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DEVELOPMENT OF CCT TUNABLE LED LIGHTING SYSTEM USING RED-BLUE-WHITE LED

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ABSTRACT

This study proposed a CCT tunable LED lighting system, which comprises of Red-Blue-White (RBW) LED luminaire, LED driver and Dimming-controller-unit (DCU). Here, first RGB LED at different intensity was blended with Warm-White (WW) LEDs to produce variable CCT. To achieve higher CCT than WW colour, it was found that only blue LED blended with WW LEDs is sufficient. On the other hand, for lower CCT range, red LED mixed with WW LEDs is enough. This new algorithm is capable to produce CCT ranging from 2700K to 9723K. Measured maximum deviation from set point value was found 18K for Red LEDs and 344 K for Blue LEDs blending respectively. The LED driver is designed to operate in voltage protection mode and in current control mode for a typical dimming cycle. The current control mode is implemented using an op-amp based PI (proportion-integral) controller.

Keywords: DCU, LED driver, RGBW LED, current control, PWM dimming, variable CCT

1. INTRODUCTION

Due to rise of energy price researcher are trying to develop new technology and lighting systems to utilize the electrical energy efficiently [1]. Now a days Light Emitting Diode (LED) gradually becomes a popular alternative light source over all other conventional light sources because LEDs are very energy efficient, start instantly, operate in cold temperature, have very low UV emission, as well as long life, compact size, light weight, breakage resistance, again they are easily controllable and environment friendly [1, 2,13] also.

To save electric energy, artificial light may be integrated with natural daylight. The colour of the artificial light source should match with that of natural daylight. The CCT of day light varies throughout a day, starting from 2000 K at sunrise through 5000 K for direct daylight at noon and can exceed 10 000 K in overcast conditions [3]. So, to create an exact visual sensation colour tuneable artificial light source should be introduced for daylight harvesting. Apart from daylight harvesting, colour tuneable light source may be used for mood lighting, which affects the emotional feeling of human [4].

It is well known that the three primary colours of visible light red (R), green (G) & blue (B) can be mixed to get a wide range of colours. In some of the previous studies, monochromatic RGBY (Red-Green-Blue-Yellow) LED was mixed to get different colour combination of white light [3]. But CCT of monochromatic light cannot be measured and CRI of the produced light is also poor. In this study RGB LED at different intensity is blended with Warm-White (WW) to produce variable CCT. Finally an algorithm is proposed to vary the CCT using only red and blue LED with warm white LED.

2. RGBW LED LIGHTING SYSTEM

The experimented RGBW (Red-Green-Blue-White) LED lighting system consists of one Dimming-Controller-Unit (DCU), four LED drivers and a RGBW LED module. The four LED drivers are used to drive each of the LED string at four independent current. The DCU is responsible to generate four independent PWM duty ratios, which will ensure four independent current through each LED string. A block diagram of the developed system is shown in Fig. 1.

2.1. Basics principle of CCT control

The basic principle of the CCT control can be explained by CIE1931 (x, y) chromaticity diagram, any colour sensation can be represented by a couple of (x, y) coordinates. The colour temperature of a light source is the temperature of an ideal black-body radiator that radiates light as comparable with white light source. Lower the CCT value (2700K-3000K) is called warm white and higher the CCT (5000K-6000K) is called cool white.

Grassman law states that the superposition of colour is a linear phenomenon. So, when colour coordinates (x_k, y_k) of n primary emitters are known, any colour coordinates (x, y) lies inside the CIE1931 colour space diagram can be defined by eqn.(1) and eqn.(2) [5]. Y_K is the luminous flux of primary emitters.

$$\frac{\boldsymbol{x}=\sum_1^n x_k \cdot \frac{Y_k}{y_k}}{y=\sum_1^n \frac{Y_k}{y_k}}, \tag{1}$$

$$\frac{x=\sum_1^n y_k \cdot \frac{Y_k}{y_k}}{y=\sum_1^n \frac{Y_k}{y_k}}, \tag{2}$$

2.2. Prototype luminaire design

Placement of RGBW 3528 LED strip on the bakelite board is shown in Fig.2. Each LED string has 14 number of parallel path and each parallel path consists of 3 series connected LEDs.

3. DESIGN OF LED DRIVER

In this article a switch mode power supply (SMPS) based LED driver is designed using fly-back topology and the hardware circuit has been implemented on a printed circuit board (PCB). Linear power supply has a poor efficiency as semiconductor device operates in active region. By switching (either ON or OFF) of active devices the efficiency of the converter can be made high than the linear power supply.

