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CIE Metrics to Discover Color Rendering of RGB LEDs

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Abstract : Good quality of light is a basic requisite in any commercial or domestic buildings. The Solid State Lighting due to its inherited property of color tuning has crossed the threshold of the market replacing conventional light source. A systematic understanding of performance of LEDs at different Correlated Color Temperatures (CCTs) is required to design tunable LED module. Optics in LEDs dictates the quality of light output from the luminaire. This paper brings out the outcome of the experiment conducted on multichip RGB LED at different CCTs. Color quality of the LED module is assessed using CIE TC1-90 recommended metrics.CollimatorPL119940 is identified as suitable secondary optics for LED luminaire that produces optimized spectral profiles with high color rendering index.

Keywords : Correlated color temperature, lumen output, spectral power distribution, CRI, color quality scale, color rendering index.

1. INTRODUCTION

The lightings in illumination are playing a vital role in color perception and color rendition of objects. The various conventional lamps are used in architectural building, retail and hospital lighting to enhance the ambience of the building and ease the operational/task services. The dynamic color tuning fails in conventional light source which is overcome by Solid State lighting technology (SSL)/LEDs.

The different shades of white light are achievable using LEDs. White light generation using RGB is more advantageous compared to the phosphor converted method[1], [2].This dynamic color blending has attracted LEDs towards application of daylight matching scheme. The challenges posed with LEDs integrated with dynamism arecolor point inconsistency, inconsistent lumen output and efficacy with rise in LED junction temperature.

Thermal management and selection of secondary optics are primary sectors to achieve effective color mixing.The Muthu et al. worked to generate the different shades of white light using temperature compensation technique, flux compensation and color compensation [3]. Temperature compensation technique used indirect technique for measuring junction temperature.The temperature of the heat sink and ambient temperature was measured and difference resulted in rise in temperature. Sun et al. [4] addressed the problem to minimize the color fringes using light pipe and a diffuser. The experimental outcome illustrated that the diffuser thickness and its positionidentificationresulted in uniform color.The light pipe length-width ratio is also an important criterion to improve color uniformity. The color uniformity can also be improved using addition components such as mixing rods, volume scattering, frosted glass, holographic and deterministic diffusers.Cassarly et al. [5] has investigated the color uniformity using mixer in which he observed that tapered mixer perform much better than straight mixer and suggested to use a diffuser

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with combination of short straight mixer along with tapered mixer to obtain effective uniformity in color. These color mixing techniques are applicable when distance between the illuminant source and object is very short.

The design of LED luminaire requires identification of the temperature dependent parameters. The parameters like lumen output or light intensity, spectral power distribution (SPD), peak wavelength, LED forward voltage are temperature dependent parameters. These parameters are controlled by feedback circuitry to achieve color point stability, constant CCT and lumen output.Improving the SPD enhancescolorrenderence, gamut area and wide spectral profile. The improved SPD in the range 446–477 nm in SPD finds its application in circadian lightings for regulating melatonin hormone[6]-[9].

The relative Spectral Power Distribution(SPD)of multichip RGB LED is given by

$$S_{R/G/B} = kS(\lambda_R, \lambda_G, \lambda_B) \quad (1)$$

Where k is proportions of relative SPD, λ_R, λ_G, λ_B refer to peak wavelength of red, green and blue LEDs[10].

A wide research is in progress to optimize SPD to obtain a high color quality for user satisfaction in residential, commercial and hospital lightings. Color mixing is a challenge in LED luminaire design. The color mixing depends upon position of the lens from LEDs and type of diffuser. Collimator is a secondary optics which comprises lens and diffuser in a single structure. Type of collimator used in color mixing effect the spectral profile and CRI of the LED module. Hence to build a LED luminaire proper choice of collimator is an important criterion which is addressed in this paper. In this paper an investigation is conducted to understand the performance of RGB LEDs at different CCTs from warm to cool. The investigation preferred CIE TC 1-90 metrics such as color rendering index (CRI),color quality scale (CQS) andCIEL**a***b**(CIELab)color space. Comparative analysis of color quality usingtwo types of collimators has helped in selecting a suitable secondary optics to build a complete LED luminaire. The experimental investigations are discussed in the remaining sections.

