Colour temperature tuning to improve efficacy of white light

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Abstract

Quality of white light is always an aspect in lighting application. The white light produced may not be of good quality. Using the MacAdam’s ellipse we can produce light near to daylight quality. Using the colour mixing principle in RGB light source, the designed fixture uses a warm white and cool white chip on board LED. The correlated colour temperature and intensity of the lighting is varied using the PWM dimming method. ZigBee based wireless control transmission is used to transmit the PWM signals. Different white light is produced using this set up. The efficacy can be improved along with reduction in power consumption.

Keywords: Correlated colour temperature; efficacy; MacAdam’s ellipse; PWM dimming; colour mixing

1. Introduction

Light and colour has always amazed and attracted the mankind. After the invention of fire the concept of lighting changed on a whole. Then the evolution of lighting from incandescent lamp to the most modern LED lamps was a swift transition. Quality of white light has been in discussion ever since the modern technologies have arrived in the field of lighting. Colour mixing was the foremost principle used in obtaining the white light. The mixing of RGB colours to obtain different shades of white light was the basic technology used. By varying the colour temperatures of the RGB LEDs different white shades could be produced. This can be achieved by varying the proportion of the forward current of these LEDs. But we will require three separate drivers and PWM to drive these LEDs separately. This can be avoided by using a new combination of warm white and cool white LEDs. Here the green content is eliminated and we will have a mix of red and blue shades in the white light produced. The efficacy can be improved
by using this combination. The PWM will be used to drive the driver with a buck topology. The microcontroller will generate the PWM to adjust the duty cycle of the buck IC.

1.1. *CIE xy chromaticity diagram*

The theory of additive colour mixing was used for colour classification put forward by CIE. A tristimulus method is used for specifying the colour of light. Different humans have different perception towards different colour. It is always not same for two different people to perceive the same colour. The tristimulus value corresponds to the band-pass filtered chromaticity response of cones in the human retina [1]. The *xy* chromaticity diagram is drawn using the CIE colour system coordinates shown in Fig 1.

![Fig. 1. CIE *xy* chromaticity diagram](image)

The derivation of chromaticity diagram from spectral power distribution and the tristimulus value is shown in Fig 2.

![Fig. 2. Deriving CIE chromaticity from spectral power distribution.](image)

The retinal cones of the human eyes have one of the three sensitivities to dominate one of the primary colours. X, Y and Z are the trichromatic values [1].
2. Colour temperature control

When we mix white light with different colour temperatures we get a bouquet of white lights. The luminous flux obtained will be the sum of the white LEDs with different colour temperatures. By varying the drive current of these LEDs we can change the luminous flux and the colour temperature [2]. For the system using the warm white and cool white LED the relation between mixed colour and each colour of the LED should be determined [3]. According to colour mixing the chromaticity coordinate of the mixed light is the weighted linear sum of the individual chromaticity coordinates. The warm white cool white module colour coordinates can be calculated as follows:

\[
\begin{align*}
x &= \frac{\sum^n_{i=1} x_i y_k}{\sum^n_{i=1} y_k} \\
y &= \frac{\sum^n_{i=1} y_i y_k}{\sum^n_{i=1} y_k}
\end{align*}
\]

Equation (1) can be transformed into a system matrix

\[
\begin{bmatrix}
x \\
y_k
\end{bmatrix} =
\begin{bmatrix}
0 & 1 \\
-x_m & -x_m
\end{bmatrix}
\begin{bmatrix}
x_w - x_m \\
y_w - y_m
\end{bmatrix}
\begin{bmatrix}
x_cw - x_m \\
y_cw - y_m
\end{bmatrix}
\begin{bmatrix}
x_y - x_m \\
y_y - y_m
\end{bmatrix}
\begin{bmatrix}
x_{cw} \\
y_{ww}
\end{bmatrix}
\]

Equation (2) can be simplified as

\[
Y_k = [M] \ast [Y_{mix}]
\]

The unique advantages of solid state lighting (SSL) is that it open up a new dimension of lighting, called smart lighting, where lighting together with sensors create an intelligent networked control system to achieve new levels of functionality, efficiency, and performance [6]. The LEDs attract more attention because of its advantages such as long life, energy saving, ruggedness, free of mercury and so on [7]. These features help us in choosing a LED for colour temperature mixing as it can be advantageous than other sources.

