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# An Investigation on the Optical Characteristic of the Phosphor-Converted White Light-Emitting Diodes-Based Flash Light Source of Commercial Smartphone

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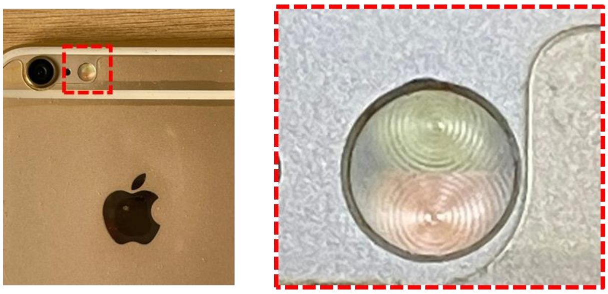
ABSTRACT

*We experimentally investigated and evaluated the optical properties of a commercial smartphone's phosphor-converted white light-emitting diodes-based flash light source. Four types of smartphone flashlights including Samsung smartphone, iPhone 6, iPhone 12, and iPhone 13 were selected for investigation. The emission spectra revealed interesting information about each type of smartphone's light source optical properties. The difference in emission bands between different flashlight lamps is clearly shown in the wavelength of the cyan blue region (490 nm) and red light emission (640 nm), respectively. The general color rendering index (CRI) for four types of smartphone flashlights including Samsung smartphone, iPhone 6, iPhone 12, and iPhone 13 were 69.1, 62, 91.7, and 95.5, respectively. In addition, there is an interesting relation between high CRI values for smartphone lamp's emission spectrum and Sunlight spectrum, a higher similarity to Sunlight lead to a high CRI value for emission spectrum.*



## 1. INTRODUCTION

The light source is an important component to make the smartphone more useful in human life. Along with the development of semiconductor lighting, the application of light sources on the smartphone become popular due to its advantages such as compact size, low energy consumption, and high luminous efficiency [1-4]. The application of light sources with white light emission on a smartphone is flexible, e.g. searching for things in the dark, providing light when taking photos at night, or using as a spotlight. The light source is mounted as close to the camera component of the smartphone as shown in Fig.1. It can be seen that the color of half of the circle is yellow while the rest of the circle is orange. The top of these parts are covered by two mini Fresnel lenses which control the light rays paths after they pass through these optics components.



(a) (b)

**Fig. 1.** (a) An design of a flash light on comercial flash light. (b) Enlarged photo of red dash line in photo (a).

For making white light, it can combine three types of color light emitting diodes (LED) red, green, and blue LEDs. However, this method showed some drawbacks such as requiring additional circuit design to operate these LEDs due to different forward voltages, drawbacks of color uniformity in spatial distribution, and drawbacks of requiring a large volume package [5-7]. Thus smartphone designers do not prefer to apply these light sources as light sources on smartphones. Another method for making white light is using the LED as an excitation light source to excite luminescence material which converts the absorbed excitation wavelength to a long and broad emission band. Such a light source based on this method is called phosphor-converted white light emitting diodes (pcW-LEDs). This method satisfies the criteria to become a good candidate for smartphone's light source applications, e.g. high luminous efficiency, compact size, spectrum controllable, high CRI value, and low power consumption. The principle for making white light based on this method is illustrated in Fig. 2. Making white light using excitation light source of blue LED and wavelength conversion luminescent material, e.g. the blue LED combines to one type of phosphor, or blue LED combines multiple phosphor types. For the method shown in Fig. 2(a), the luminescent material absorbs the excitation blue light and reemits radiation in the yellow region from 480 nm to 750 nm. A portion of unabsorbed blue light is transmitted through the luminescent layer to mix with the converted radiation in the yellow region. This mixing of light will cause a white light perception for human eyes. A similar method is shown in Fig. 2(b), the many types of luminescent material (e.g. cyan blue, yellow, red phosphors) absorb the excitation of blue light and reemit radiation in the yellow region from 480 nm to 750 nm. In this way, the radiant flux of radiation in region cyan blue light and red light will be much more than that in the method described in Fig. 2(a).