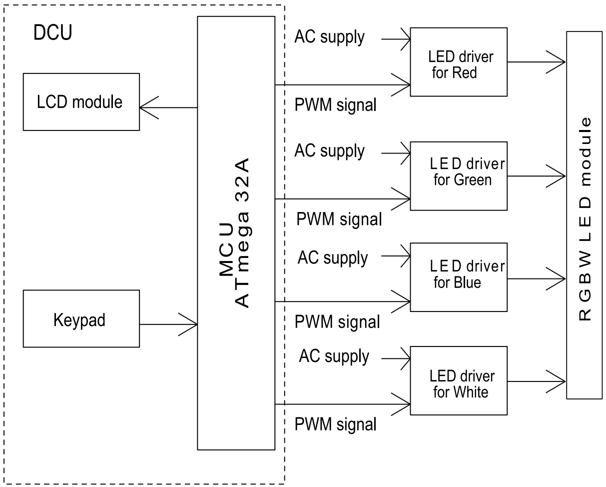

Fig.1. Block diagram of CCT controllable LED lighting system

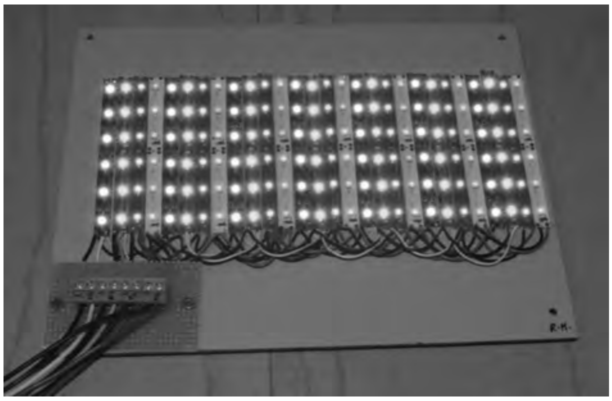

Fig.2. Prototype of RGBW luminaire

MOSFET 2N60 is used as a switching device which is 2A, 600V N-channel MOSFET.

3.1. Principle of designed LED driver

At first AC power is converted to DC by using rectifier, and then the DC is converted to the desired level of DC to drive the LED using a high frequency switch & a transformer. The logical block diagram of LED driver is shown in Fig.3

The self-oscillating fly back converter is a popular circuit for cost-sensitive applications due to its simplicity and low component count [6]. A detailed design-oriented steady-state analysis and a small-signal model of the self-oscillating fly-back converter has been found already [6].