3. Design of the hardware of the lighting system

The lighting system is designed in such a way that it produces different shades of white light. The colour temperature can be varied from 3000 K to 5000 K. The colour temperature can be tuned to the equivalent of daylight. The luminous flux is around 1000 lm. The aim is to obtain different shades of white light and to improve the efficacy along with a simple and minimal hardware.

3.1. Overview design

![Fig. 3. Schematic representation of the proposed system.](image-url)
Fig 3 represents the hardware design of the proposed system. The work is to integrate daylight inside a working environment using a warm white LED and a cool white LED. The correlated colour temperature of these LEDs vary from 3000 K to 5000 K. Using the PWM control method for adjusting the brightness and colour temperature of the light we can replicate the daylight inside a working space.

The required components are mainly the driver IC with a PWM port and a microcontroller. The wireless communication is done using the ZigBee 802.15.2 protocol. A colour sensor will be used to read the colour coordinates of the day light and will help to replicate the same inside the room. This system is simple in design and less complex to implement.

3.2. LED selection

The LED lights that provide the required CCT and flux should be selected for the application. The warm white and cool white LEDs should be selected to satisfy the required colour temperature. Here we select LEDs manufactured by Seoul semiconductors, whose basic characteristics are listed in Table 1.

Table 1. LED SELECTED (IF=350mA, Tc=25°C).

<table>
<thead>
<tr>
<th>Type No.</th>
<th>CRI</th>
<th>IF(mA)</th>
<th>VF(V)</th>
<th>CCT(K)</th>
<th>L(lm)</th>
<th>Efficacy(lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDW02F1C</td>
<td>70-80</td>
<td>350</td>
<td>37</td>
<td>5000</td>
<td>1780</td>
<td>136</td>
</tr>
<tr>
<td>SDW82F1C</td>
<td>80</td>
<td>2700</td>
<td>1440</td>
<td>110</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig 4 represents the relative luminous flux vs. the forward current of the selected LED.

Fig. 4. Relative luminous flux vs. forward current (Tc=25°C).

Fig 5 represents the forward voltage vs. forward current of the selected LED.

Fig. 5. Forward voltage vs. Forward current (Tc=25°C).
3.3. Driver selection

The driver IC selected to drive the LED is ILD4035, 350mA step-down LED driver from Infeneon. The driver is capable of driving high power LEDs with average currents up to 400mA. The IC includes a wide input voltage range and an internal power switch. The IC has a multifunctional control pin that enables us to control the brightness of LEDs by PWM or analog voltage dimming.

Table 2 shows the maximum ratings of the driver IC.

<table>
<thead>
<tr>
<th>Supply voltage(V)</th>
<th>Peak output current(mA)</th>
<th>Total power dissipation, $T_s\leq 85°C$(mW)</th>
<th>Junction temperature(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>550</td>
<td>1000</td>
<td>150</td>
</tr>
</tbody>
</table>

This driver is used to provide the required PWM to each of the LEDs to provide the required lux output along with the desired colour temperature. The IC is then integrated into an evaluation board for the suitable application as a LED driver. The circuit of developed evaluation board is shown in Fig 6.

![Fig. 6. Circuit of ILD4035 driver evaluation board.](image)

This driver is used to drive the LEDs. Two evaluation boards are made to drive both the LEDs separately. They provide a voltage up to 40 V and current is regulated between 50mA to 350mA.

3.4. Microcontroller PWM generation

The Arduino Uno uses ATmega328 as microcontroller is chosen for its low cost and less complex in programming. It has a 32 KB flash memory and can be programmed for various purposes at the same time.