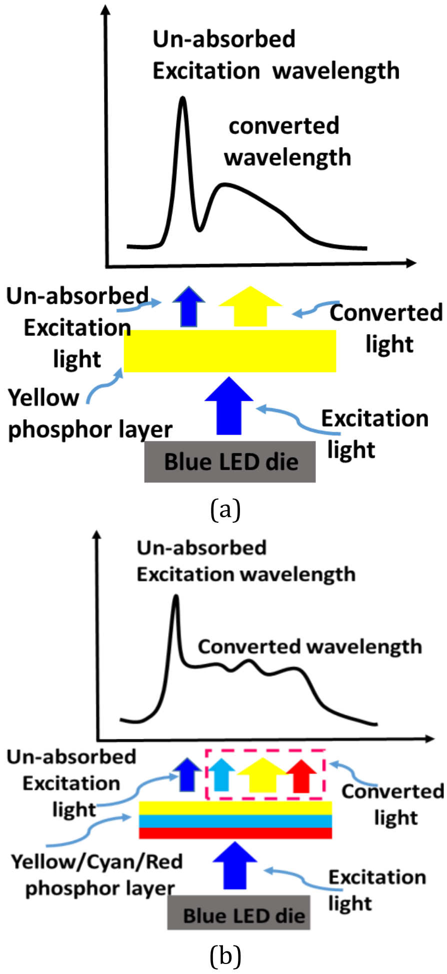



**Fig. 2.** Typical method for making white light using excitation light source of blue LED and converted wavelength luminescent material. (a) blue LED and one type of phosphor, (b) blue LED and multiple types of phosphor.

A photo of the light pattern of white light is shown in Fig. 3. It can see the white light of emitted light, some location close to the lamp it can see the yellowish color which is related ro the "yellow ring" effect of pcW-LEDs.

**Fig. 3.** Light pattern of white light that emitted from flash light lamp on smartphone.

Along with the development trend of intgration more and more function into smartphone. There are many studies focus on research related to the flash light source on commercial smartphone [8-17]. Vu et. al. has developed tools for characterizing the temporal and spectral profiles of smartphones (Apple iPhone 5s, iPhone 6s, iPhone 8, iPhone XR, and Samsung Note8 ) torch and flash emissions, and their dependence on phone power state [8]. Butler et. al. have investigated the effect of different smart phone models' s light sources on image quality which helps understand the feasibility of utilizing smartphone flashlights as an alternative endoscopic light source. The results indicated the iPhone 4 and iPhone 6 consistently underperformed in comparison to the Storz 11301D3 portable light source ($P < 0.05$). Galaxy S6, Galaxy S7, and newer generation iPhone 8 and iPhone X provide comparable pixel intensities to Storz 11301D3 portable light. Smartphones incorporate different types of light-emitting diodes. Newer Galaxy and iPhone provide adequate illumination for the endoscopic assessment of the airway when compared to commercially available portable light sources [9]. Fan et. al. conducted an investigation wherein the flashlight LED of the smartphone was studied and used as the light source for visible light communication (VLC). The encoding and decoding methods appropriate for the flashlight have been proposed and demonstrated. This VLC technique has been applied in the access control system, which is simple, reliable, convenient, and low-cost, and can be a supplement to the conventional access control system [10]. Baskoun et. al. studied the feasibility of using smartphones as an alternative light source in endoscopic procedures by comparing it to conventional light sources. The results have shown that the illumination is adequate, and the results obtained are satisfactory from the combination of an iPhone 6S [11]. Kimme et. al. have applied the advantages of flash light-emitting diodes (LEDs) of modern mobile phones which is the color gamut increase from their displays in recent years. The influence of this discrepancy on the color reproduction of smartphones is investigated based on the CIECAM02 color appearance model, and a metric introduced to judge the color reproduction of mobile phones under flash LED illumination [12]. Solyman et. al. have studied the characteristics of LED flashlights of a sample of smartphone types currently in use by ophthalmologists in Egypt to evaluate for potential photobiological implications when used in conjunction with + 20-diopter indirect ophthalmoscopy condensing lens for indirect photography of the retina. The LED flashlight of the tested smartphones appeared to be within safe limits when used for indirect smartphone retinal photography. However, the high composition of the short wavelength blue light spectrum may be a concern, particularly with prolonged and repeated examinations [13]. Pincenti et al. have conducted an evaluation related to LED-based flash solutions for use in a camera phone application. The performance of a given flash solution is measured in terms of color accuracy and signal-to-noise ratio (SNR), both of which are standard test methods used in industry. The measuring color accuracy and SNR provide an evaluation method that builds on developed techniques and provides a practical foundation for flash evaluation as it applies to the camera phone industry [14]. Liang et. al. reported a solution for fabricating an affordable, portable, and reliable point-of-care testing (POCT) sensor. Addressing this challenge, a smartphone-based visual POCT platform was designed by integrating the flashlight illumination and camera imaging functions [15]. Mondal et. al. have developed a stand for smartphone torches to check the applicability of smartphone torch-based light sources in microscopy. A developed smartphone torch stand with an optical diffuser can serve as an emergency light source in microscopy, which is a useful tool for settings with a frequent power outage [16]. In genneral, reports on evaluation of optical properties of flash light source on commercial smartphone is not available. It thus is interesting to fill in this gaps.