2. METHODOLOGY

2.1. Light source

CREE-MCE-RGB multichip LED is used to tune the color from warm to cool. The twelveSPDs were considered for the investigation. TIR collimator PL1590WI andPL119940 from Kathod optical solutions are the secondary optics under investigation. The details of the LEDs and collimators used in experimental investigation are listed inTable1 and 2. respectively.

2.2. Measuring Instruments

The experimental setup includes the integrating sphere of 0.5m diameterintegrated with Spectrometer SMS-500to capture SPD, Constant current Regulator omnidrive suite to control individual LED currents. ChromameterKonica Minolta CL200A is used to measure the light level and CCT.The experimentation is conducted in a dark room.

Table 1

Specification of LEDs

Color	*Wavelength(nm)*	*Lumen output(lm)*
Red	622	25.2
Green	535	54.92
blue	461	8.221

Table 2
Details of collimators used in experimentation

Details	*PL1590WI*	*PL119940*
Material	PMMA	PMMA
T_{op}	40^{o}C….85^{o}C	40^{o}C….85^{o}C
Total flux ϕ (lm)	350	170
Total illuminance (lux)at distance of 5m	28	22
Room temperature	25^{o}C	25^{0}C

2.3. Procedure

The test RGB LEDs aremounted in a integrating sphere. The spectrometer is calibrated as per IESNA standards to achieve accuracyduring measurement.The current levels are adjusted to obtain nominal CCT 3500K. At desired CCT, the SPD is captured byspectrometer.The captured SPDs are fed as input to theSylvania color simulator toolto extract details of CRI, CQS and CIELab of the test LED source. This routine is repeated for all CCTs from warm to cool. The same experimental procedures are repeated for two different types of secondary opticswhich are integrated to RGB LEDs.The block diagram of the experimental procedure is shown in Figure 1.

