Red, Green, and Blue LED based white light generation: Issues and control

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***Abstract*—The recent improvements in high-power light-emitting diodes (LED) technology with 100+ lumens per LED chip and efficacy exceeding that of incandescent lamps, brings the solid-state lighting close to a reality. An LED light source made of Red, Green and Blue (RGB) LEDs can provide a compact light source with unique features such as instant color variability. However, the white light generation using many compact, discrete RGB light sources has the following issues: uniform spatial light mixing and distribution, white color point maintenance and thermal management. Specifically, the white color point maintenance is a stringent requirement in many applications. Meeting this requirement is a severe challenge due to the variation in the optical characteristics of the RGB-LEDs with temperature, time and forward current and the spread in the LED performance. This results in 1) an unacceptably high variability in white light color point and 2) difficulties in manufacturing reproducible LED lamps.**

In this paper, we highlight the issues that introduce the variability in the color point and present feedback control schemes to overcome these problems. We also show the results of experiments and theoretical modeling for practical control systems.

Keywords—LED; white light; color control; light sensing; color filters; tristimulus values

I. Introduction

Lamps based on high brightness red, green and blue (RGB) LEDs can produce nearly any color, including white light. The white light luminous efficacy of LED lamps is now in the range of 25-30 lm/W, and exceeds that of incandescent lamps. By the year 2005 they are expected to reach 50 lm/W, approaching the efficacy of compact-fluorescent lamps. RGB-LED lighting has the ability to change the color and dimming level instantaneously in addition to many other advantages such as long lifetime [1-2]. They therefore have great potential in many applications such as general illumination, LCD backlighting, and video projection.

There are two approaches to white light generation with LEDs: 1) phosphor based white LEDs, and 2) multi-colored LED solution – including RGB-LEDs. The RGB-LED solution has the advantages of variable color point and theoretically has higher efficiency than phosphor LEDs.

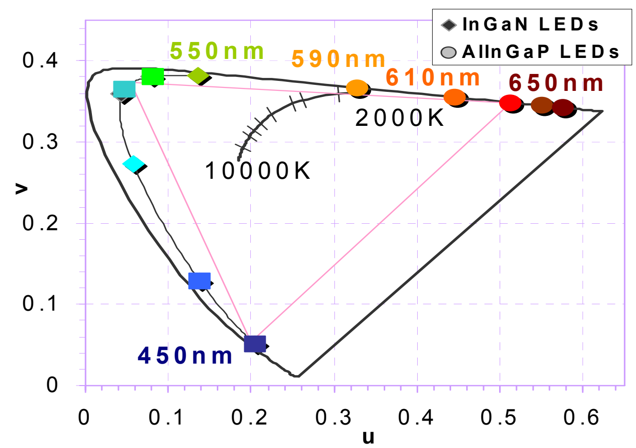

Figure 1. The 1964 CIE uv coordinate system showing the coordinates of InGaN and AlInGaP LEDs. It also includes the blackbody line over a color temperature range of 2000 K to 10000 K.

However, realization of RGB-LED white lighting has many challenges.

A requirement in white light applications is that lamps of the same type have the same color point. The color point may change with time or temperature, but lamps sharing the same history must all change in the same way. For example, it is unacceptable if all fluorescent lamps in an office are not the same color. It is also unacceptable if a LCD monitor displays a different white color point at different points on the screen.

LED characteristics are far less reproducible than conventional lamps. LEDs vary in lumen output and wavelength, and in their dependence on temperature and time. Since mixing one or more red, green and blue LEDs is creating white light, variation in one color (or one LED) can have a significant effect on the color point. In addition uniform spatial mixing of the light from a small number of high power LEDs is difficult to achieve. Great care must be taken to ensure that color uniformity over the spatial light distribution from the LED lamp is at acceptable levels.

In this paper we discuss the effect of the variation in LED characteristics on the color point stability of RGB-LED white light sources. We show that with suitable feedback control system it is possible to achieve white light sources based on RGB-LEDs that meets the requirements of an application. Two different feedback schemes are compared.

II. Issues with RGB LED based white light generation

The white light generation requirements for illumination applications are reported in [3] and summarized here. Figure 1 shows the CIE 1960 UCS color coordinate system (*uv*) [4]. It is commonly used to analyze just-noticeable-color differences. Figure 1 also shows the blackbody locus over the color temperature range of 2000 K to 10,000 K. Most white light applications require that the color point of the lamp lie on, or close to, the blackbody locus.