In this paper, we experimentally investigated and evaluated the optical properties of a commercial smartphone's phosphor-converted white light-emitting diodes-based flash light source. Differences in emission spectrum, color rendering index (CRI) were judged. These results provide general information on the state of the art of smartphone light source optical properties. They are helpful for interested researchers in improving the features and quality of light sources on smartphones.

## 2. PROCEDURE OF EVALUATION

To investigate and evaluate the optical properties of a commercial smartphone's phosphor-converted white light-emitting diodes-based flash light source, several samples of smartphone flash lamps from well-known branches of Samsung and iPhone have been selected including Samsung, iPhone 6, iPhone 12, and iPhone 13 which are shown in Fig. 4.


**Fig. 4.** Four type of smartphone lamp in investigation.

Optical properties are extracted from the measured spectrum by the spectrometer. The setup for measurement is shown in Fig. 5. Each lamp is placed close to and opposite the spectrometer. Each smartphone's flash lamp is turned and the emission spectrum is detected by a spectrometer, respectively. After finishing the measurement, the spectra were handled for further evaluation.

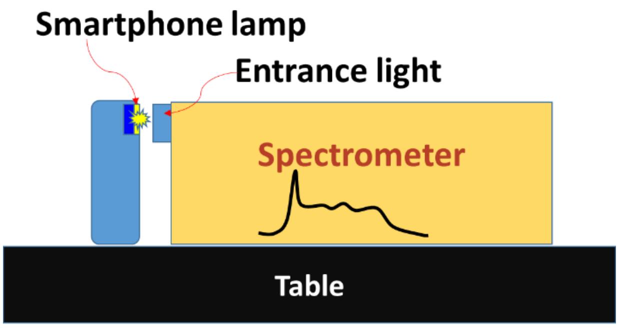



**Fig. 5.** Illustration of experimental setup for measurement of spectra (side view).

## 3. RESULTS AND DISCUSSION

### 3.1 Characteristic of emission spectrum

In general characteristics, all the tested smartphone's flash lamps showed a broad emission spectrum from 400 nm to 750 nm. These spectra include two sub-emission bands of a narrow blue emission band ( 400nm to 490 nm) and a second broad emission band (490 nm to 750 nm). The narrow blue emission band ( 400nm to 490 nm) is related to the unabsorbed excitation of blue light emitted from blue LED chips. The second broad emission band (490 nm to 750 nm) is converted wavelength by phosphor after absorbing the excitation wavelength of blue light. The difference in emission bands between different flashlight lamps is listed in Table 1.

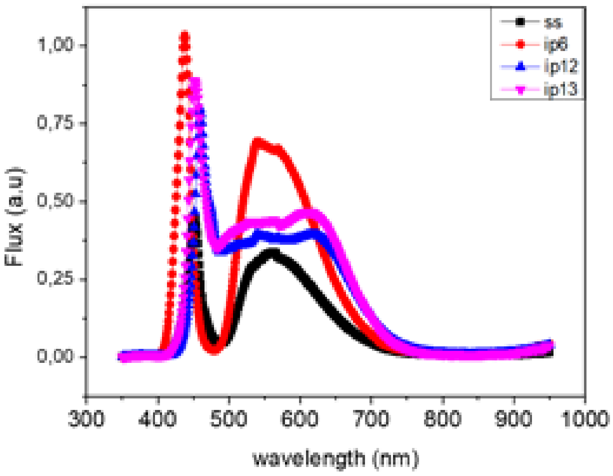



**Fig. 6.** Emission spectra of different smartphone.

**Table 1.** Difference of emission bands between different flash lamp light.

| Element | Smartphone type | | | |
|---|---|---|---|---|
| | Samsung | iPhone 6 | iPhone 12 | iPhone 13 |
| Intensity of Cyan blue (480 nm) | low | low | strong | strong |
| Intensity of Red emission band (640 nm) | low | low | strong | strong |
| FWHM of converted emission band (480 nm to 750 nm) | narrower | narrower | broader | broader |