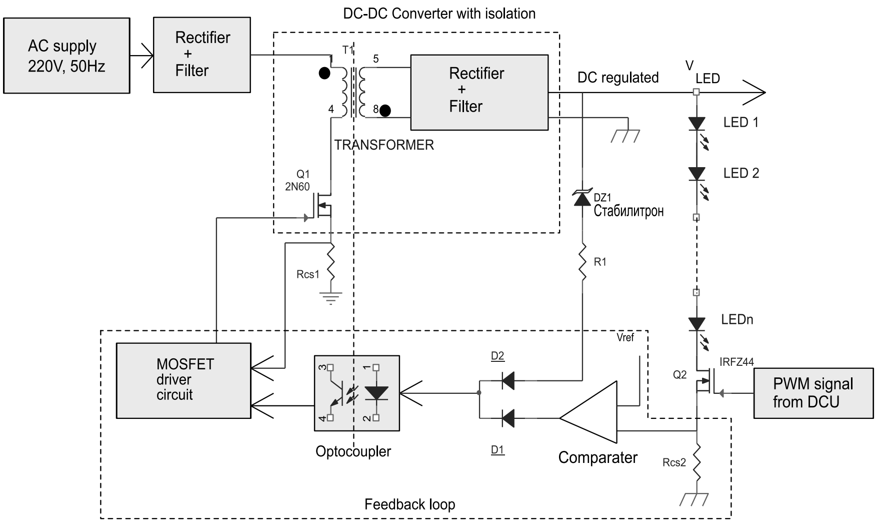

Fig.3. Block diagram of the LED driver

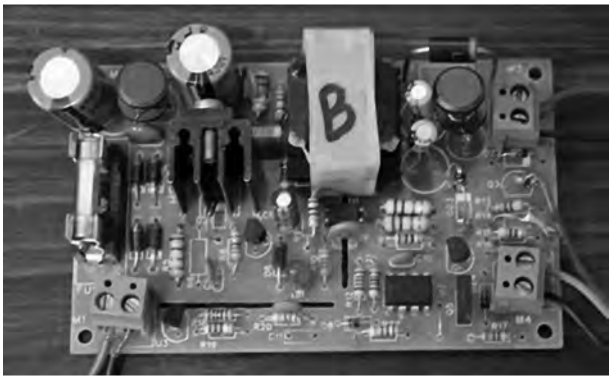

Fig.4. Prototype of the LED driver

So in this work a self-oscillating fly-back converter topology is designed and the circuit has been implemented to drive the LED strip. When the MOSFET Q_1 turns ON, current starts flowing through the primary coil of the transformer, and the energy is stored in the primary coil. The primary current I_p can be measured across a low value resistance R_{CS1} which is connected between MOSFET's source and ground terminal. In absence of feedback, the peak value of primary current I_p*R_{cs1} reaches base-emitter threshold voltage of an NPN transistor, which reduce the gate-source voltage of MOSFET Q_1. Because of regenerative action Q_1 rapidly turns OFF and the primary stored energy 1/2 L_p*I_p is transferred to the secondary, where L_p is the primary inductance. In the presence of voltage or current feedback the value of I_p*R_{cs1} is modified so that the required secondary voltage or current is modified.

The MOSFET driving circuit will rapidly turn ON and turn OFF the MOSFET Q_1 according to feed back signal or primary current. Opt coupler was used to isolate the secondary coil of the transformer from primary coil. Fig.4 shows the developed prototype of LED driver.

Table 1 shows the different specification and component value used to design the LED driver.

Table 1. Specifications of LED driver

Specifications	Values
Nominal input voltage, V_{in}	230V,50Hz AC
Nominal output voltage, V_{out}	16 V
L1 Primary inductance	430 µH,
L2 secondary inductance	8 µH
Rated LED current, I_{LED}	312mA
LED type and number of LED	LED strip 3528 (Red, Green, Blue, White)
Dimming frequency, F_{Dim}	244Hz
Current Sense resistor	0E5

3.2. Control mode of the LED driver

The control circuit at the secondary is designed to operate in voltage protection mode and in current control mode. In a typical cycle of PWM for dimming the secondary control signal goes through voltage protection mode and in current control mode. In a cycle during turns ON of MOSFET Q_2 the current control loop will be activated to protect the LED and during turns OFF voltage control loop will be activated to protect the MOSFET Q_1.