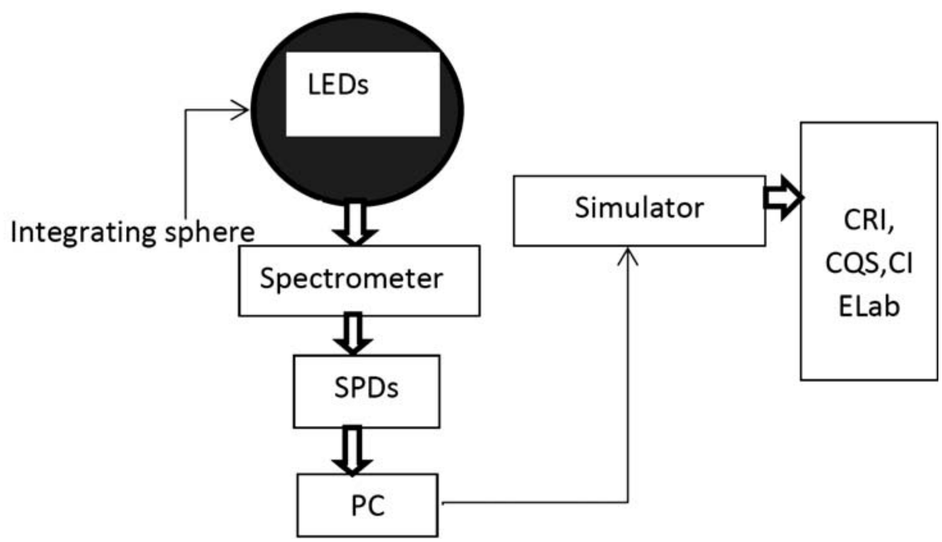


Figure 1: Block diagram of the methodology adopted for experimentation

3. RESULT AND DISCUSSIONS

3.1. Chromaticity distribution

CIE Technical Committee (CIE-TC) recommends, 1976 $u'v'$ uniform color scale (UCS) chromaticity diagram to observe more uniform distribution of chromaticity coordinates in the chromaticity diagram. The color rendering ability of light source can be predicted by thedistributed pattern of chromaticity coordinates in the CIE chromaticity diagram around the planckian locus. The tolerance limit for the deviation of Duv is followed as per seven step MacAdam ellipse which is ±0.006. The experimentation was initially conducted without secondary optics. Each LEDs current level was adjusted using a manual control, constant current regulator Omnidrive suite. The strength of the individual LED currents resulted in the light output with required CCT. The SPD of this experimental CCT is captured by spectrometer and processed using PC to evaluate the color quality metrics such as CRI, CQS and CIELab.

The Fig. 2(*a*) shows chromaticity coordinates are sparsely scattered around the planckian locuswithout secondary optics. The chromaticity distribution pattern is also achieved with two types of secondary opticsPL1590WI and PL119940. The Fig. 2(*b*) illustratesdistributionof chromaticity coordinates below planckian locus when secondary optics PL1590WI is integrated to RGB LEDs. The Chromaticity coordinates are more closely distributed near the planckian locus at the top region when secondary optics PL119940 is integrated to RGB LEDs as depicted in Fig. 2(*c*). This observation strengthens further to investigatecolor quality of RGB LEDs.

