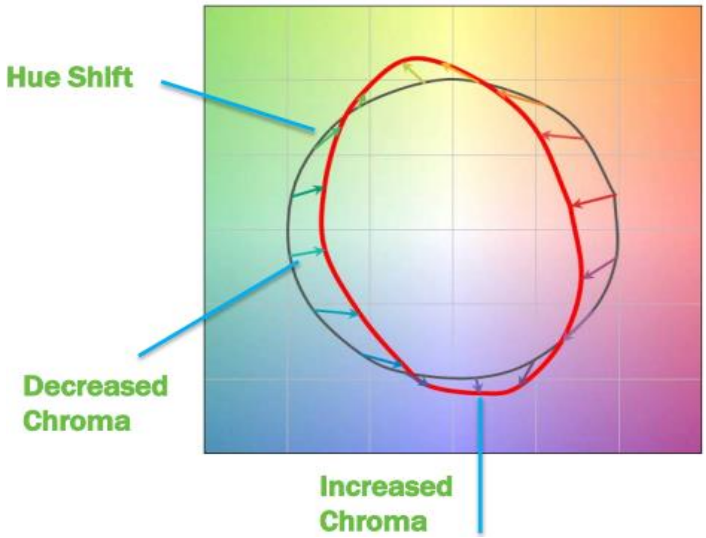

Fig. 13 *Color vector graphic representative [26]*

To summarize, IES TM-30 method for color rendering of the light sources are relatively new and more detailed description of the color in comparison with the CIE CRI. Besides average values, this system also provides graphical representation which helps to analyze color quality visually, rather than measured values. This system is not approved yet by CIE and therefore neither many manufacturers provide data for it on the datasheets of lamps nor spectrogram measures values. According to my investigation, CIE is going to revise traditional color rendering method and suggest new one, which may be IES TM-30. However, because these values for light sources, LED in our case, are not easy to find and obtained values are not usually verified, we will not compare this quantities of the LED in this research paper.

2.3 Solid State Lighting

Solid State lighting term is used for the lighting source that uses semiconductor light-emitting diodes (LEDs), organic light emitting diodes (OLEDs) and polymer light-emitting diodes (PLEDs). As the essential part of the thesis and lighting industry, only LED light sources will be described. [3].

Light emitting diodes' working principle is due to the physical phenomena called electroluminescence, which is the light emission from the material while current passing through it. Diodes are consisting of two electrodes (anode and cathode) and two type of semiconductors (p-type and n-type). Doping of the intrinsic semiconductor with element which has higher number of valence electrons than the intrinsic material creates n-type semiconductor which is the element with free electrons and with element which has lower number of valence electrons creates p-type semiconductor which is the element with "holes" or simply lack of electrons. These two type of semiconductors construct transition area p-n junction. Conduction point is in the p-n junction and current only passing in one direction (from positive to negative, p-n), but not opposite. When there is not current in the circuit, electrons and holes close to the junction combine and create depletion zone, where none of the electrons are allowed to pass and combine with holes.

While current passing from p-type semiconductor to n-type semiconductor, electrons and holes are combining again in the junction area and junction becomes conductive medium. Combination process make electrons to drop to the lower energy state and as a result of dropping, they radiate electromagnetic radiation in special wavelength. Wavelength of the emitting radiation depends on the type of semiconductor used in p-n junction. By proper choosing of the semiconductors, different colors in the visible light range can be obtained, which is the operation principle of the LED sources. Types of materials and their mixing to produce white light will be one of the main discussion of the research. [3][27].

For basic LED packages, LED chip (semiconductor chip) is mounted to the electrodes and surrounded by the lens which is made from the epoxy resin (Fig.14). [3].

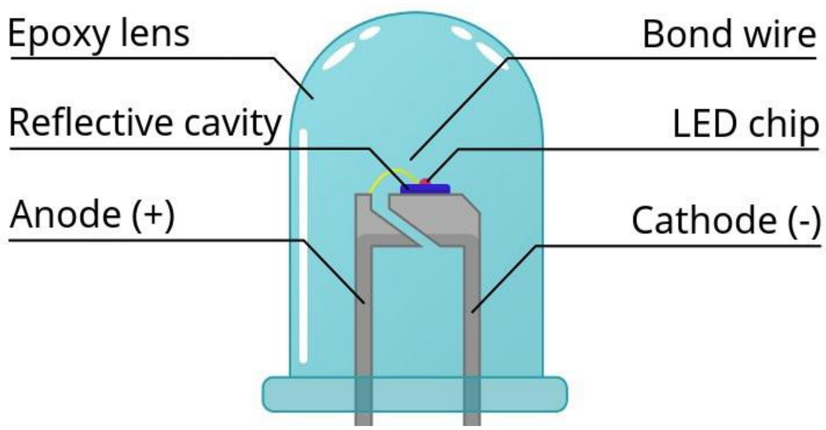

Fig. 14 *Simple diagram of the LED package [28]*

LEDs are monochromatic light emitters; therefore, they can't directly emit white light. However, there are two main methods for white light generation: Color mixing method and Phosphor converted LED. Both methods have some advantages and disadvantages and special application areas.

2.3.1 White light generation technologies

2.3.1.1 Color mixing LED technology

Color mixing method uses combination of 2,3 or more LED chips of different color to produce aimed color. It is known that, proper mix of red, green and blue light appears as white to the human eye. Color mixing technology in this case RGB LED technology uses exactly this color mixing method for white light generation. Construction of RGB WLED (Fig. 15) is similar to the diode, but with extra 2 anodes so current can reach all three chips of different colors.

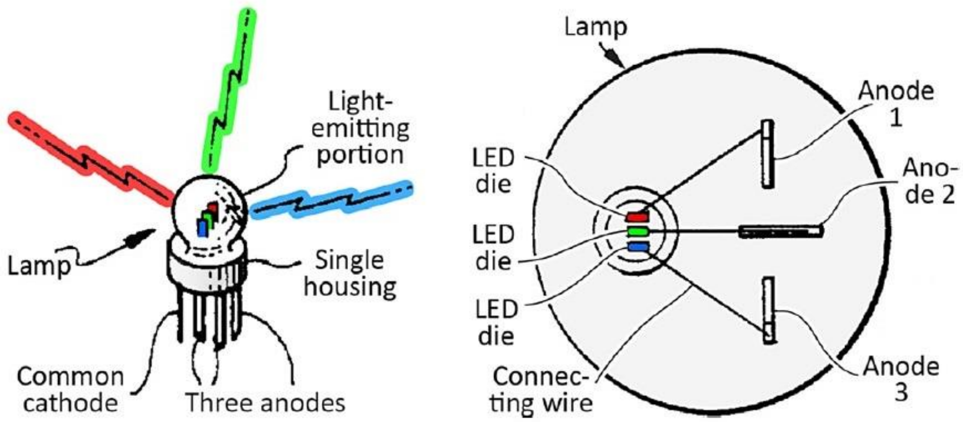

Fig. 15 *RGB WLED simple diagram [29]*

While constructing RGB LED, usually following semiconductors used for obtaining different color:

AlGaP (Aluminum Gallium Phosphide)-Green

AlGaInP (Aluminum Gallium Indium Phosphide)-orange-red, orange, yellow and green

GaAsP (Gallium Arsenic Phosphide)-Red, orange-red, orange and yellow

GaN (Gallium Nitride)-Green and Blue

InGaN (Indium Gallium Nitride)-Near UV, blue-green and blue [11][27]

Primary advantages of this method for white light generation is color-mixing ability, which means we can obtain millions of the color from the proper mix of these three colors, longer life-time and theoretically higher efficacy. Application are of RGB technology is quite big such as indicating signs, signals or LCD display backlights, however this technology still has several disadvantages such as degradation of the color over years, low CRI and high temperature dependency. Increasing the temperature of source, shifts chromaticity coordinates of RGB WLED towards the higher color temperatures on Planckian locus. This is mainly caused by the red light emitting chip, because it is more dependent on the temperature in comparison with green or blue chips. Shifting issue of the chromaticity point is the serious issue for LCD backlight display and can be overcome while monitoring and adjusting relative power intensively. For obtaining better CRI value RGBA system which stands for red, green, blue and amber color LED chips can be used, however it will reduce luminous efficacy, because of shifting of peak wavelengths of the spectra from the peak of the luminosity function. [3][7][30].

Theoretically luminous efficacy of multicolor LED light sources are around 120-200 lm/W and CRI can vary from according to the application area, for color-critical applications CRI around 90 can be obtained using RGBA technology. Real life values for luminous efficacy of RGB LED are usually lower than theoretical value. Approximate spectral power distribution for RGB and RGBA technology is described on the following diagram. [31][32].

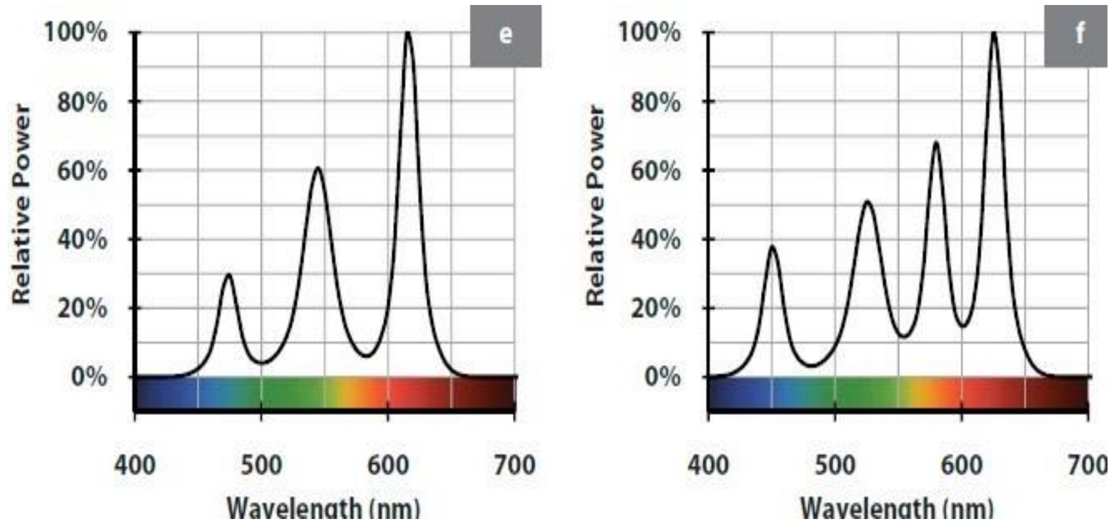

Fig. 16 *Approximate SPD for e) RGB LED and f) RGBA LED technology [3]*

2.3.1.2 Phosphor converted LED

Another common method for white light generation is exciting one or more phosphors with shorter wavelength of radiation such as UV from non-visible spectra or blue from visible spectra, which is similar to the operation principle of fluorescent lamp. Constructed LED chip usually is constructed by InGaN and emits light in shorter wavelength. Emitted light is partly absorbed and converted to the longer wavelength by converting material (usually phosphor) and reemits as a white light. We can roughly explain that, used phosphors emits yellow light and white light which is emitted from the bulb is the combination of the blue and yellow lights. Using only one type of phosphor results lower CRI for light sources because of the lower values on the longer wavelength part of SPD (red), hence to solve this problem more than one phosphor type usually used for emitting in longer wavelength of the spectra. While increasing the CRI value, we need to take it into consideration that, luminous efficacy of the source will decrease because of peak value of the SPD will move far from the peak of the luminosity function. Luminous efficacy for PC LED usually varies between 70-100 lm/W, but modern version can already extend this range [3][7][27]. Structure of the PC LED is similar to simple diagram of the LED package and only difference is used phosphor coated LED chip (Fig.17).

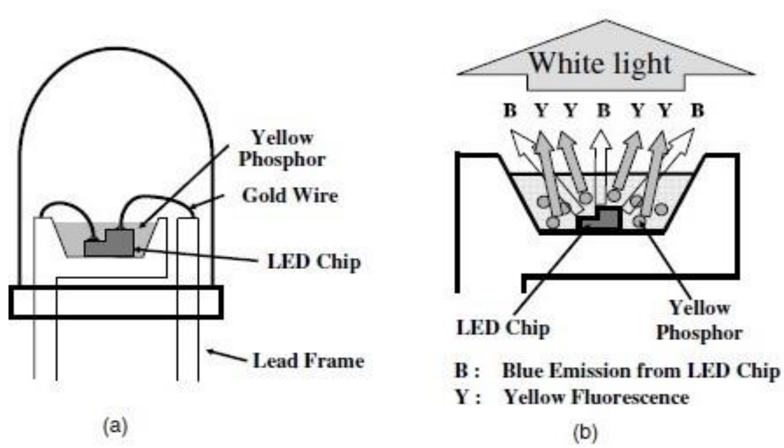

Fig. 17. a) *Basic structure of the PC LED b) Illustration of white light generation process [33]*

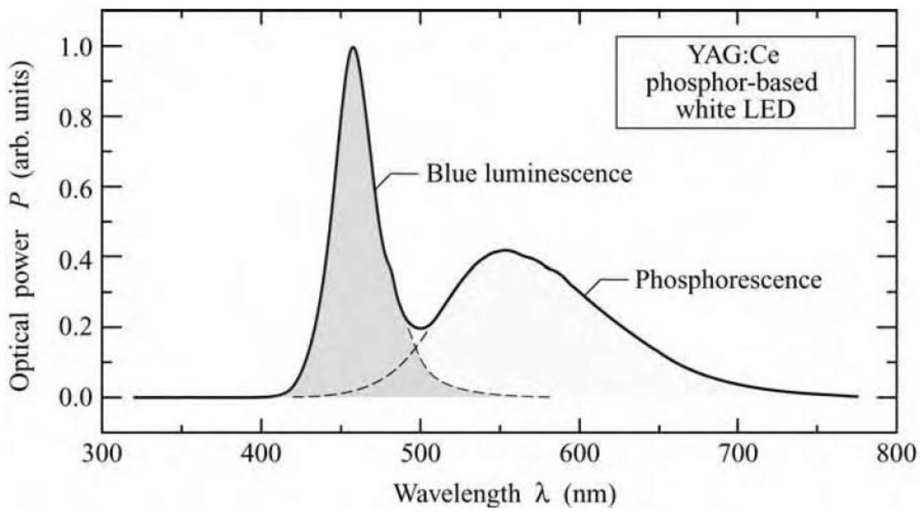

Fig. 18 SPD for the phosphor-based WLED [7]

As a fundamental core of conversion process, selection of used phosphor is pretty affective to the quality of the source. In this part of chapter, we will discuss various phosphor types and their affect to the luminous efficacy or color rendering index.