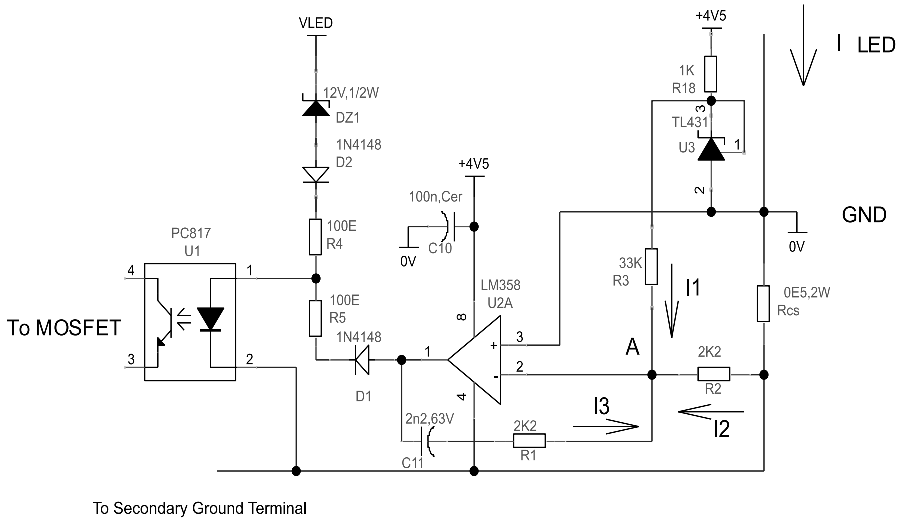

Fig.5 Circuit diagram of the PI controller based current control

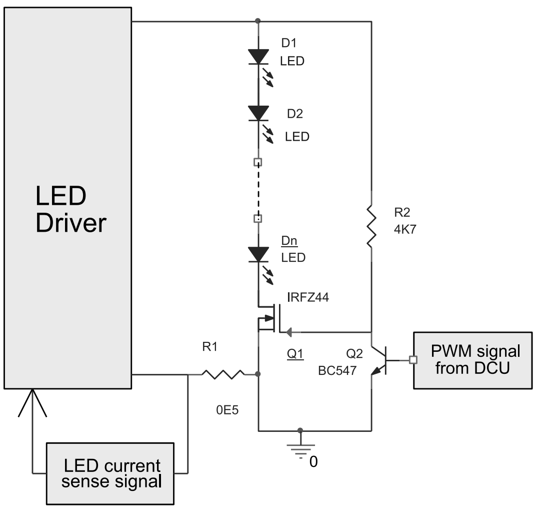

Fig.6. Schematic of series connected switch for dimming

3.2.1. Current Control mode

As LED is a current driving semiconductor device, its brightness is proportional to the current which will flow through it. The current control mode is implemented using a PI controller as shown in Fig.5. This control loop will work when the output terminal gets shorted or LED gets shorted, or load exceeds maximum allowable current.

The feedback control scheme of the secondary is implemented through a resistance divider and then the scaled voltage is amplified by using a transconductance type amplifier (TL431) [6].

In this article the feedback control scheme is modified by using A PI controller, which is required to control the LED current preciously.

Applying KCL at node A of Fig.5

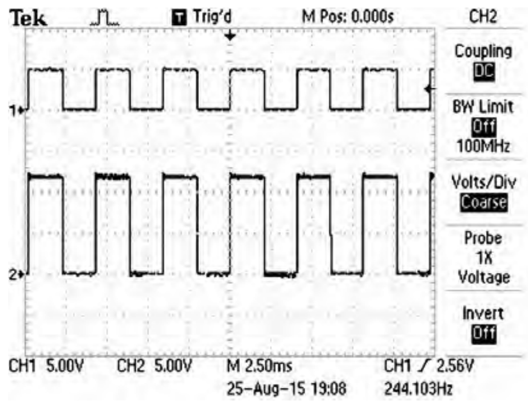

Fig.7 DCU signal (CH1–5V/div), Drain to source signal (CH2–5V/div) at 50 % duty cycle. Time scale-2.5 mS/div

$$I_1+I_2+I_3 = 0 \quad (3)$$

$$I_1 \frac{V_{ref}}{R_3}, \quad (4)$$

$$I_2 = -\frac{I_{LED} \cdot R_{CS}}{R_2}, \quad (5)$$

$I_3 = 0$ at steady state.

The maximum driving current that will be delivered by the LED driver can be calculated by using eqn.(6).

$$\text{So, } I_{LED} = \frac{R_2 \cdot V_{ref}}{R_3 \cdot R_{CS}}. \quad (6)$$

So limit of maximum current can be set by varying any parameters R2, Vref, R3, R_{CS}. Operation-