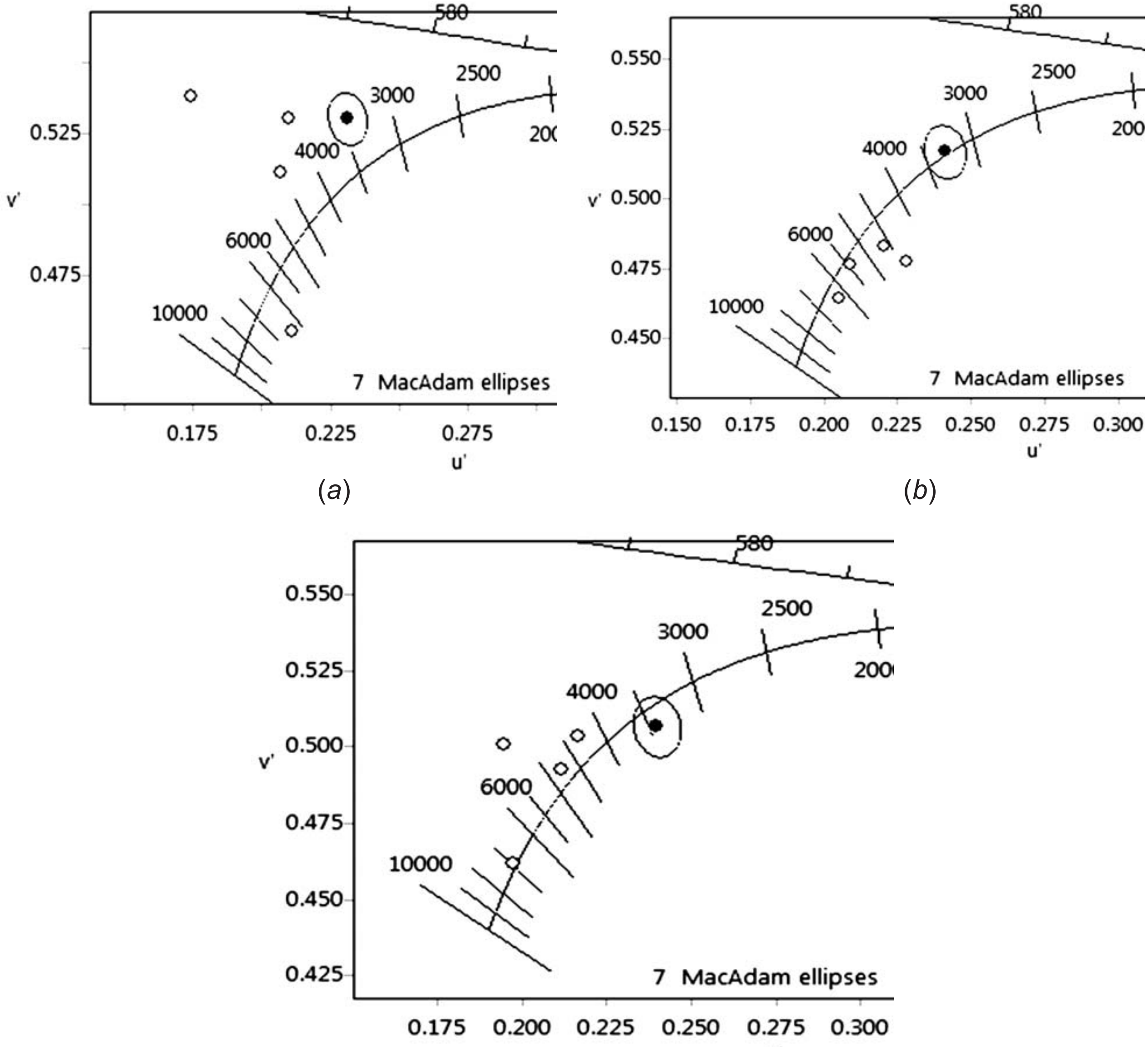
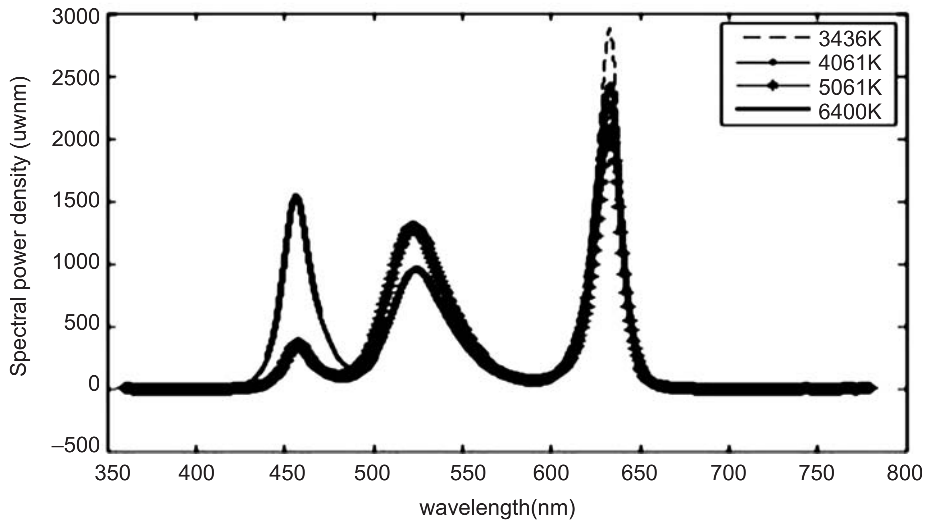


Figure 2: Distribution of *u′v′* chromaticity coordinates of RGB in 1976 UCS diagram (*a*) without collimator (*b*) with collimator PL1590WI and (*c*) with collimator PL119940