To begin, we need to know what is the main criteria while choosing phosphor material for WLED. Criteria are following [34]:

a. **Excitation spectrum** can be obtained by the exciting phosphor under the influence of the LED chip and for better efficacy this spectrum should match decently with the emission spectra of the LED chip. For this reason, phosphor should absorb high amount of intensity of the produced light. [34][35].
b. **Emission spectrum** is the total spectra with the combination of phosphor and used LED chip which generates white light. From previous explanations, it is obvious this is important for color quality properties (CCT,CRI) and efficacy of light source. [34][35].
c. **The Quantum efficiency** of phosphor can be characterized by two main quantities: Internal Quantum Efficiency – the division of the total emitted photons by the number of absorbed photons
   External Quantum Efficiency- the division of the total emitted photons by the number of incident photons.
   To obtain higher luminous efficacy, phosphor with higher quantum efficiency should have chosen. [34][35].
d. Phosphor should have **stability** during the whole usage time of WLED. Stability refers to having the same spectra and quantum efficiency, being stable against chemical attacks (e.g. moisture, O_2) and temperature change. [34][35].
e. **Uniform particle size and morphology** are one of the main reason for higher quantum efficiency and luminous efficacy. Morphology of the particle is usually spherical for many applications. [34].
f. Finally, **the manufacture cost** for phosphors should be cheap. [34].

According to the aforementioned properties, many types of phosphors produced and used in the PC LED industry. Over the time, it results as the increasing in the quality of the light sources and investigations for obtaining higher efficacy and color quality is still continuing. Types of phosphors can vary from each other for different properties and here we will discuss some of the mostly preferred phosphors for LED light industry.

YAG:Ce (Ce^{3+}**-**doped garnet-type phosphor**)** type of phosphor are widely used in the PC-WLED manufacturing industry nowadays, due to highly matching excitation spectrum with highly efficient blue LED chip, higher quantum efficiency and high thermal quenching. In detail, components of this phosphor is (Gd)Y_3 (Ga) Al $_5O_{12}$: Ce and still used for acquiring high luminous efficacy. Disadvantages of this type of phosphor is the low color rendering index because of the lack of longer wavelength in the spectra. [34] [35].

(Oxy)nitride phosphors are red light emitting phosphors which uses Eu^{2+}-doped nitridosilicates , for instance, (Ba) $Sr_2Si_5N_8$: Eu^{2+} and (Sr) $CaAlSiN_3$: Eu^{2+}. These phosphors also have well matching excitation spectra with blue LED chip, higher temperature stability and higher color rendering index. However, increased CRI leads to the decrease in the luminous efficacy of the source, because emission spectra has higher values on the longer wavelengths of the spectra. [34] [35].

Earth orthosilicates (Ba_2SiO_4: Eu *and* Sr_2SiO_4 : Eu) are different types of used phosphor for PC WLED with high quantum efficiency, low manufacture cost etc. and are usually used with blue LED chips with short wavelength. However, drawbacks of this phosphors are low CRI and low thermal stability which is not desirable for high-power applications. [34] [35].

Alkaline earth sulfides will be final discussion of types of phosphor. (Sr)CaS:Eu phosphor can be one of the example for this type and it emits red color in the range of 600-655nm. High CRI values can be obtained through this phosphor also, however low stability to the moisture and temperature makes it unpractical for usage. To overcome this issue, surface of phosphor is usually coated with Al_2O_3 *and* SiO_2. Another example of this family is $SrGa_2S_4$: Eu and it emits green color with 535 nm peak wavelength and CRI of this technology is also high. Nevertheless, low thermal and chemical stability are the main obstacles for the broad usage of this technology in the WLED area. [34].

For LED based light lamps, manufacturer uses mainly PC LED because of the better CRI, high efficacy and as a result of improvement of phosphor types increasing quality of the bulbs. We will summarize WLED generation technologies and making comparison between them on the following table:

RGB WLED		**PC LED**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Obtaining millions of light besides white	Rendering color unnaturally (low CRI)	Better color rendering index than RGB WLED	Poor rendering in the higher wavelength (e.g. red)
	High temperature dependency	Good luminous efficacy	Using more phosphor to increase CRI decrease luminous efficacy
	Color degradation over years	More commonly used in light bulbs	Still not dominating market entirely because of lower efficacy than some of light sources

Fig. 19 *Comparison table of 2 different technology for white light generating LED*

3. Existing LED sources

3.1 A Real sample of LED sources and their spectrum

As a new trend of lighting, there are several companies which is competing either to increase luminous efficacy, color rendering index or both of them at the same time. In today's world, LED lighting is already one of the most preferable lighting system and this increasing trend is promising about the future of the industry. To demonstrate real life example of LED, we will describe properties of several lamps both from datasheet from internet and laboratory measurements.

To begin with, we will use datasheets of two products from PHILIPS which are "Standard LED bulbs" and "SceneSwitch LEDbulbs" and describe main properties. First example. "Standard LED bulb" has good luminous efficacy and CRI. According to the properties, this can be considered as good replacement of other types of bulbs on daily usage. Following table and spectra will give us more detailed information. [36].

Fig. 20 *PHILIPS Standard LED bulb [37]*

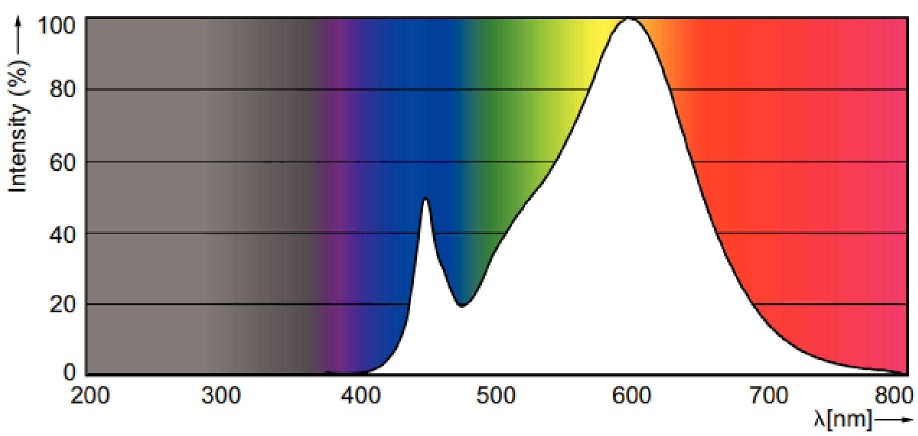

Fig.21 *Spectra of the PHILIPS Standard LED bulb [37]*

Color Designation	White
Nominal Lifetime (Nom)	25000 h
Luminous Flux (Nom)	806 lm
Power (Rated) (Nom)	9 W
Correlated Color Temperature (Nom)	3000 K
Color Rendering Index (Nom)	80
Luminous Efficacy (rated)(Nom)	89.56 lm/W

Fig.22 *Table for the properties of PHILIPS Standard LED bulbs [37]*

Another sample that will be described is "SceneSwitch LED bulb" and this sample provides 3 different modes for costumer. While relaxing, studying or amusing customer can switch between three modes. [37].