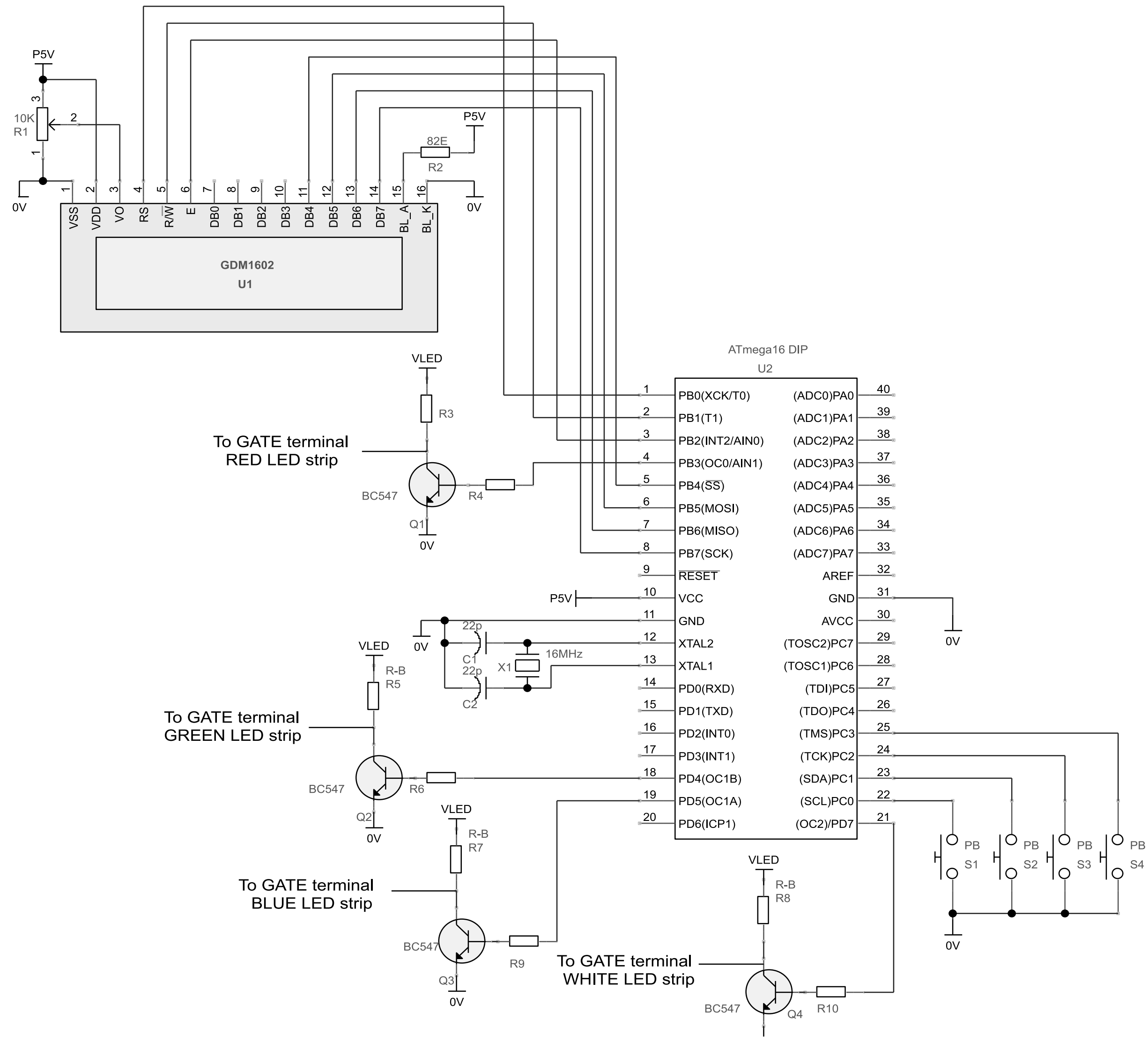

Fig.8. Pin connection of LCD and keypad to Microcontroller

al-amplifier (OP-AMP) LM358 is used to compare between reference voltage and driving current. I_{LED} can be calculated from eqn.(6). It is equal 312 mA. The reference voltage 2.5V is generated by using a precision shunt regulator TL431. In current control mode $I_1<I_2$, so output of the comparator will be high.

3.2.2. Voltage Control mode

In voltage control mode $I_1>I_2$, and output of the comparator will be low.

LED terminal voltage V_{LED} will be decided by voltage drop of zenor diode DZ_1, D_2 and opt coupler diode. The output voltage at LED terminal must not go beyond the supply voltage of LED under any circumstance.

4. DESIGN OF DCU (DIMMING-CONTROLLER-UNIT)

A DCU is used to generate four independent PWM signals. The DCU comprises of ATmega32A microcontroller from Atmel Corporation, a 16X2 LCD display and a 4X1 keypad module. The PWM dimming frequency generated from the DCU must be higher than 100Hz to avoid flickering as described by [7, 8,14]. It was set to 244Hz for RGBW channel to avoid flicker.

4.1. Principle of LED dimmer

As LED is a current driving semiconductor device, its brightness is proportional to the current, which flows through it. The light output of LED can

Fig.9. Test set up for CCT measurement by Konica-Minolta colorimeter

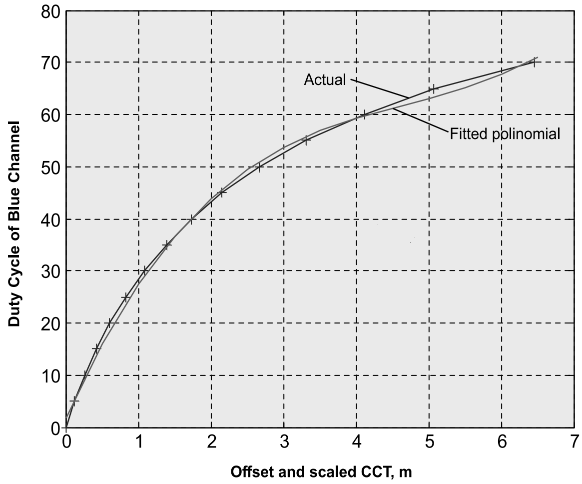

Fig.10. Scaled CCT vs duty cycle for blue channel

be varied by modulating the amplitude of the current. However, this type of linear dimming is not recommended for RGB colour dimming as chromaticity changes with amplitude of the current and with varying junction temperature [9]. For semiconductor device most flexible way of dimming is to use a pulse-width modulated (PWM) current signal on the LED array with varying duty cycle. It will change the illuminance value without changing the peak current of LED's string. PWM dimming technique has some advantages over analogue or amplitude dimming like stability of chromaticity during 0–100 % dimming and it has also linear relationship between duty cycle & light intensity of LED. From the previous study it can be concluded that PWM dimming is most suitable for this purpose as analogue dimming changes the colour of LEDs [9]. So, a PWM based dimming technology is implemented as one most suitable for this purpose.