The human eye can detect changes in color temperature of 50 to 100 K near a 4000 K color temperature. In an area lit by multiple lamps it is therefore important that the color difference among the multiple lamps be close to the minimum-perceptible-color-difference (MPCD) [5]. The MPCD depends on the color. It can be represented by Δuv where,

$$\Delta uv = \sqrt{(u-u_o)^2 + (v-v_o)^2} \qquad (1)$$

(u,v) being the color coordinates of the light source, and (u_o, v_o) are the required color coordinates. This is the distance in (u,v) color space of the lamp from the desired color point. Fluorescent lamps are usually specified to be within $\Delta uv=0.003$ of the designed color point.

In applications such as LCD backlighting, where the light source is viewed directly, a color variation of $\Delta uv > 0.002$ on a white LCD screen may be unacceptable in high end application. Figure 1 shows the chromaticity coordinates obtainable with AlInGaP and InGaN LEDs. The area inside the triangle represents the achievable color coordinates in an LED lamp using 450nm Blue, 530nm Green and 650nm Red LEDs. Any color coordinate (including white) inside the triangle can be obtained by combining the appropriate amounts of light from the red, green and blue LEDs. Because the triangle obtained with phosphors in a CRT is smaller than the triangle of Figure 1, LCD backlighting and direct view displays can use LEDs to increase the display color gamut.

For white light applications, the individual RGB LED contributions can be varied instantaneously to change the color coordinates on the blackbody locus. This can be expressed by the following equations:

$$\left. \begin{aligned} u_m &= \frac{\sum_{n=R,G,B} u_n \cdot \frac{Y_n}{v_n}}{\sum_{n=R,G,B} \frac{Y_n}{v_n}}, \qquad v_m = \frac{Y_m}{\sum_{n=R,G,B} \frac{Y_n}{v_n}}, \\ Y_m &= \sum_{n=R,G,B} Y_n \end{aligned} \right\} \qquad (2)$$

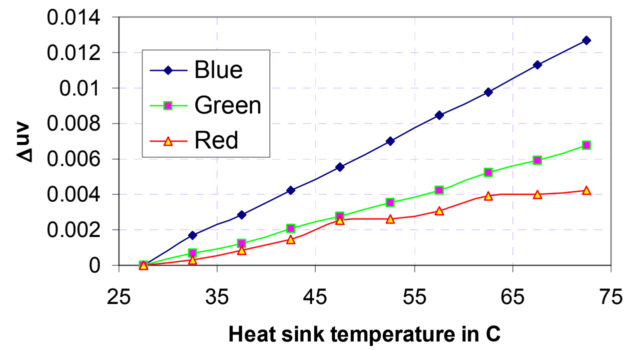

Figure 2. Measured color coordinate variation in 610nm Red, 540nm Green and 470nm Blue LEDs as a function of temperature.

Where, (u_m, v_m, Y_m) represent the color coordinate and the intensity of the mixed light, and (u_n, v_n, Y_n) represent the color coordinates and the intensity of the RGB LEDs. Thus by controlling the intensities (Y_n's), white light can be produced.

LED technology has increased the flux per package by a factor of 1000 over the last 30 years [2]. State-of-the-art high power production LEDs are available in 5W packages from Lumileds Inc. [6]. Nichia Corp. [7] produces 1W packages. The typical LED package size (with optical lens and heat sink) is about 10mm-by-10mm. A 5W LED from Lumileds can produce more than 100 lumens at 25 ^{o}C. The wall plug efficiency of the LEDs varies from 5-10% in InGaN Green LEDs, 20-25% in InGaN Blue LEDs and 30-40% in AlInGaP Red LEDs. Thus, 60 to 90% of input power is lost as heat, which is 3 to 4.5W in a 5W LED.

The increase in LED flux/package provides a compact, high intensity light source. However, the heat generated per unit area also increases. Therefore, white light generation using multiple, compact light sources must provide: 1) uniform spatial color mixing and uniform intensity distribution. 2) Color and intensity maintenance of the white light. 3) Thermal management. Mixing of the light from the discrete LEDs and intensity distribution are application specific and appropriate optical solutions are required. This subject will not be addressed in this article. Color and intensity maintenance is a common requirement in many applications and is discussed next. As we will show later, the thermal management directly affects the color and light maintenance of the lamp.