Fig. 23 *PHILIPS SceneSwitch LED bulb [38]*

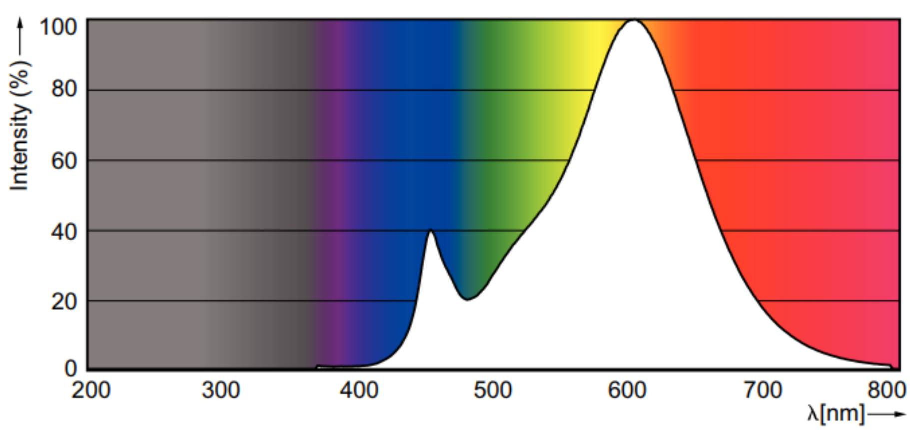

Fig. 24 *Spectra of the PHILIPS Standard LED bulb for 3rd mode (806 lm) [38]*

Nominal Lifetime (Nom)	15000 h
Luminous Flux (Nom)	806-320-80 lm
Power (Rated) (Nom)	8-5-2 W
Correlated Color Temperature (Nom)	2700-2500-2200 K
Color Rendering Index (Nom)	80
Luminous Efficacy (rated) (Nom)	100 lm/W

Fig. 25 *Table for the properties of PHILIPS Standard LED bulbs [38]*

Above table reveals the fact that, luminous flux, power and CCT varies according to the chosen mode. To switch between modes switching on and off is enough and no extra configuration is required. Both of the lamps has quite high luminous efficacy with good CRI which makes them high quality lamps. [38].

To compare white light generating LED technologies, we will analyze **RGB White LED** products of two companies. Firstly, LIFX GLS LED lamp from SYLVANIA:

Fig. 26 *LIFX GLS LED lamp [39]*

Average Lifetime (Nom)	40000 h
Luminous Flux (Nom)	1000 lm
Power (Rated) (Nom)	17 W

Color Rendering Index (Nom) (R_a)	90
Luminous Efficacy (rated) (Nom)	58.82 lm/w

Fig. 27 *Table for the properties of SYLVANIA Standard LED bulbs [39]*

As we can see, luminous efficacy of RGB technology is usually low for real sources and interesting fact is that CRI for 8 samples is quite high, however R9 value or extended CRI is not mentioned in the datasheet, which doesn't represent enough information about color quality.

Next example will be from SGM company and it is also RGBW LED technology and will give brief technical details about it:

Fig. 28 *R-2 RGBW LED [40]*

Average Lifetime (Nom)	50000 h
Luminous Flux (when all lights on)	1095 lm
Typical power consumption	37-42 W
Color Rendering Index (typical)	82
Luminous Efficacy (rated) (Nom)	35 lm/W

Fig.29 *Table for the properties of SYLVANIA Standard LED bulbs [40]*

According to the given data, we can observe that this lamp source has very low efficiency in comparison with available LED sources.

While comparing only special types of two different technology can't help to compare the quality difference between them properly, however combining theoretical information with these values especially for efficacy once more proves that why PC LED are usually the essential part of lighting industry. These improved technologies gives customers the broad range for the selection of LED light sources for appropriate application, such as decorative lighting or general usage.

3.2 Measurement of the LED sources

To have the real data from bulbs, we have done simple measurement with the help of two different spectrometer for photometric and colorimetric measurements and power analyzer to calculate luminous efficacy. Used tools for measurements are:

a. C.A 8220 Power Analyser
b. AEMC MN93 Current Probe
c. MAVOSPEC BASE GOSSEN Spectrometer
d. GL SPECTIS 1.0 Touch Spectrometer
e. Integrating sphere
f. Photometric bench

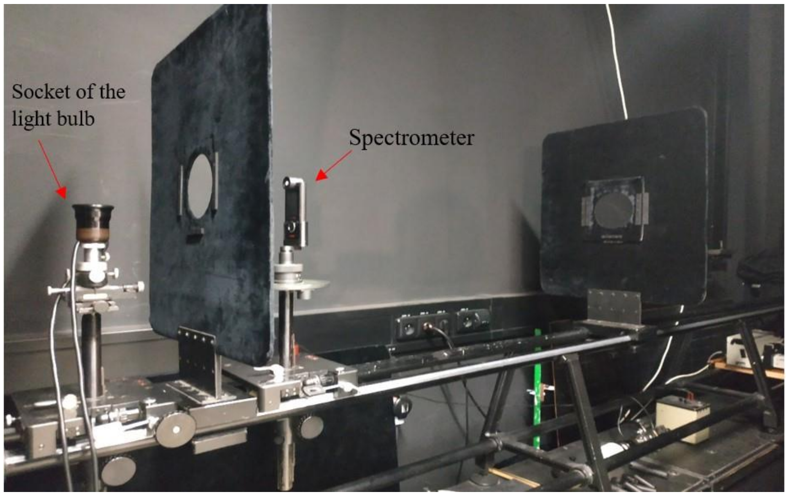

Fig.30 *Photometric bench for the measurement*

g. 2^{nd} generation commercially available DEN LED with 3 step (mode)