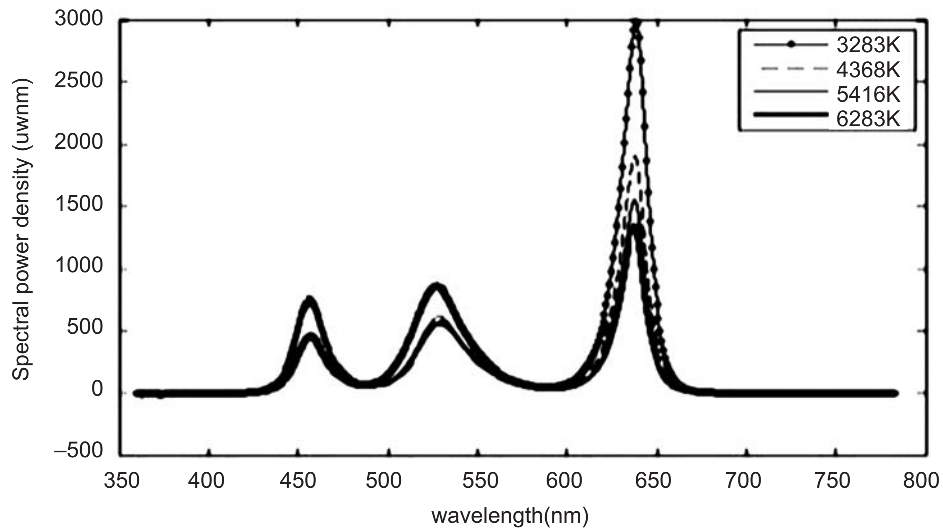
3.2. Spectral Analysis

The SPD profiles captured at each CCTs for settings with and without secondary optics is demonstrated in Fig. 3. The SPDs captured using secondary optics PL119940 shows a good spectral profile with wide spectral area and spectral peak amplitude as shown in Fig. 3(c). The blue wavelength region under secondary opticsPL119940 has higher peak amplitude compared to remaining SPDs. Hence this blue enriched spectrum is ideal for circadian lights. The colorimetric properties achieved during experiment is listed in Table 3. The nomenclature SPD3kwc indicates SPD captured at nominal CCT 3500K without secondary optics, SPD3KC1 indicates SPD captured at nominal CCT 3500K with PL1590WI collimator and SPD3KC2 indicates SPD captured at nominal CCT 3500K with PL119940 collimator and same is followed for remaining SPDs also.

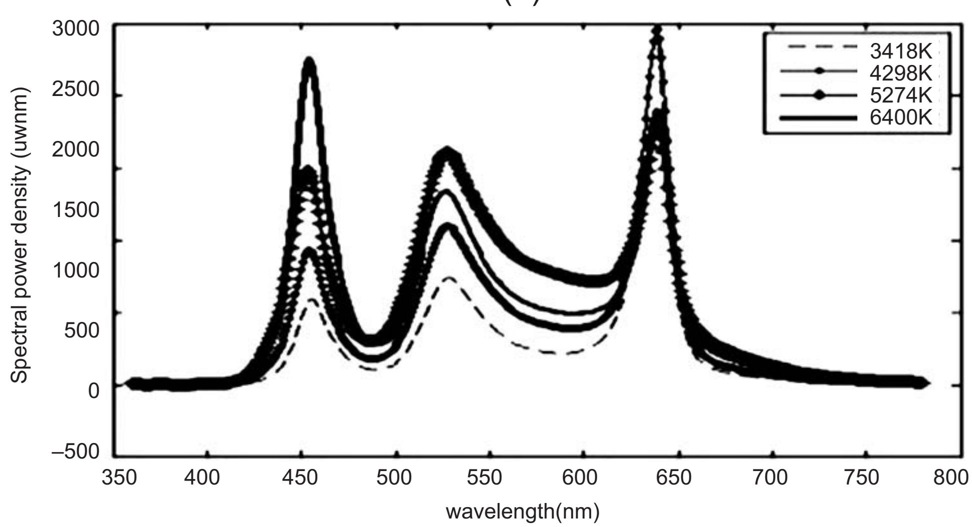
3.3. Color quality analysis



(*a*)



(*b*)



(*c*)

Figure 3: SPD of RGB (*a*) without collimator (*b*) collimator PL1590WI and (*c*) collimator PL119940