### 3.2 Characteristic of color rendering index

The color rendering index (CRI) is a metric for color rendering evaluation [17]. The procedure for the calculation is, first, to calculate the color differences $\Delta E_i$ (on the 1964 W*U*V* uniform color space – now obsolete) of 14 selected Munsell samples when illuminated by a reference illuminant and when illuminated by a given illumination. The first eight samples are medium saturated colors, and the last six are highly saturated colors (red, yellow, green, and blue), complexion, and leaf green. The reference illuminant is the Planckian radiation for test sources having a correlated color temperature (CCT) < 5000 K, or a phase of daylight for test sources having CCT ≥ 5000 K. The process incorporates the von Kries chromatic adaptation transformation. The Special Color Rendering Indices $R_i$ for each color sample is obtained by

$$R_i = 100 - 4.6\Delta E_i \text{ , } (i = 1, \ldots, 14). \qquad (1)$$

This gives the evaluation of color rendering for each particular color. The *General Color Rendering Index* $R_a$ is given as the average of the first eight color samples:

$$R_a = \sum_{i=1}^{8} R_i / 8 \text{ ,} \qquad (2)$$

The score for perfect color rendering (zero color differences) is 100. Although "CRI is often used to refer to $R_a$, but the CRI actually consists of 15 numbers. CRI is the index to let us know how fidelity of color of illuminated object will be reflected.

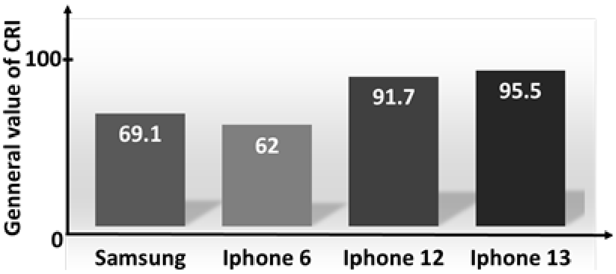



**Fig. 7.** Genneral color rendering index of different tested smartphone.

The color rendering performance of a source is determined by its spectral power distribution. High CRIs generally require a broad emission spectrum distributed throughout the visible region; the sun and blackbody radiation have a CRI of 100. Generally, for illumination purposes, CRI values of 70 are considered 'acceptable', and values greater than 80 are regarded as 'good' [17]. CRI of pc-WLEDs for generally lighting purpose is usually have value of 80.

Figure 7 shows the difference in general CRI for different tested smartphones. The general CRI for four types of smartphone flashlights including Samsung smartphone, iPhone 6, iPhone 12, and iPhone 13 were 69.1, 62, 91.7, and 95.5, respectively. The emission spectra of the iPhone 12, and iPhone 13 show higher values of general CRI values than that of the Samsung smartphone and iPhone 6. The reasons for this difference are mainly caused by the intensity of the emission band in the red band (at ~ 640 nm of peak emission wavelength) and cyan blue (at ~ 490 nm of peak emission wavelength) of emission spectra of iPhone 12, and iPhone 13 are significantly stronger than the cases of Samsung smartphone and iPhone 6.

For a clearer understanding of the difference in CRI value, each emission spectrum is further studied on the special color rendering index value. Figures 8 & 9 showed the difference in special CRI index for different tested smartphones. It is easy to see a significant difference in special CRI from the emission of smartphone flash lamps. The values of special CRI are extremely high for the emission spectra of iPhone 12 and iPhone 13. However, the values of special CRI are relatively poor for the cases of Samsung smartphones and iPhone 6. Especially, the value of the special CRI of R9 of Samsung smartphone and iPhone 6 are negative which causes a low fidelity rendering for red color. The value of R9 of iPhone 12, and iPhone 13 is still very (e.g. 94 and 95). This is a significant difference for the optical properties of the flashlight iPhone 12, and iPhone 13.