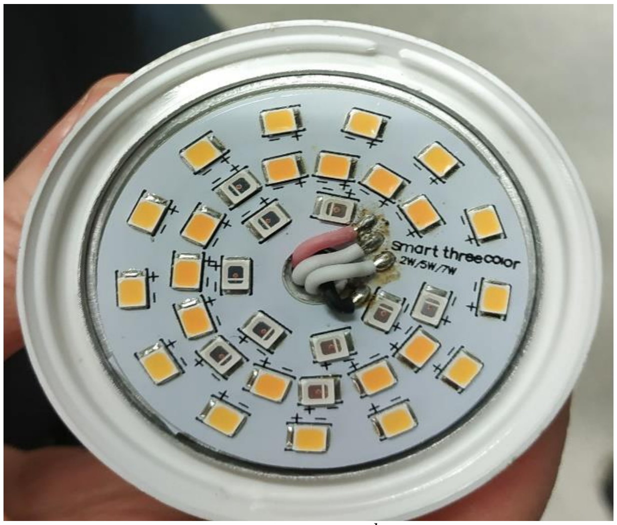

Fig. 31 *Top view of 2^{nd} generation LED*

h. 3^{rd} generation commercially available DEN LED with 3 step (mode)

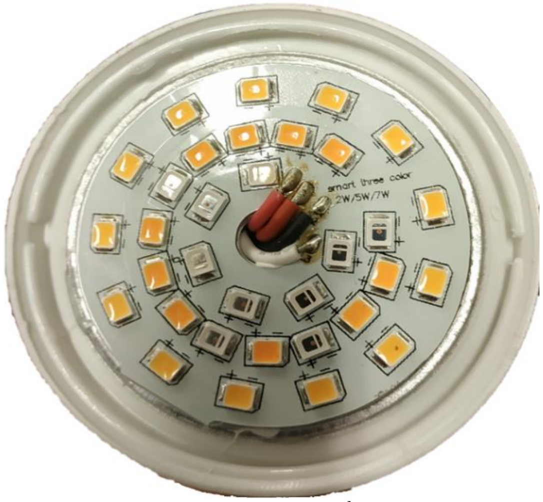

Fig. 32 *Top view of 3^{rd} generation LED*

Before describing the procedure for the measurement, properties of some of the used tools will be discussed. Both spectrometers were high quality one, however while analyzing datasheet for these products, they differ from each other for measurement range of several quantities. Here we will shortly describe some of the basic technical information about devices to evaluate the output more correctly.

Fig. 33 *GL SPECTIS 1.0 touch spectrometer [41]*

Illuminance measurement range [lux]	1-200,000 lx
Spectral range	340-780 nm or 640-1050 nm
Detector	CMOS image sensor
Integration time	10 ms - 10 s in automatic mode (100 s-manual mode)
A/D conversion	16 bits

Fig. 34 *Technical data sheet for GL SPECTIS 1.0 touch spectrometer [41]*

Illuminance measurement range [lux]	10-100,000 lx
Spectral range	380-780 nm
Detector	CMOS image sensor
Integration time	10 ms – 3000 ms automatic,manually
A/D conversion	16 bits

Fig. 36 *Technical data sheet for GOSSEN MAVOSPEC BASE spectrometer [42]*

Fig.35 *GOSSEN MAVOSPEC BASE spectrometer [42]*

According to the information from the developer of the lamp, 2nd generation LED lamp uses pure amber light (not PC amber, but amber) for first step and 3rd generation LED lamps uses commercially available monochromatic LED lights. 2nd and 3rd step technology for both lamps are same and are commercially available LED 2700 K, Duv<0.005, CRI 98 and LED daylight circa 4000 K, Duv<0.005 and CRI 90+ respectively. To draw SPD graph, we will use excel templates which is provided by GOSSEN company([42]) for spectrogram.

Measurement started with the determining input power of the light source with power analyzer and current probe clamped around the connection wire. After determining input power for all three steps (modes), we continued to the second part of the measurement with integrating sphere to determine luminous flux of the source. Firstly, we placed standard source with known luminous flux to the sphere. Then we connected supply cables of the integrating sphere to the current and voltage clamp patch panel. After adjusting voltage on the regulatory transformer to the nominal value, we have waited approximately 4-5 minute for heating up the source. Finally, we obtained deflection ($E_n = 155\ \mu W$) which is proportional to the luminous flux of standard light source from photocurrent measure device which will help us to calculate luminous flux later. After obtaining this data, we replace standard bulb with measurement lamps and obtain deflection (E_z) for 3 steps of used lamps. To calculate luminous flux of test source, we will use following formula:

$$\phi_Z = \phi_n \cdot \frac{E_z}{E_n} \cdot \frac{E_{kn}}{E_{kz}} \qquad (32)$$

Ratio of E_{kn} and E_{kz} are correction values and need to be calculated when dimensions of test source and standard source differs so much, however in our measurements they were approximately same size, so we will neglect this part of calculation. Luminous flux of standard bulb (ϕ_n) is equal to the 1838 lm and to calculate luminous flux of test source (ϕ_Z), we need to use all obtained values in the formula.

Last part of the measurement was for measuring the color quality of LED bulbs with spectrometer. While using photometric bench we installed both spectrometers in 30 cm photometric distance respectively and measured several quantities for the light sources again for 3 different steps.

Firstly, we discuss about 2nd generation LED lamps and will describe measured and calculated values for all 3 steps of the source . Data for **2nd generation LED** is:

Input Power	1.75 W
$\boldsymbol{E_z}$	2 μW
Calculated luminous efficacy	13.55 lm/w

Fig. 37 *Quantities for the first step of 2nd generation LED*

Because first step of the lamp is not for producing white light, discussing CCT or CRI doesn't make sense, so we will only calculate luminous efficacy which is expected to be low.

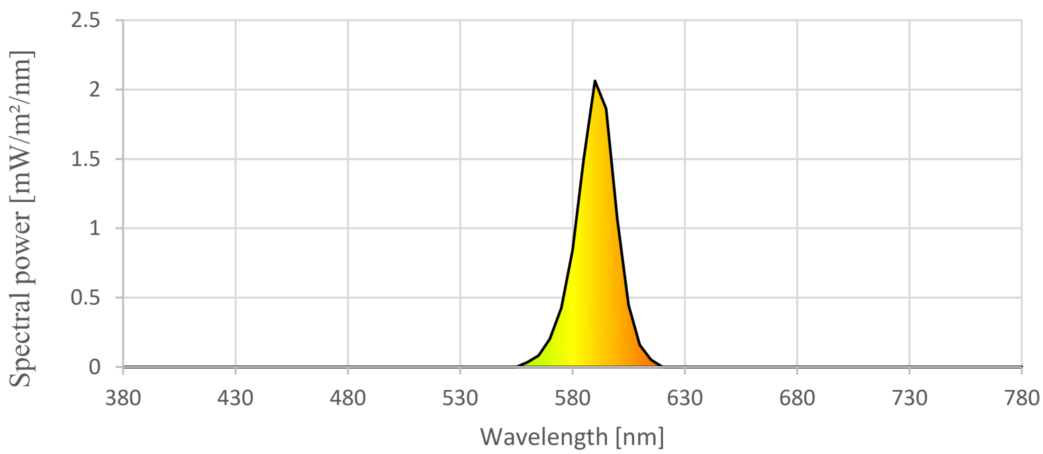

Fig. 38 *Spectra for first step of 2nd generation LED*

Second and third steps of lamp is generating white light with different quality and measured values are:

Measured quantities	**GOSSEN MAVOSPEC BASE**	**GL SPECTIS 1.0 TOUCH**
CCT	2743 K	2796
Duv	0.0044	0.006
CRI $(\boldsymbol{R_a - 8\ samples})$	97.86	97.5
CRI $(\boldsymbol{R_e - 15\ samples})$	96.42	95.9 (14 samples)
R9 sample	92.7	91.8
Chromaticity coordinates *(x, y)*	x=0.4645, y=0.4237	x=0.4601, y=0.4236
Measured Input power	5.90 W	
$\boldsymbol{E_z}$	31 μW	
Calculated luminous efficacy	62.30 lm/W	

Fig. 39 *Quantities for second step of 2nd generation LED*

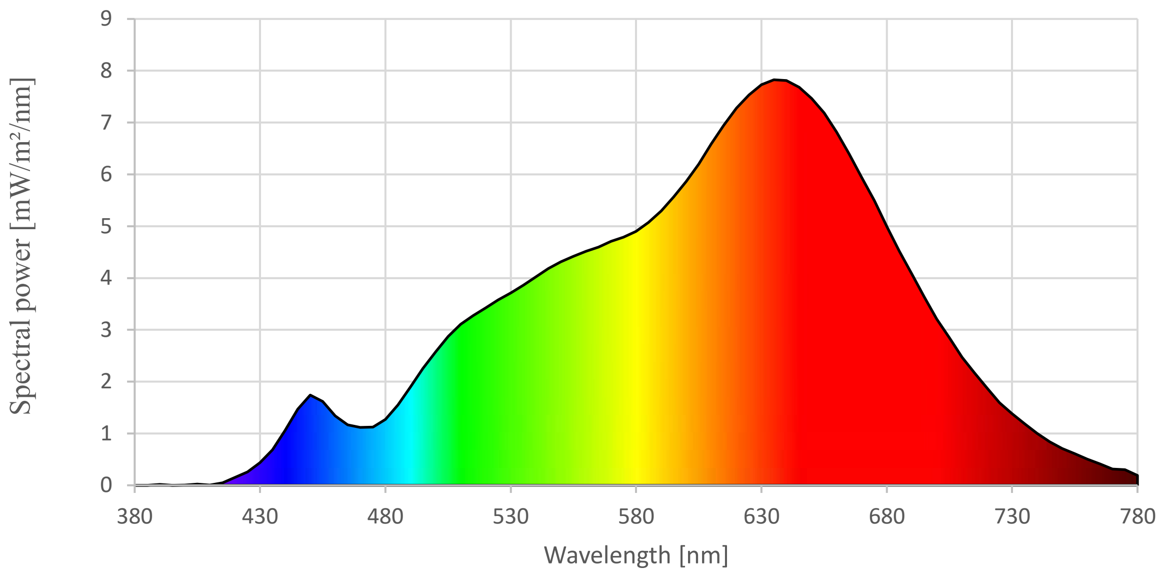

Fig. 40 *Spectra for second step of 2nd generation LED*

Measured quantities	GOSSEN MAVOSPEC BASE	GL SPECTIS 1.0 TOUCH
CCT	3941 K	4003
Duv	0.0026	0.004
CRI $(\boldsymbol{R_a - 8\ samples})$	97.46	96.3
CRI $(\boldsymbol{R_e - 15\ (14)\ samples})$	95.64	94.25 (14 samples)
R9 sample	94.79	92.1
Chromaticity coordinates *(x, y)*	x=0.385, y=0.3853	x= 0.3827, y= 0.3856
Measured Input power	7.35 W	
$\boldsymbol{E_z}$	45 μW	
Calculated luminous efficacy	72.6 lm/W	

Fig. 41 *Quantities for the third step of 2nd generation LED*

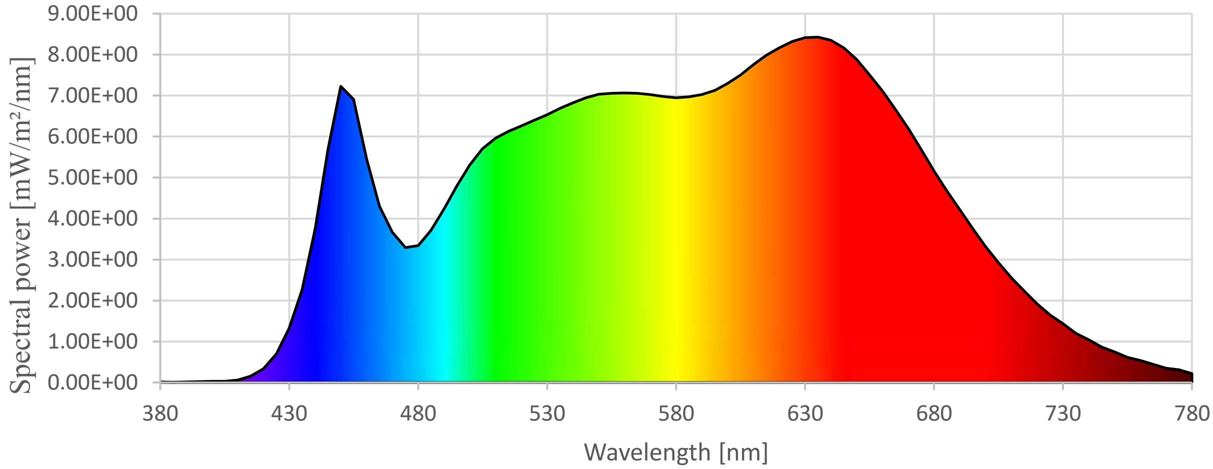

Fig. 42 *Spectra for third step of 2nd generation LED*

For second lamp, **3rd generation DEN LED**, according to the information of manufacturer, the CRI is improved and for first step of the light bulb, human skin looks more natural. The only major difference in the spectra of the lamp can be observed in the first step, therefore 2nd and 3rd step spectra will not be drawn again, because they are quite similar to 2nd generation lamps. However, measured values will give us better idea about the improvement:

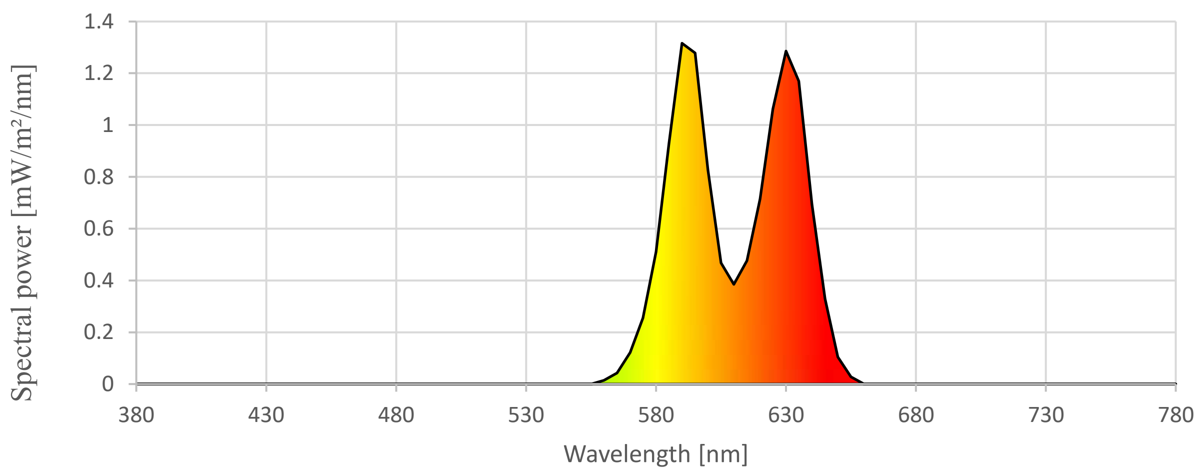

Fig. 43 *Spectra for the first step of 3rd generation LED*

Input Power	2.083 W
E_z	2 μW
Calculated luminous efficacy	11.38 lm/W

Fig. 44 *Quantities for the first step of 3rd generation LED*

Measured quantities	GOSSEN MAVOSPEC BASE	GL SPECTIS 1.0 TOUCH
CCT	2709 K	2756
Duv	0.0023	0.004
$\boldsymbol{CRI\ (R_a - 8\ samples)}$	97.22	97.6
$\boldsymbol{CRI\ (R_e - 15\ (14)\ samples)}$	96.89	96.98 (14 samples)
R9 sample	98.78	99.3
Chromaticity coordinates *(x, y)*	x=0.4631, y=0.4176	x=0.4598, y=0.4178
Measured Input power	5.75 W	
$\boldsymbol{E_z}$	32 μW	
Calculated luminous efficacy	65.99 lm/W	

Fig. 45 *Quantities for the second step of 3rd generation LED*

Measured quantities	GOSSEN MAVOSPEC BASE	GL SPECTIS 1.0 TOUCH
CCT	3961 K	4007
Duv	0.0009	0.002
$\boldsymbol{CRI\ (R_a - 8\ samples)}$	96.95	95.7
$\boldsymbol{CRI\ (R_e - 15(14)\ samples)}$	95.35	93.79
R9 sample	95.67	93.4
Chromaticity coordinates *(x, y)*	x=0.3828, y=0.3801	x=0.3812, y=0.3805
Measured Input power	7.15 W	
$\boldsymbol{E_z}$	47 μW	
Calculated luminous efficacy	77.94 lm/W	

Fig. 46 *Quantities for the third step of 3rd generation LED*

Obtained results were approximately same as it is provided by the manufacturer and revealed several facts for us, firstly, both lamps has excellent color rendering index. From the comparison of the same steps of the light bulb, it can be seen that, R9 (strong red) value and general CRI significantly increased in the 3rd generation LED lamp especially for 2nd step mode. Recalling our knowledge about the importance of R9 value shows that, it can be used in color-critical applications because of excellent CRI. CCT also increased for the lamps, however more important is the decrease of Duv (chromaticity distance) nearly twice which makes light looks more natural. When we look at the data table, we can realize that values for measured CCT and Duv is different, however when we are comparing these values with the data from manufacturers, we see that data from spectrometers are in the correct range and difference between values probably comes from different methods of calculation, because there several methods as it is described briefly before. Besides increasing of color quality, luminous efficacy of the sources also increased slightly and is in the acceptable range for LED sources.

4. Possibilities of quality improvement

Quality of the lighting sources are always main concern for both customers and manufacturers. Manufacturers were trying to improve mainly two components of light sources, namely color quality and luminous efficacy. These two quantities are not usually increased at the same time, the reason for this is coming from the luminosity function. As we described before, human eye doesn't perceive all colors with same sensitivity or roughly, brightness. Human eye are more sensitive in the narrow range (approx. 500-600nm) which means if light source has narrow spectra around this wavelengths, it will have higher luminous efficacy. However, the problem arise here is humans usually prefer white light for lighting purpose and emitted color from this narrow spectra contained mainly green and yellow colors are not desirable at all. In this case, we need to add more colors to the spectra to make it appear white to the human eye, which can be done by adding wavelength to the red and blue region of the spectra. As result, we will have wider spectra which is similar to daylight and will emit white light. Having wide spectra means that luminous efficacy will decrease because added wavelength are not as effective as green or yellow to create perceived brightness. However, adding small amount of those colors are not still desirable light for many of the customers, because they usually prefer warm-white color for daily usage, which means lower CCT and higher CRI, or simply a lot of red wavelength in the spectrum instead of blue color. If more red wavelengths will be added to the spectrum, consequently luminous efficacy will also decrease. The dilemma between color quality and luminous efficacy is the main issue about light sources so far, but some companies has announced that they are already able to get higher efficacy LED with good color rendering. In this chapter, we will describe briefly suggested methods for improving LED according to the information provided by manufacturer and discuss the customer preference for the quality of LED.

4.1 "Brilliant mix" technology by OSRAM

As it is discussed previously, commercially available LEDs are usually phosphor coated LED with blue LED chip. Conversion process of blue light to white light were done by phosphorus, however because of the quality of phosphorus and conversion losses, luminous efficacy was dropping off especially while adding red phosphorus to increase CRI and decrease CCT. Suggested method by OSRAM Opto Semiconductors company is to use new concept which is called "Brilliant mix" to obtain higher CRI with better luminous efficacy. This concept is the mixture of color-mixing technology and PC LED technology to create warm-white LED. In this method, instead of red phosphorus, Amber or Red LED used to improve color quality and combination of this chip with "EQ White" LED produce warm-white light around 2700K – 4000K. According to the explanation of manufacturer, "EQ White" LED is the combination of blue led chip and green phosphorus to create white light, and main advantage of this is the low conversion loss rate for phosphorus. The company claims that, luminous efficacy of this technology used lamps will be approximately 30% more than PC LEDs with similar color quality and power consumption parameters. Following diagram will show the representation of this method on CIE color space and it is mentioned that all the colors on the line between EQ White LED and Amber LED emitters can be obtained through this technology (Fig.47). [43].

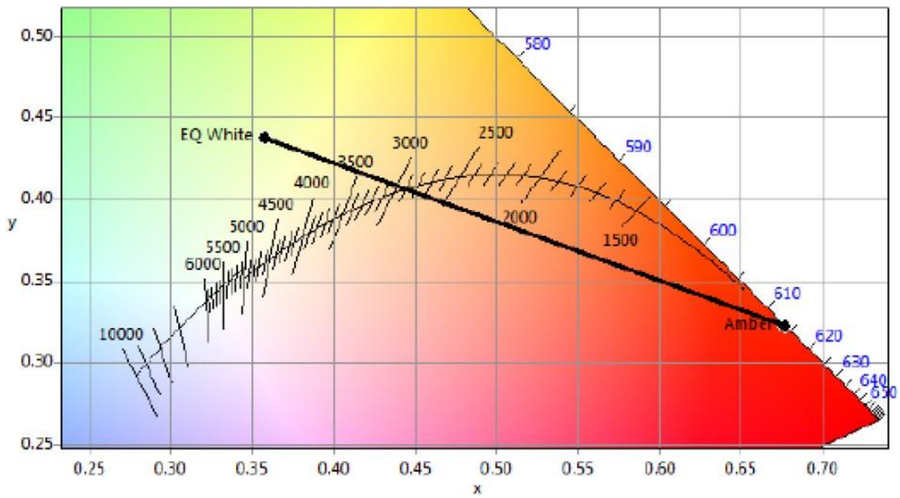

Fig. 47 *CIE color space for Brilliant mix method [43]*

Related CRI for different temperatures of white are described as:

Source	R_a	R_9	R_{13}
Brilliant Mix 2700 K	92	83	97
Brilliant Mix 3000 K	91	78	98
Brilliant Mix 4000 K	83	48	85

Fig. 48 *CRI values for different temperatures of Brilliant mix method [43]*

From the values and color space diagram, we can realize that, white color with different temperatures can be obtained through while adjusting chromaticity coordinates during production. While discussing about the advantages of this method, we need to know what are the disadvantages and challenging part of this method also. Manufacturer mentions two main disadvantages for this technology, first one is more complicated electronics and optics which is understandable because it is mixing of two technology and second one is decreasing of the higher luminous flux at operational temperature of LED in comparison to traditional one. And there are several challenges like, optical mixing of two technology (EQ White and Amber LED) and LED controlling to obtain desired color temperature, luminous flux and color point stability. [43]

This technology is still improving and maybe better CRI with even higher efficacy level can be obtained in the future.

4.2 Philips TLED prototype

Competition in the lighting industry is quite high and each company try to use different approach for increasing quality of the sources. Philips company in 2013 announced that they are working on the prototype of the TLED which exceeds 200 lm/W luminous efficacy which is approximately twice more efficient than current most efficient technology and can reduce electricity cost by 50%. emits warm-white light. They claimed that this technology has several advantages such as producing warm-white light with good color quality and less heat generation from LED which may simplify technology for cooling [44].

To produce white light, company uses the combination of red and blue LED chips and green phosphorus to convert some part of blue light to the green light which together generate warm-white light. Following diagrams from the manufacturers explain more detail about this technology:[44]

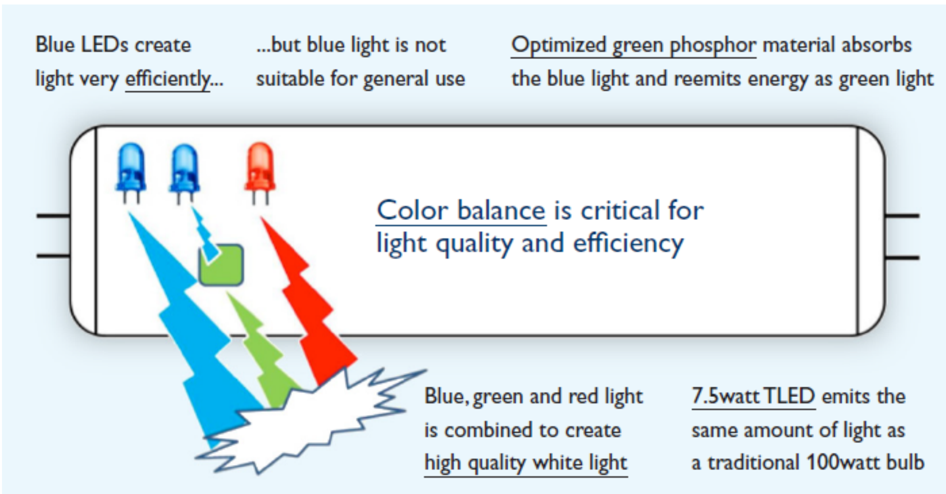

Fig.49 *General working principle of TLED Philips [44]*

Technical parameters	Philips TLED prototype
Luminous efficacy	200 lm/W
CCT	>80
CRI	3000-4500K

Fig.50 *Technical parameters for Philips TLED prototype [44]*

Because this model is still prototype, there is not many information about other characteristics of this technology, however our investigation shows that Philips already produced LED tubes with efficacy around 150 lm/W which shows that in near future tubes or lamps with higher efficacy can be produced. [36]

4.3 Quality improvement and customer preference of LED light sources

Improvement of quality of light is the main priority for lighting industry as well as customers, however the decision is up to the customer to choose between products according to the properties. Improvement in any technology is main goal, but usually increasing quality of light sources either increase the cost of product or decrease another property which affects the general quality. As it is described in this research, nowadays LED lamps come with high color quality with different modes in one lamp to give chance to the customer for choosing light, depending on the mood or the time of the day. On the other hand, some of the LED products comes with higher luminous efficacy but relatively poor color rendering. Improving phosphor types and mixtures, improving LED chips to get higher efficacy and proper mix of two commonly used technologies for white light generation are promising developments for LED industry. We have mentioned only two method for increasing quality, however many companies trying to get best quality LED, nevertheless they usually don't publish more detail about it. According to my investigation, common factor about this high quality technologies are high prices which is another criteria for the customers. It can be explained shortly as, if customer wants bright light without paying attention to the color quality, he or she will choose higher luminous efficacy lamps probably with lower price, which may be LED or fluorescent lamps while another part of customers wants lamp with higher color quality either for decorative lighting or daily usage and will not attach importance to the luminous efficacy rate or price. These real life assumptions shows dilemma of quality improvement of lamps also apply to the customer's decision. The ideal case for LED lamps will be high luminous efficacy lamp with excellent color rendering property and color temperature for convenient price which is not available still with the current technology. At the end of the day, it will always be customers' choice which will shape the future of lighting industry.

5. Conclusion

The main objectives of this research paper are:

1. To describe common technologies of white light generation with LEDs and explain working principle.
2. Giving brief information about photometric and colorimetric quantities and comparing luminous efficacy and color quality (CCT, CRI) of described white LED technologies.
3. Discussing possibility and conditions for increasing luminous efficacy and color quality of white LED sources.

There exists two main technologies to generate white light with LED sources which are color mixing and phosphor-conversion methods. For household lighting, generally phosphor-conversion WLEDs are selected, while for decoration or obtaining millions of colors color-mixing technology is desired. These mentioned technologies differs from each other from the point of color quality and luminous efficacy and these factors also determines the application area of these technologies. In this research paper, we have used some real life examples of LED sources and measured two LED sources with improved quality to have real data from LEDs to verify theoretical information. Our comparison for two technologies revealed that, luminous efficacy and color quality of PC LED technology is overtopping multi-color (RGB) LED and is available with excellent CRI and different modes on the market. However recent improvement of RGB WLED technology is also noticeable and several companies are trying to reduce the quality gap between technologies.

Main challenge of increasing the color quality and luminous efficacy is that these quantities can't be increased at the same time for different technologies because of the spectral distribution. To overcome this issue, manufacturers are proposing to use mixture of different color LEDs with proper phosphorus to have high luminous efficacy LED with good color quality. These proposals and possible improvement chances are discussed in the last chapter of the research.

To conclude, LED lamps have already dominated lighting market due to the superior color quality and luminous efficacy and still planned maximum values are not obtained yet which , hopefully, will come into fruition in the future.

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