The color rendering capability of any light source depends upon how well the objects under test source reveal their true color. CRI is a traditional quantitative measure to evaluate the test source with respect to reference source. The red color is a one of the metric used to judge the color renderence of the light source. Light source with poor CRI makes red color to appear brown or dark of different shade. R9 is CRI index which quantifies the test light source for red colors. In the experimental investigation it is found the test RGB light source without secondary optics has negative scores for R9 at all CCTs. Using the collimator PL1590WI shows no much improvement. A significant improvement is obtained with collimator PL119940, R9has scored positive at CCT 5274K and also improved comparatively for remaining CCTs. The skin tone renderence under light source isanother important feature of CRI metric. Applications such as medical examination, critical care units, operation theatres depend much upon the skin tone color appearance under the light source. R13 is an index in CRI, which evaluates light source for skin tone. The commercial or residential lighting use nominal CCT of 4500K for routine work as per IESNA handbook (2009) [11]. Considering 4500K CCT as reference for the investigation. The good score of 80 for R13, average CRI score Ra 73 is obtained at 4298K, Duv0.0062, LER 297 with collimator PL119940.

Table 3
Colorimetric properties of the RGB LEDs obtained from the investigation

Type	*x*	*y*	*R9*	*R13*	*Ra*	*Vs7*	*Vs9*	*Qa*	*Duv*	*CCT(K)*	*LER*
SPD3kwc	0.4245	0.4327	-138	36	35	32	49	45	0.0133	3436	257
SPD3KC1	0.4193	0.3996	-197	24	23	17	45	42	0.0010	3283	268
SPD3KC2	0.405	0.3803	-99	54	53	51	75	69	-0.0046	3418	277
SPD4kwc	0.3959	0.4449	-123	53	47	50	65	50	0.0246	4061	322
SPD4KC1	0.3589	0.3339	-230	25	26	16	64	45	-0.0146	4368	255
SPD4KC2	0.3715	0.3842	-39	80	73	86	87	83	0.0062	4298	297
SPD5kwc	0.3539	0.4851	-62	75	64	74	73	53	0.0513	5061	348
SPD5KC1	0.3343	0.3388	-211	43	39	30	75	50	-0.0020	5416	267
SPD5KC2	0.3397	0.3882	94	87	85	87	89	90	0.0194	5274	323
SPD6kwc	0.3177	0.3046	-226	26	32	16	62	45	-0.0126	6400	257
SPD6KC1	0.3178	0.3202	-219	45	42	33	80	52	-0.0040	6283	262
SPD6KC2	0.3065	0.3192	-15	86	81	95	87	88	0.0013	6959	276

The CIE TC 1-90 recommended to use Color Quality Scale (CQS) to evaluate the LED light sources. CQS focuses on color preferences for user satisfaction. The primary colors green and blue which are VS7 and VS9 in test sample are tested using CQS. At nominal CCT 4500K scores obtained with collimator PL119940are 86 for green VS7, 87 for blue VS9, average CQS score (Qa) is 83at 4298K, Duv 0.0062,LER 297. The comparison plot of average CRI (Ra) and Qa is shown in Fig 4.a and b respectively.

The CIELab is another metric recommended by CIE TC 1-90 to evaluate colour rendering ability of test LED source[12]-[14]. ***Lab*** color space is a color-opponent space. The L indicates lightness ranging from 100 to 0, a* is x-axis whose positive score imply the colour is tending more towards red, negative indicate color is more towards green. Similarly b* is y-axis whose positive score imply the colour is tending more towards yellow, negative indicate color is more towards blue. In this investigation nominal CCT 4500k is considered for CIELab analysis. The reference lamp is inbuilt black body radiator in the color simulator tool.