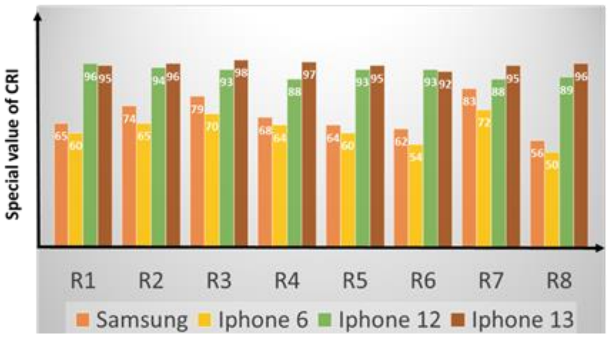



**Fig. 8.** Comparison of the special color rendering index value(R1-R8).

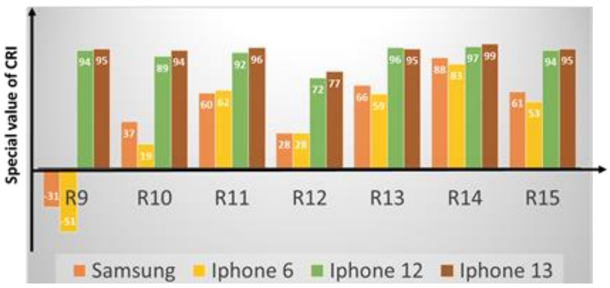
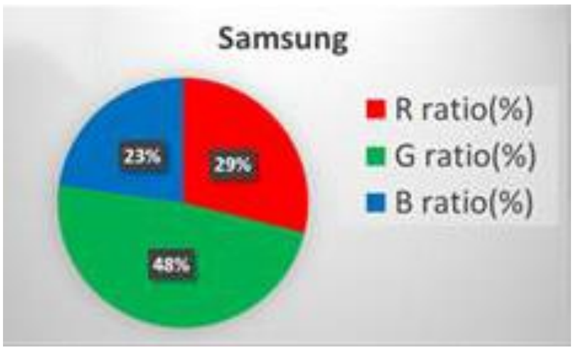


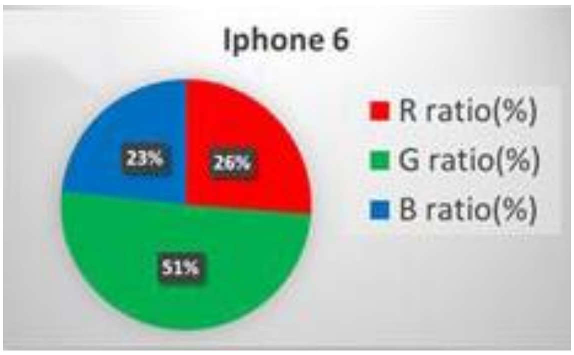

**Fig. 9.** Comparison of the special color rendering index value (R9-R15).

### 3.3 Characteristic of red/green/blue (R/G/B) percentage in emission spectrum

Figures 10 (a) &(b) show a similar characteristic related to the spectrum of Group 1 of Samsung smartphones and iPhone 6. Figures 10 (c) &(d) show the spectrum of Group 2 of iPhone 12 and iPhone 13 which shows a similar characteristic compared to each other. There is a difference between group 1 and group 2 in spectral composition. In group 1, the green emission ratio is dominant compared to the red and blue composition. however, the ratio is more uniform for each spectral composition in group 2. It should compared to the natural light emission spectrum of the Sun, the Sunlight spectrum is detected by a spectrometer (detected wavelength ranged from 350 nm to 950 nm), as shown in Fig.10(c). The ratio for each spectral composition in the emission spectrum of Sunlight is 45:27:28, which shows a more uniform distribution of each spectral composition. The percentage of 45% indiacates the emission spectrum of Sunlight contains a strong red emission composition. When compare the value of each composition of group 1 and 2 to that of the emission spectrum of Sunlight , The group 2 show a higher similarity to that of Sun light, while the group 1 show a big difference of each spectral componenent of R, G, B.




(a)