A. *Color and intensity maintanence issues*

Because the LED is a semiconductor device, many factors affect its light-emitting characteristics. Like any semiconductor, its energy band gap changes with temperature and current. This results in changes in LED spectrum and light output. Also, the LED manufacturing process is not sufficiently reproducible. As a result, the electrical and optical characteristics differ for nominally identical LEDs. When

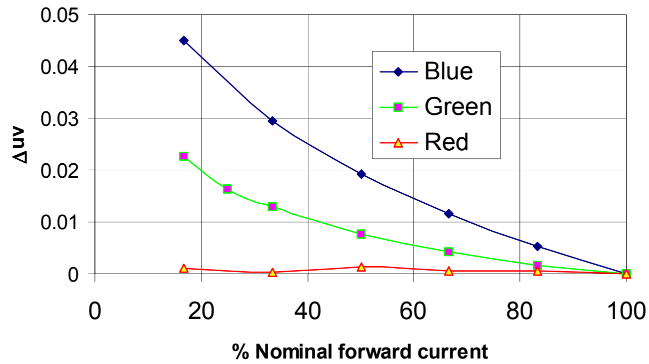

Figure 3. Variation in RGB LED chromaticity coordinates with the forward current at a constant heat sink temperature.

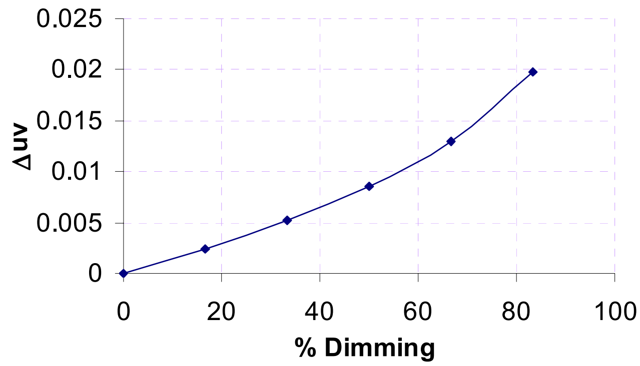

Figure 4. Measured variation in the D65 color point with dimming for RGB-LED.

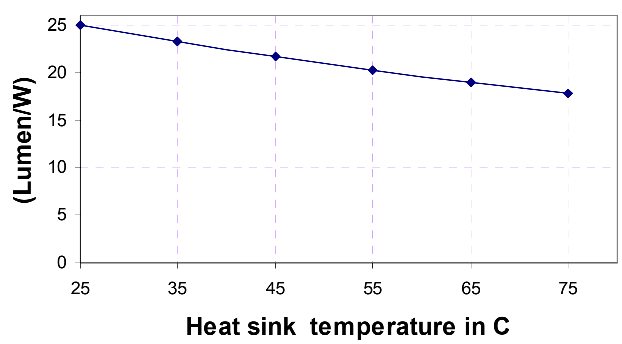

Figure 5. Degradation of white light lumen-per-watt with temperature.

white light is generated with such devices, the color point of the white light varies with temperature, forward current and time. The effects of the LED performance variation on the color and intensity maintenance of the white light are now discussed in detail:

1. Effect of temperature: The electrical power input to the LED that is lost as heat leads to a rise in the LED 'pn' junction temperature. The Red AlInGaP LED light output typically reduces by 10% for every 10 ^{0}C increase in temperature. The InGaN green and blue LED light output reduce by about 5% and 2% respectively, for every 10 ^{o}C increase in temperature[3]. The spectrum of the LED shifts towards longer wavelength with increasing temperature. Figure 2 shows the experimentally measured variation in color coordinates with temperature for red, green and blue LEDs. The blue LED has higher color point variation than the red and green LEDs.

The combination of intensity and spectral changes for a shift in temperature of 10 ^{o}C moves the color point by Δuv=0.005 at 3500 K (towards the blue-green). This shift is dominated by the large reduction in the Red LED light output.

2. Effect of aging: The light output of the individual LEDs changes over time [8]. In some cases, the LED light output increases from its initial output and later decreases. In general, the light output decreases in time and reaches about 50% of the initial light output at 50,000 hours of operation. Individual devices have considerable variability. This results in changes in the color point of an RGB-LED with time that cannot be predicted.