The dimming duty ratios are calculated with the help of details from the LED datasheets. The duty ratios are made as a look up table for different colour temperatures and it is programmed to work as per the required colour coordinates. Table 3 shows the duty ratios required for different colour temperatures.

<table>
<thead>
<tr>
<th>SLNo:</th>
<th>Duty ratio 1(%)</th>
<th>Duty ratio 2(%)</th>
<th>Colour temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>61.42</td>
<td>0</td>
<td>3000</td>
</tr>
<tr>
<td>2</td>
<td>48.57</td>
<td>14.28</td>
<td>3500</td>
</tr>
</tbody>
</table>
4. Experimental setup

The flow chart of the overall setup will give you an idea on how the whole device is built. The flow chart is shown in Fig 7.

![Flow chart of the overall setup](image)

The whole experimental setup was designed and implemented to obtain the various shades of white light. The overall experimental setup is shown in Fig 8.

![Experimental setup](image)

The experimental setup contains the lighting fixture of two LEDs along with the microcontroller and the wireless communication protocol, ZigBee. The two driver evaluation boards to drive the LEDs are also packaged in the setup.

The powering of the circuit is done with a DC source of 37 V supply to operate the LEDs. The current is controlled from 50 mA to 215 mA in order to obtain the required colour temperatures.

The variation in the white shades of the light is obtained using the above setup. The colour temperature is varied between 3000 K and 5000 K.

5. Results

The colour temperature mixing was obtained by controlling the current to different drivers depending upon the lumen required by each light for obtaining a particular colour temperature. Two drivers will be working at different current ratings at the same time to produce a particular colour temperature. The colour mixing done here is from 3000 K to 5000 K. This is from warm white (evening light) to cool white (day light).
Fig 9 shows the variation from 3000 K to 4000 K. The 3000 K is in the range of warm white and 3500 K is between warm white and neutral white. The colour temperature of 4000 K is the neutral white shade. The variation from warm white to the cool white temperature is visible with the naked eyes. The colour rendering is better for warm white colour temperature, i.e. for 3000 K colour temperature. The proper colour rendering of the objects is obtained in warm white lighting. The warm white lightings are usually used for commercial purposes such as in textile shops and jewellers shop.

Fig 10 shows the colour temperature variation between 4500 K to 5000 K. The variation is between daylight and cool white. 4500 K is near to daylight and 5000 K is almost cool white.

The variation of different colour temperature and the efficacy for different colour temperatures were obtained from this experimental setup. The efficacy improves as the colour temperature increases and the colour rendering improve when the colour temperature decreases.

The efficacy of the different shades of white light is shown in table 4.

<table>
<thead>
<tr>
<th>SLNo</th>
<th>Colour temperature (K)</th>
<th>Efficacy(lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3000</td>
<td>59.76</td>
</tr>
<tr>
<td>2</td>
<td>3500</td>
<td>65.23</td>
</tr>
<tr>
<td>3</td>
<td>4000</td>
<td>68.46</td>
</tr>
<tr>
<td>4</td>
<td>4500</td>
<td>70.61</td>
</tr>
<tr>
<td>5</td>
<td>5000</td>
<td>73.38</td>
</tr>
</tbody>
</table>

The efficacy is the highest for 5000 K but we require the daylight and the light will be run mostly in the daylight region. In the daylight region, 4500 K, the efficacy is 70.61% which is still on the higher side. Fig 11 shows the graph for CCT versus Efficacy.
6. Conclusion

The experimental setup for producing different white shades was developed and implemented. The efficacy of the lighting was improved. The same fixture can produce different shades of white light which help in saving the space along with providing a convenience of changing the colour temperature without changing the fixture. This setup can be further modified and implemented with the smart lighting for smart homes along with energy saving buildings.

References

[1] LED Color Mixing: Basics and Background, CREE.