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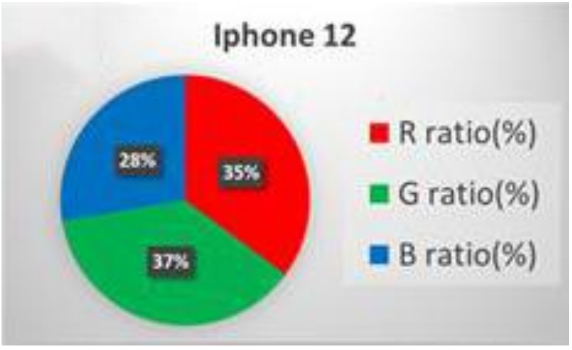
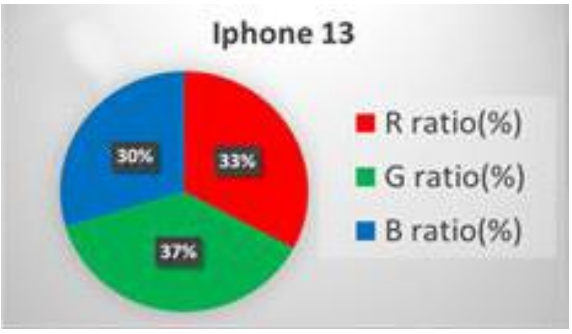
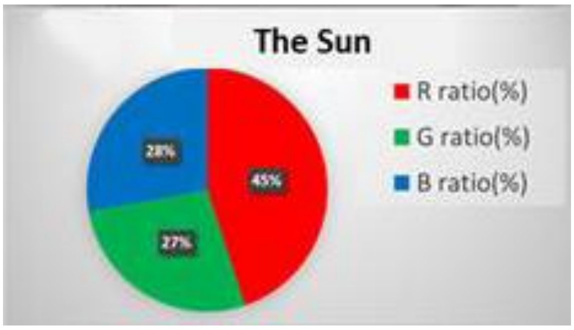



(c)




(d)




(e)

**Fig. 10.** Comparison in spectral composition emission of red, green, and blue (R/G/B) percentage.

### 3.4 Correlated color temperature

Color performance is an important of the light source [17,18]. The termilogy of Color temperature is used to described the relationship of a white light source with a Planck's blackbody radiator. At increasing temperature, it emits visible radiation in the red, orange, yellow, white and ultimately bluish white. If a light source generates a different spectrum from a blackbody radiator, a correlated color temperature (CCT) is used, which is an extrapolation of the light source to the color of a blackbody radiator of a given color temperature such that they appear the same color to the human eyes. CCT is given in Kelvin (K). Figure 11 shows the values of CCT of tested smart phone flash lamp which are stay in the range of 4701 K to 5504 K. It can see that the CCT values of all smart phone belongs to cool white type and genneralizes as 5000K±500K. For the pcW-LEDs, the CCT of out put light is controlled by the power ratio between excitation blue light (PB) and converted light by phosphor (Pc). The higher of blue light power lead to increase the value of CCT. It thus, the ratio power ($P_B/P_c$) in emission spectrum of the case iPhone 12 and 13, are higher than that of the case of samsung and iPhone 6. Because there is not significant difference in the CCT deviation range of 500 K, so CCT of smart phone show a similar color to the color of the Sun light as comparision to CCT of sun light.

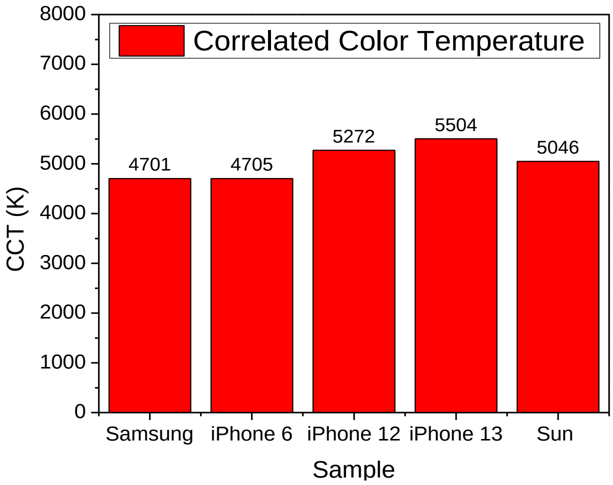
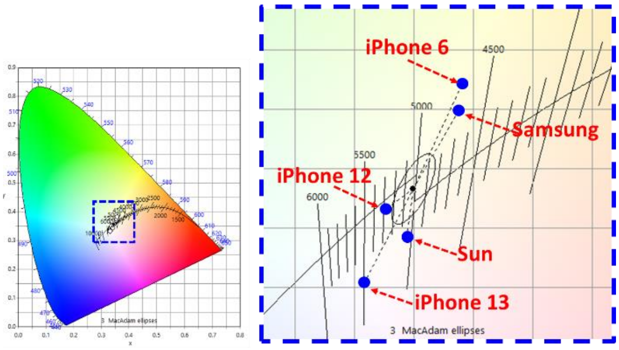