3. Effect of forward current: LED spectra shift towards shorter wavelength with increasing forward current. The resulting color point variation at a constant heat sink temperature is shown in Figure 3. The color point change in the red LED is negligible in comparison with the shifts in the green and blue color points. Without taking into account this considerably large effect for the green and blue LEDs, the color accuracy of the white point cannot be maintained when dimming the lamp, if amplitude modulation (AM) is used to control the LEDs. The variation in white point is calculated as a function of dimming level and is shown in Figure 4. This effect will be reduced if the LEDs are driven using pulse-width-modulation (PWM).

The RGB LED spectra shift towards shorter wavelength with increasing current is opposite to the effect of increasing temperature. Thus, if a control system were employed to regulate only the white light intensity, the controller would increase the amplitude of the forward current in order to compensate for a decrease in LED light output with increasing temperature. The current-dependent spectral shift towards the shorter wavelength would be partially canceled out by the temperature-dependent spectral shift towards longer wavelength, resulting in a smaller white point color error.

4. Spread in the performance of the individual LEDs: To accommodate for individual LED performance variations, LED manufacturers bin LEDs based on intensity and peak wavelength. Still, the performance of LEDs within a single bin varies considerably. For example, Lumileds' Luxeon LEDs in a single bin nominally vary in light output by over a factor of two [6], and the peak wavelength spread of Nichia's LEDs is 10 nm for one bin [7]. For cost reasons, LED manufacturers wish to avoid smaller bins. For the current bins, the result is that the white light performance of the RGB LEDs differs lamp-to-lamp, *i.e.* reproducibility of LED lamps is not possible, without using a feedback scheme. Suitable calibration at the factory for each lamp can only overcome

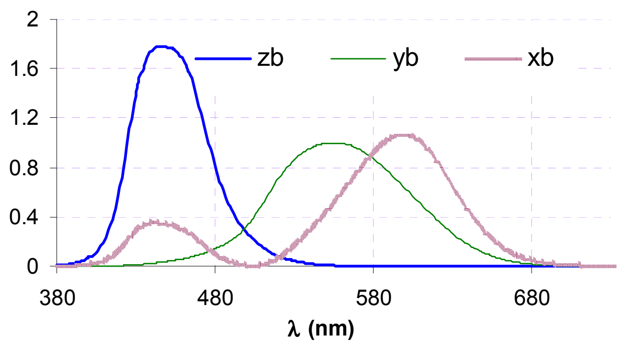

Figure 6. CIE 1931 color matching functions.

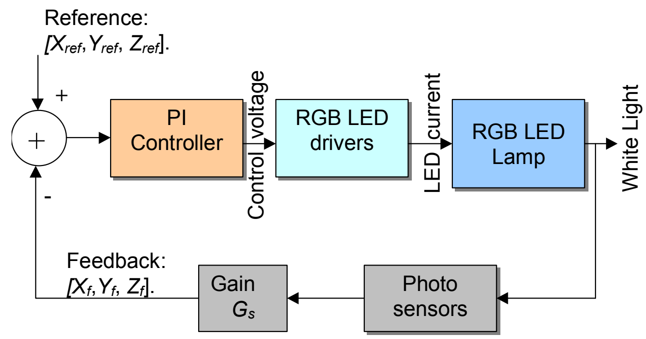

Figure 7. Direct white light control system employing sensors with responses matching the CIE 1931 color matching functions.

part of this problem. In addition, with time, the LEDs in a given bin do not change identically, resulting in additional LED-to_LED variation. Therefore, a simple factory calibration alone is not sufficient to guarantee color accuracy for the entire lifetime of the lamp.

B. Thermal Management issues

The luminous efficacy of the white light decreases with increasing temperature, as shown in Figure 5. For a 50 ^{o}C change in temperature, the white light efficacy can decrease by 25%. For energy savings and small color variation, the LED operating temperature must be kept low. However, when LEDs are housed inside applications such as an LCD backlit display, thermal management and ventilation of the LEDs are an issue.

Thermal management becomes more difficult with increasing power rating of the LEDs. The typical junction-to-case thermal resistance is more than 10 ^{o}C/W [2, 6, 7]. If the combined junction-to-ambient thermal resistance is higher than ~ 20 ^{o}C/W, the junction temperature in a 5W LED will exceed its maximum temperature rating, i.e. the LED needs to be operated at a lower power level. Achieving 20 ^{o}C/W at the application level will require good thermal management solutions.