A semiconductor switch is used in series with each of the RGBW LED string to turn ON and OFF LED's individually, according to the duty ratio. The average current that will be supplied by LED driver to LED can be expressed as eqn. (7)

$$I_{avg} = \frac{I_{LED} \cdot T_{on}}{T_{on} + T_{off}}, \quad (7)$$

I_{LED} is equal to maximum allowable current through LED, can be calculated from eqn. (6).

T_{on} and T_{off} is the turned ON and OFF time of LED respectively. Duty cycle can be varied from 0–100 %, so light output from the LED will vary also from 0–100 %. The schematic diagram of series connected switch is shown in Fig.6. The switch Q2 is an N-channel power MOSFET IRFZ44. To ensure proper turn ON and turn OFF of the series dimming MOSFET (IRFZ44) Q_2 a NPN transistor Q_3 (BC547) is used to provide the necessary GATE current for Q_2.

Fig. 7 shows that when DCU signal is high, drain terminal of Q2 is also high as GATE terminal of the MOSFET Q2 is grounded through Q3 and when DCU signal is low the gate terminal of Q2 will be high, so LED string will be ON during low DCU signal

4.2. PWM signal generator

ATmega32A is a low-power CMOS8-bit microcontroller based on the AVR enhanced RISC architecture. It has the following features like, 32 Kbyte of In-system programmable flash memory with read-write capability, Four PWM channel, 32 Programmable I/O line, speed 0–16MHz, 1024Kbyte EEPROM, 32 General purpose resistors etc. [10] By enabling Timer 0, Timer 1, Timer 2 of ATmega32A four PWM signals are generated.

The program for PWM generation, keypad and LCD module interfacing program is written in Atmel Studio 6.2 software (from Atmel Corporation) [11] and the HEX file is loaded into the ATmega32A microcontroller using USBASP AVR Programmer.

Register TCCR0 of Timer0 of ATmega32A is used to set the different modes and frequency selection. OCR0 register is used to set the duty cycle of the generated wave by comparing OCR0 and TCNT0 register value.

Frequency of the generated wave can be calculated by using eqn. (8) [10]:

$$F_{generated\ wave} = \frac{F_{oscillator}}{256 \cdot N}, \quad (8)$$

N is the prescaler value that may be (1/8/64/256/1024) the value of the prescaler chosen 256, oscillator frequency is equal to16 MHz. So, $F_{generated\ wave}$ will be 244.14 Hz.

Now the duty cycle of the duty cycle of the generated wave can be calculated as eqn. (9) [10].

$$\text{Duty cycle } = \frac{OCR0+1}{256} \cdot 100, \quad (9)$$

Value of OCR0 may vary from 0 to 255. Value of OCR0 register can be set through keyboard according to the RGBW mixing ratio. The percentage of duty cycle corresponding to each RGBW LED string is displayed in LCD screen for user interfacing. Same could be repeated for Timer1 and Timer2.

Duty cycle can be varied by setting OCR0, OCR1A, OCR1B, OCR2 register of ATmega32 through a keypad module for RGBW LED string respectively.