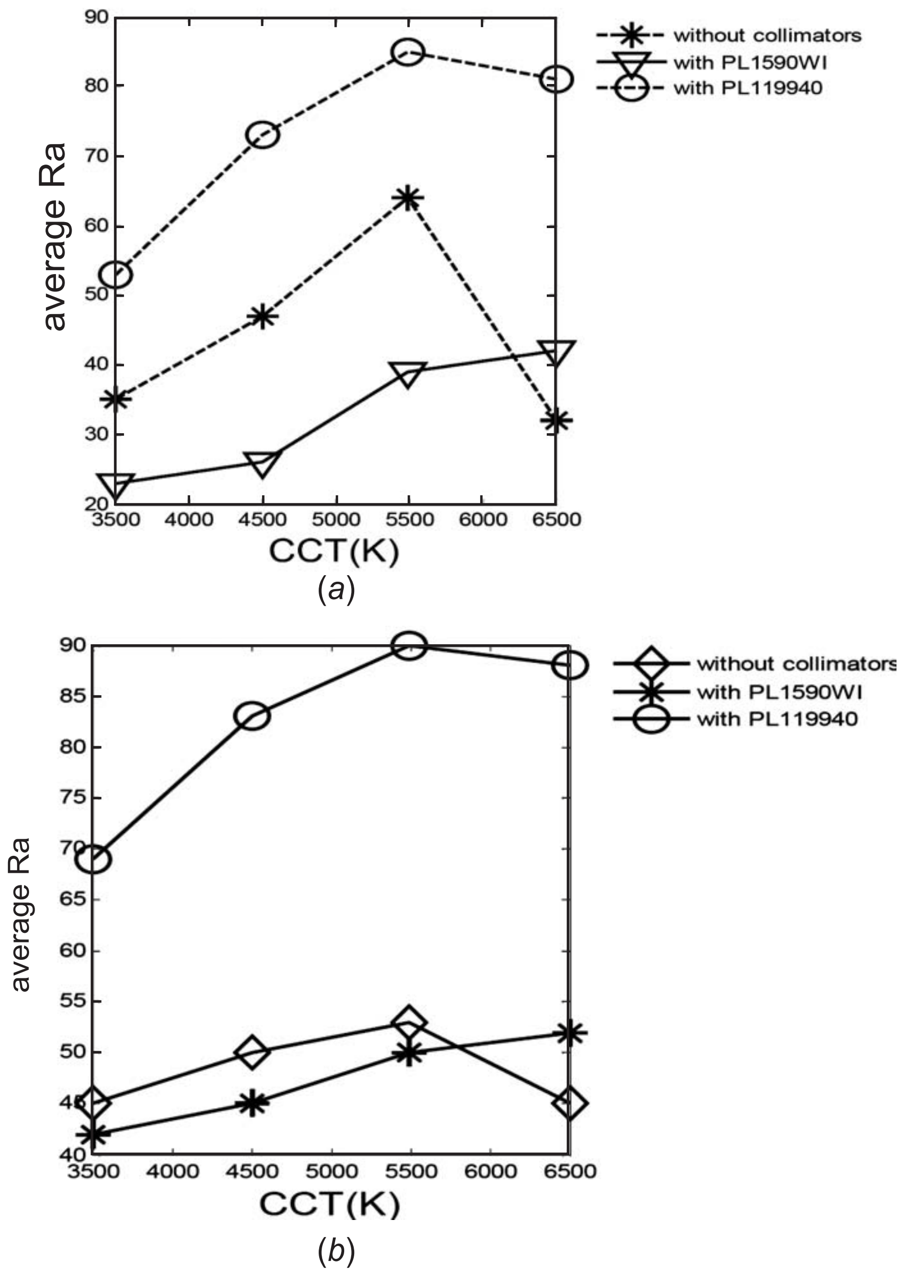


Figure 4: Comparison plot of (*a*) average CRI (Ra) and (*b*) average (Qa)

The RGB test lamps without collimator deviates away from the reference lamps as observed in Fig 5 (*a*) The plot with collimator PL1590WI has equal value for blue and yellow as represented by curve passing *b** axis and also equal values for red and green as represented by *a** axis. The disadvantage is it deviates away from the reference lamp as shown in Fig 5(*b*) The CIELab plot illustrated in Fig 5(*c*) is obtained for RGB test source with collimator PL119940 has its boundary close to the reference lamp. It is enriched with more yellow and equal proposition of red and green.