**Fig. 11.** Difference of correlated color temperature.

For a better visualation, it is necessary to visualize the CCT of white light in color space. Theoritically, CCT value can be determined by drawing a perpendicular line from the measured CIE chromaticity coordinates to the blackbody locus to obtain the (x,y) intercept. Then the CCT of white light would corresponding to the surface temperature of a blackbody radiator with the same (x,y) chromaticity coordinates. Figure 12 show the location of color point of emission spectra of tested smartphone and the Sun, respectively. Qualitatively, the Samsung and iPhone 6 smartphone type shows the location of the color point furthest from the black body locus curve. The reason is related to the power ratio of blue light and the light converted from fluorescent materials. In the case of iPhone 6, the amount of yellow light is more than the blue light, the color point location is far away from the absolute blackbody emission curve and towards the yellow light region in the color space. In the case of iPhone 13, the amount of blue light is more than the light converted from fluorescent materials, the color point location is far away from the absolute blackbody emission curve and towards the blue light region in the color space.




(a) (b)

**Fig. 12.** (a) Location of color point in color space, (b) Enlarging of the dashed rectangle in the Fig. (a).

Quantitatively, the deviation of the color coordinates from the black body locus curve is shown in Fig. 13. In general, the color deviation should be controlled to be as small as 0.005. iPhone 12 shows the smallest deviation, and iPhone 6 shows the largest deviation. Samsung shows an over deviation of 0.007. The color deviation of iPhone 12 and 13 cases are 0.02 and 0.05, respectively. In general, the color quality of iPhone 12 and 13 - output light is better than that of Samsung and iPhone 6.

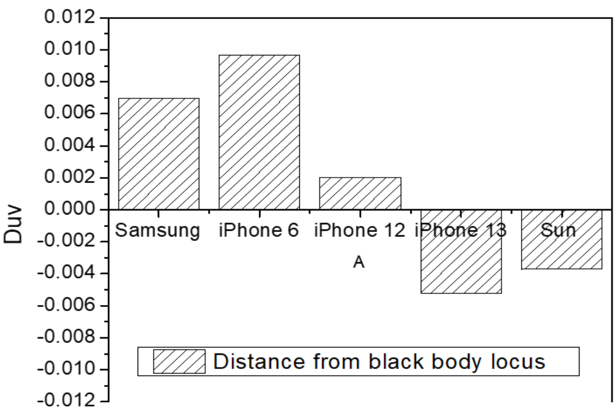
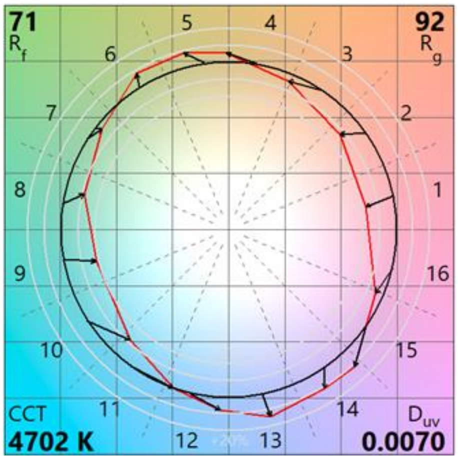