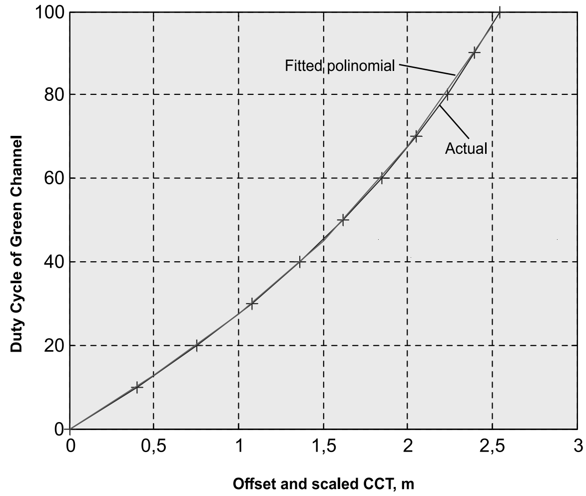

Fig.11. Scaled CCT vs duty cycle for green channel

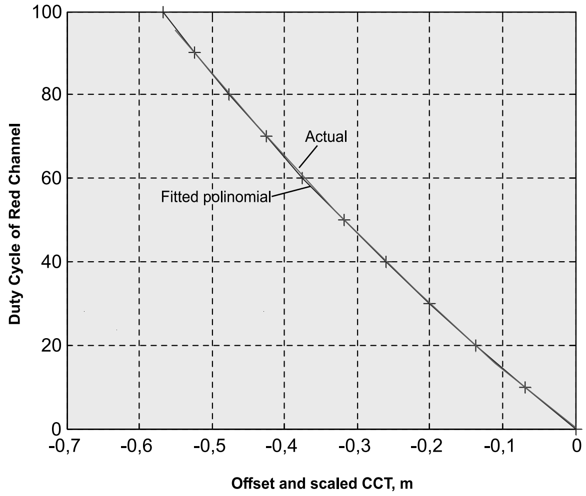

Fig.12. Scaled CCT vs duty cycle for red channel

4.3. Keypad and LCD module

Key pad module is used to change the duty cycle of the individual channel according to blending ration.

Pin connection of LCD, keypad and dimming signal to the microcontroller is shown in Fig .8.

JHD162A LCD module is used to display the dimming parameters (i.e. percentage of blending ratio), which is capable to display 16 Characters and 2 Lines [12]. The keypad interfacing program is written in such a way that the keyboard debounces or multiple key presses can be restricted.

5. EXPERIMENTAL RESULT

Here CCT is measured by varying the intensity of Red, Green and Blue LED individually with respect to WW LED. Various CCT produced by the RGBW luminaire is measured using Konica-Minolta CL200A Chroma Meter. The experiment has been carried out in a windowless dark-painted room at Electrical Engineering Department of Jadavpur Univertsity, and the Chroma Meter is placed 1 meter below the RGBW light source. The experimental set-up is shown in Fig.9.

As CCT of Warm white LED (3268 K) does not change so much throughout the 0–100 % dimming, the reading has been taken keeping the warm white LED at 100 % brightness, which will also increase the illuminance level. To achieve different illuminance level, duty ratio of the white channel can be varied. CCT is measured up to 70 % duty cycle of the blue channel, because beyond this, CCT cannot be measured by the Konica Minolta CL200A Chroma Meter as blue content is very high. The measured CCT with respect to duty cycle of blue channel is given in Table 2.

Table 2. CCT vs duty cycle of blue LED

Sl. No	Blue channel duty cycle, %	CCT, K
1	0	3268
2	5	3394
3	10	3539
4	15	3692
5	20	3880
6	25	4100
7	30	4360
8	35	4664
9	40	4996
10	45	5420
11	50	5940
12	55	6581
13	60	7389
14	65	8341
15	70	9723

Based on Table 2 above we can automate the process of producing white light of a certain CCT. A new variable, m, representing an offset and scaled value of the CCT as defined below

$$m = (\theta\,(\Delta_B) - \theta\,(0))\,/\,1000, \tag{10}$$

where θ (Δ_B) is the CCT of the white-blue composite array at a duty cycle Δ_B of the blue channel, is used below.

The variable ΔB is now plotted as a function of *m*. Using MATLAB®, a cubic polynomial is then fitted through this graph. Actual varying CCT of blue channel and fitted polynomial is shown in Fig.10.

The polynomial equation is given by

$$\Delta_B = 0.4132 * m^3 - 5.8318 * m^2 + \\ + 31.0856 * m + 1.8145. \tag{11}$$

An increase in the order of the polynomial was avoided for two reasons. The first is that it did not provide any higher accuracy throughout the range. The second reason is that it increases the computation time of the method described below.