The CIELab metric gives more user based result with color perception and vision. RGB integrated with PL119940 gives one of the optimal solution for good uniform colour mixing and tuning.

4. CONCLUSION

This paper highlighted the investigation of RGB LEDS with and without collimators. This paper presented systematic analysis and choice of suitable collimators. The collimator PL119940 consistently performed well at all CCTs and CIE metrics.

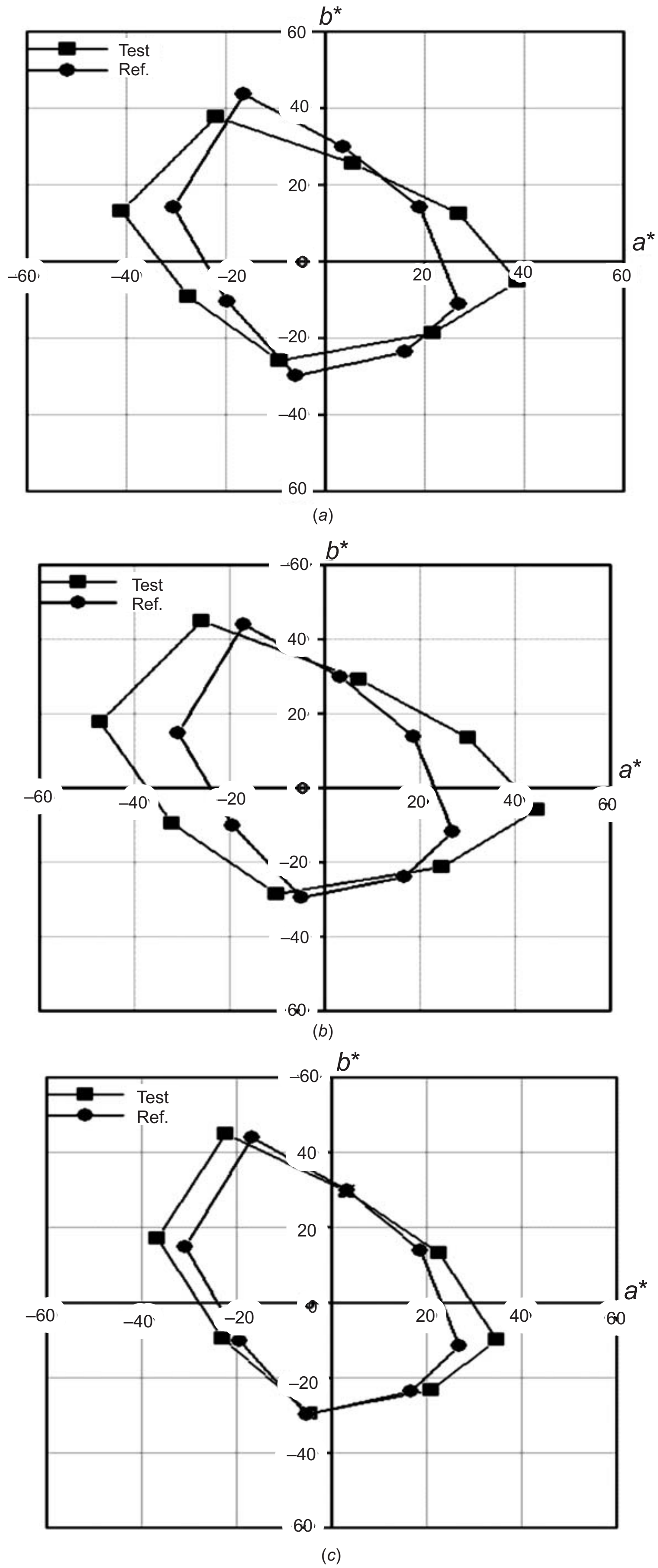


Figure 5: CIELAB pots for RGB (*a*) without collimator (*b*) PL1590WI and (*c*) PL119940

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