III. Color and Intensity Maintanence solutions

A number of feedback control methods have been investigated [3] and can be separated into 1) compensation methods and 2) direct feedback control. Compensation schemes provide compensation for the white light variation due to the variation of junction temperature. In these schemes, the heat sink temperature is sensed to estimate the junction temperature and the corresponding LED color coordinates. The required RGB LED light outputs to produce the target white color coordinates are calculated using these estimates. Then the individual RGB LED light outputs are re-adjusted to produce the 'correct' white light. A photo sensor feedback is employed for this purpose.

A high degree of color accuracy is possible with this approach provided that the variation in the color coordinates of the RGB LEDs with the heat sink temperature is known accurately. Because the spread in LED performance is large, variations of the RGB LEDs' color coordinates with temperature for every individual lamp are required for accurate color control. Obtaining the RGB color coordinates as function of temperature for each lamp in the factory is expensive and time consuming. If the nominal temperature dependencies of the LEDs are used instead, the accuracy of the color control scheme will vary from lamp-to-lamp. [3]. Therefore, high reproducibility of the color control is not possible with the compensation scheme.

Wavelength-sensitive filters can be used to sense the variation in the peak wavelength of the RGB LED spectrum and estimate the color coordinates. Compensation schemes based on wavelength-sensitive filters can yield better color control accuracy [3]. However the implementation of the compensation systems has the disadvantage that it requires a complicated time-sequential drive method to sense the individual RGB LED light output [3]. In order to implement this, the LEDs must be switched on and off. The resulting rise and fall times of the current pulses due to the dynamics of the LED driver affect the measurement of the average value of the light measurements. The current ripple also affects the measurements. These factors reduce the color control accuracy.

A. Direct feedback control of white light using tristimulus values

Compensation methods yield an indirect control of the white light i.e. only the RGB LED light outputs are controlled. On the other hand, direct control of the white light is also possible. The color coordinates and the intensity of white light are represented by the CIE 1931 tristimulus values X, Y, and Z. In order to feedback these values, sensors with a spectral response that matches the CIE 1931 color matching functions are required. Figure 6 shows the CIE 1931 color matching functions [4, 5]. A set of sensors whose spectral response exactly matches the spectra shown in Figure 6 will output signals representative of the CIE 1931 tristimulus values of the incident light. The sensors can be made of multiple photodiodes each covered with an appropriate optical filter to represent the CIE 1931 color matching functions. Because the white light is sensed directly, this type of control does not

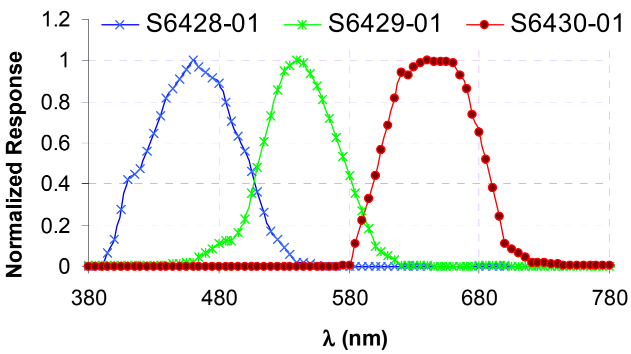

Figure 8. Normalized spectral response of the Hamamatsu integrated filter-photo diode color sensors.

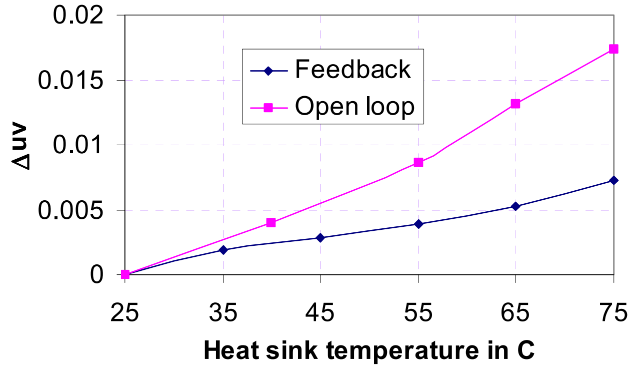

Figure 9. Color error as a function of heat sink temperature in for an open loop system and closed loop control system using color filters for feedback.

require a time-sequential measurement to sense the individual RGB LED light output. The color accuracy is not affected by the dynamics of the LED driver. Because the tristimulus values are used for the control, it can produce a reproducible control regardless of the effect of time, temperature and the spread in the LED performance.