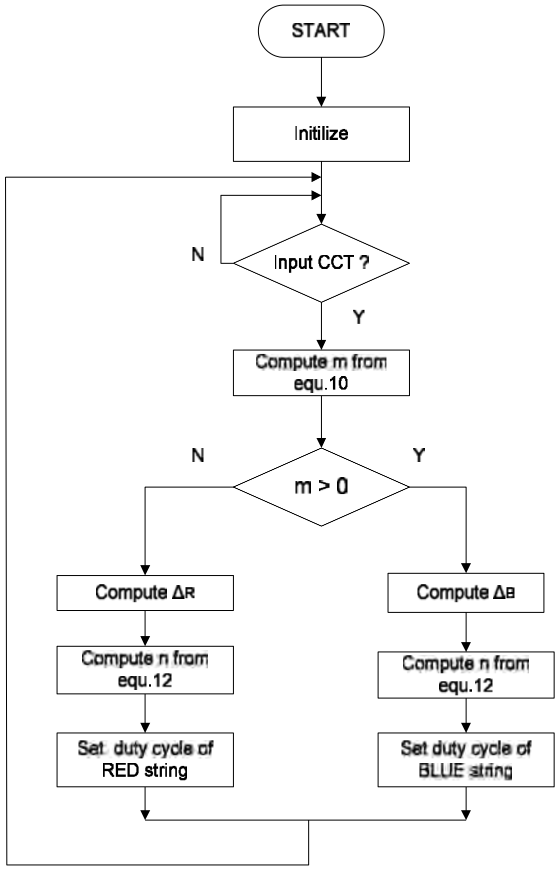

Fig.13. Flow chart of CCT varying algorithm

PWM width selection registers OCR0, OCR1A, OCR1B and OCR2 of ATmega32A are 8 bit register. So for 0–100 % dimming corresponding register value will vary from 0–255.

So, the register value n can be calculated as eqn. (12)

$$n = 2.55 * \Delta_B, \tag{12}$$

where Δ_B is the calculated duty cycle from eqn.(11).

Proposed algorithm to select the proper duty cycle of blue channel with respect to desired CCT as described below:

Step1: – Set the desired CCT value ranging from 3230° K to 9723° K;

Step2:– Compute m from eqn.(10);

Step3: – Compute Δ_B from eqn.(11);

Step4: – Compute n from eqn.(12);

Step5: – Set the 8 bit register OC1A of ATmega32A by computed value of n to achieve desired CCT.

For an example to produce CCT 4100° K using blue and WW LED duty cycle of blue channel will

Table.3 CCT vs Duty cycle of red and green LED

Sl. No.	Duty cycle of G/R LED, %	CCT, K for green blending	CCT, K for red blending
1	0	3268	3268
2	10	3673	3198
3	20	4025	3132
4	30	4192	3067
5	40	4350	3008
6	50	4628	2950
7	60	4887	2893
8	70	5316	2842
9	80	5502	2791
10	90	5665	2745
11	100	5813	2700

be 25 % and the corresponding OCR2 register value will be 64.

Same process could be repeated for Red and Green channel. The measured CCT ranges for WW-G and WW-R LED blending are 3268–5813K and 3268–2700K respectively, where duty cycle of green and red LED varied from 0–100 %. The measured CCT with respect to duty cycle of green and red channel are given in Table 3.

The fitted polynomial equations for green and red channel are given by eqn. (13) and eqn. (14).

$$\Delta_G = 2.2750 * m^3 – 0.4693 * m^2 + + 25.7082 * m – 0.1606. \quad (13)$$

$$\Delta_R = 75.2395 * m^2 – 132 * m + 0.3191. \quad (14)$$

The fitted polynomials using MATLAB® are shown in Figs.11,12 respectively.

By observing Table.2 and Table.3 it can be concluded that to achieve higher CCT than WW LED, only blue LED may be blended and on the other hand for lower CCT range red LED may be used. To automate the process, an algorithm is proposed and the flow chart of the proposed algorithm is shown in Fig.13.

Now the CCT is set in the interval of 500K by using a keypad and measured by the Konica Minolta CL200A Chroma Meter. Table 4 shows maximum deviation of 18 K and 344 K for red and blue blending from set point value respectively. This algorithm can select automatically blue LED for higher CCT and red LED for lower CCT with respect to WW CCT.

Table 4. Measured CCT and error

Sl. No.	Set CCT, K	Measured CCT, K	CCT error, K
1	2700	2718	–18
2	3000	3011	–11
3	3500	3493	7
4	4000	3946	54
5	4500	4470	30
6	5000	5022	–22
7	5500	5601	–101
8	6000	6114	–114
9	6500	6620	–120
10	7000	7039	–39
11	7500	7370	130
12	8000	7745	255
13	8500	8170	330
14	9000	8656	344
15	9500	9433	67

6. CONCLUSION

To vary CCT of light from 2700K – 9723K, it is understood that only WW, red and blue LEDs are sufficient. To change CCT only from 3268k up to 5813k, green and WW may be used. So, to get the effect of natural light, only RBW LEDs are needed instead of RGBW LEDs. It reduces the cost of total number of LEDs. Here, this work does not take care about the illuminance available on a working plane. Research is being carried out to select the CCT and Illuminance both simultaneously in a similar type of lighting system.

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