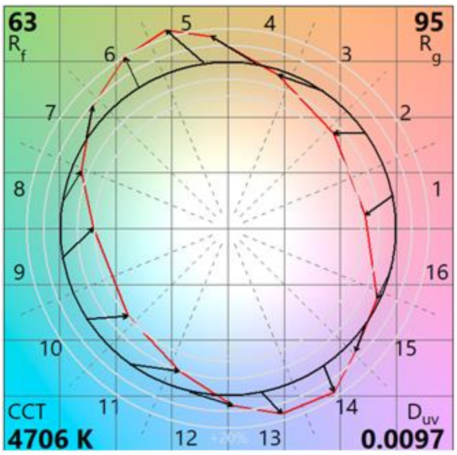

**Fig. 13.** Difference in distance from black body locus in CIE 1960 u-v space.

### 3.5 More on TM30-18 distortion graphic

Color rendition, or the influence of a light source on the color appearance of objects and surfaces, is an important part of lighting quality that arises from the spectrum of the emitted light, which is reflected by surfaces and processed by the human visual system. Poor color rendition can make the colors of objects look unpleasant or distorted, reducing environmental satisfaction and potentially influencing task performance. Importantly, luminous efficacy—another attribute dependent on a light source's spectrum—is maximized with very poor color rendition. Thus, all light source development must balance color rendition with competing performance characteristics, making accurate and thorough quantification of color rendition critical to optimization of performance and energy use. The ANSI/IES TM-30 Standards are an internationally accepted set of guidelines for characterizing the color rendition (color rendering) performance of virtually any light source, such as LEDs [19-22]. For a better evaluating light source color rendition, the ANSI/IES TM-30 method is appled in this study. Characteristics of IES TM 30 18 Color vector graphics of Samsung, iPhones, and Sunlight are shown in Fig. 14. As shown in Fig. 14 (a) and (b), Samsung, iPhone 6 shows the biggest distortion of Color vector graphics circular between its corresponding emission and reference spectrum. The significant distortion leads to a low-fidelity/low gamut property of all emission spectra. Thus, iPhone 13 shows a high overlap degree of Color vector graphics circular between its emission and reference spectrum. It indicates the best quality of output light for the tested smartphones. Figure 14 (e) shows a high matching of Color vector graphics circular between Sun light emission and reference spectrum.




(a)

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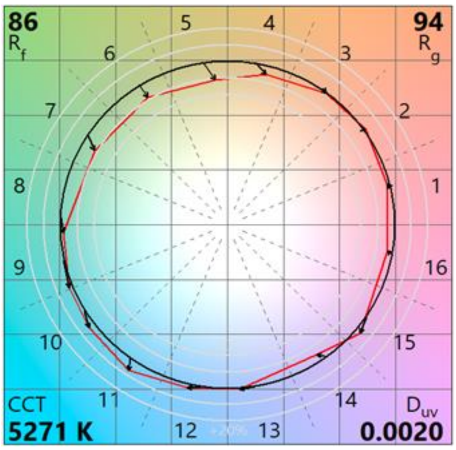
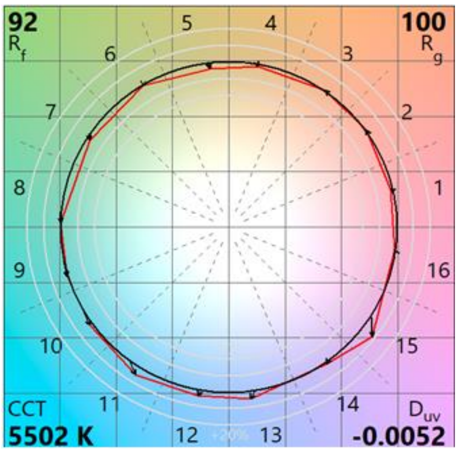



(c)

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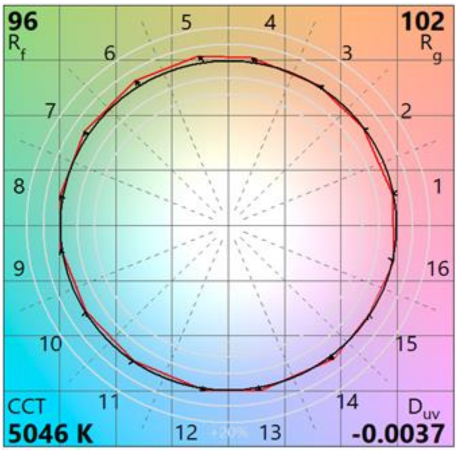


(e)

**Fig. 14.** TM30-18 distortion graphic of tested sample

## 4. CONCLUSION

In summary, we experimentally investigated and evaluated the optical properties of a commercial smartphone's phosphor-converted white light-emitting diodes-based flash light source including Samsung smartphone, iPhone 6, iPhone 12, and iPhone 13. The mission spectrum shows a significant difference in emission spectrum which causes a poor CRI for group 1 (Samsung smartphone, iPhone 6), and a high CRI for group 2 (iPhone 12, and iPhone 13). A comparison to the spectrum of natural light is conducted. When comparing the value of each composition of groups 1 and 2 to that of the emission spectrum of Sunlight, group 2 shows a higher similarity to Sunlight, and group 1 shows a big difference in each spectral component of R, G, and B. It thus indicates the emission spectrum should be modified to attain the best performance of output white light (e.g. high CRI, low Blue hazard threat). These obtained results provide a overview intervestigation on the state of the art of smartphone light source optical properties. They are helpful for improving the features and quality of light sources on future genneration of smartphones.

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