Figure 7 shows the block diagram for the control system. [X_{ref}, Y_{ref}, Z_{ref}] represent the tristimulus values of the target white light and [X_f, Y_f, Z_f] represent the tristimulus values of the mixed light that are obtained from the sensor outputs. The gain matrix G_s converts the outputs of the sensors to the tristimulus values. These feedback values are compared with the target values and the errors are fed into a controller. A properly designed controller adjusts the RGB LED forward currents such that the error between the target and the feedback value reach zero under steady-state conditions. A high degree of color accuracy is possible with this approach.

A high degree of color accuracy for all operating conditions is only achievable if the spectral response of the feedback sensors perfectly match the CIE 1931 color matching functions. However, such sensors are expensive and are not commercially available at low cost. If non-ideal sensors are used, there can be errors in sensing the tristimulus values due to the mismatch between the sensor response and the actual CIE color matching functions. The color accuracy depends on how closely the sensor responses match the color matching functions.

For one operating temperature, the feedback system can be calibrated at the factory to overcome the problems caused by the mismatch between spectral response of the non-ideal sensors and the CIE 1931 color matching functions. However, this calibration process is only accurate for this particular temperature. For other operating temperatures, the color accuracy will decrease. For improved accuracy the effect of temperature can be accounted for. By sensing the heatsink temperature, a correction to the feedback gain coefficients can be made. Such a temperature feedforward scheme has to rely on nominal temperature coefficients of the LEDs. Otherwise an expensive factory temperature calibration would be required. This extensive calibration was performed for the control system results presented in [3]. In the next section, a more pragmatic approach of calibration at a single temperature is taken. We will show in section C that statistical analysis [3] can be used to assess the combination of all these effects on the color control accuracy of such feedback schemes.

B. Experimental system

The effectiveness of the direct white light control system is illustrated in this section. The white light source is constructed from four red, eight green and four blue LEDs. The LEDs are mounted on a heat sink using thermally conductive epoxy and the heat sink is attached to a heater and a fan arrangement to regulate its temperature. Three integrated optical filter-photo diode sensors from Hamamatsu Corp. (part no #S6428-01, S6429-01, S6430-01) are used to sense the white light. The normalized spectral response of the sensors is shown in Figure 8, which clearly does not match the CIE color matching functions. The white light source and the sensors were mounted inside an integrating sphere to provide ideal mixing of the light from the LEDs, which also ensures that the sensors see all the LEDs equally. The sphere is connected to a spectral lamp measurement system to measure the spectrum of the mixed white light.

The outputs of the sensors are supplied to a TI DSP TMS320F240 controller board, which performs the functions of the PI controller in Figure 7. The control board performs the sampling of the feedback signals, calculation of the PWM pulses and the generation of the PWM signals. It supplies the necessary PWM control signals for the regulation of the white light to three DC/DC converters. The DC/DC converters provide PWM current pulses to the LEDs.

The gain G_s, which is used to convert the output of the sensors (voltage signals) to the CIE tristimulus values, is initially calculated. For this, the system is initially set to produce the desired color point by adjusting the relative drive currents of the RGB LEDs until the spectrometer showed that the desired color point is reached. At this point, the sensor outputs represent the tristimulus values and the gain G_s is calculated. This process can be automated in the factory and the gain G_s can be programmed into the controller.

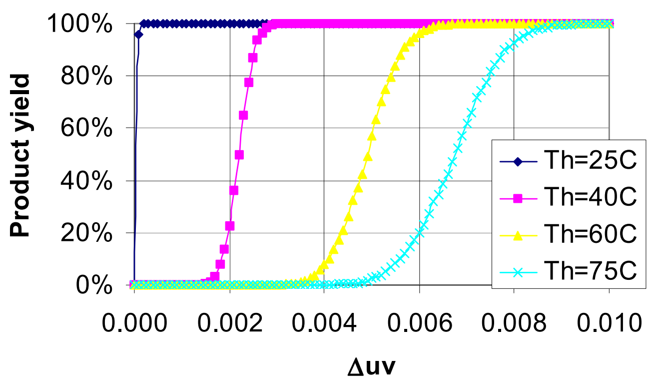

Figure 10. Product yield for RGB-LED based lamps using direct feedback control of the white light (without temperature compensation).

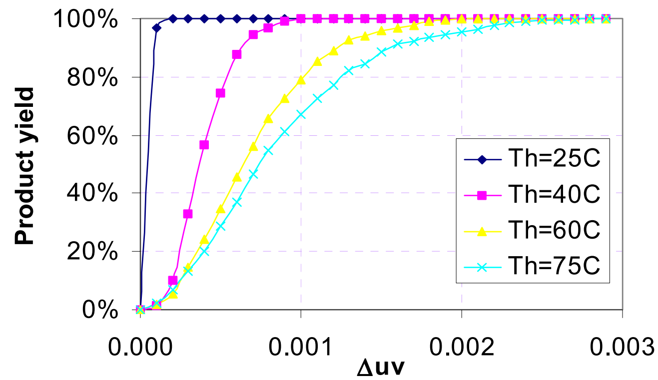

Figure 11. Product-yield for RGB-LED based lamps using direct feedback control of the white light together with a temperature feed forward system.

The experimental setup as described above is used to examine the performance of the feedback control system. Figure 9 shows the deviation in the white light with the heat sink temperature in open and closed loop control systems for a 6500 K white color point. The color variation in the open loop system of about 0.015 for a heat sink temperature change of 50 ^{o}C is reduced to 0.006 by the feedback system. (Note that this is significantly less accurate than the fully calibrated system of [3].) Even with the feedback loop closed, the color variation is relatively large for this range of heat sink temperatures. This is a remnant of the mismatch between the spectral response of the band-filtered photodiode sensor and the CIE color matching functions. No temperature feedforward compensation was used in this experiment.

C. Statistical modelling and analysis of product yield

The performance of only a single experimental test setup does not allow us to immediately draw conclusions on the performance of thousands of factory made lamps, as each lamp is built up of components which each have their own spread in performance. For this purpose we have developed a statistical simulation tool, (see [3]), that allows us to investigate the effect of the spread in the LED performance for various forms of direct white light control. This statistical tool is based on physical model describing an LED. The parameters that go into this model are Gaussian distributed, with nominal values and spread that correspond to the actual production distributions. Large numbers of lamps, ~ 10000, are constructed by randomly picking LEDs from these distributions. For each lamp, the feedback scenario under investigation is then tested for color and lumen accuracy, for a range of operating temperature. Figure 10 shows the corresponding product yield, or cumulative fraction, as function of color error Δuv, for the chosen feedback scenario. We assume that a factory calibration is done and the variation in color point at the calibration temperature is negligible. However, the color point systematically shifts with the temperature in all the products. The result shows that the maximum deviation in the color point in any product is about 0.008 for a heat sink temperature change of 50 ^{o}C. Furthermore, it can be observed that with increasing temperature deviation, the spread in color point of the products also increases. It is nice to note that the experiment and model are in good agreement as the model predicts a nominal systematic color error of 0.007 for a temperature variation of 50 ^{o}C, in close correspondence with the experimentally found value of 0.006.

The performance of the simulated control system was analyzed by incorporating temperature feedforward in the gain G_s (Figure 11). The results show that a higher degree of color control accuracy is possible with this approach: the systematic deviation of the color point with varying temperature has been removed. The spread in the color point increases with increasing temperature, due to the ever-present variations in the intrinsic properties of the LEDs. This last variation can only be overcome, if a temperature dependent factory calibration is performed for every single lamp, which is very costly.

The statistical model can also be used to evaluate different color filters.

IV. Conclusion

RGB-LEDs have enormous potential in lighting applications. The major issue to be resolved is control and maintenance of the white point. This issue arises from the variation in LED wavelength and lumen output with temperature, drive current and time. Further complications arise due to the wide spread in the performance parameters of nominally identical LEDs. In this paper we have presented solutions to these issues using electronic feedback control of the light output of the LEDs.

We have shown both experimentally and theoretically that photodiodes with color filters can be used in feedback systems to directly control the white light. Improved color control is obtained with the addition of temperature feedforward. This type of feedback system has the advantage of not requiring an extensive and costly factory calibration.

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