Politecnico di Milano

Department of Electronics, Information and Bioengineering (DEIB)

Master of Science Thesis

Smart Light Intensity Controller Circuit Design for LED with Wi-Fi Connection by Employing Optimized Light Controlling Method

(Smart WiLi)

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A.Y. 2016-2017

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2. Abstract

Constantly growing demand for electrical energy and quite questionable prospects of new sources of electrical energy make the problem of energy efficiency very topical nowadays. There are two basic ways of making the energy consumption efficient: increasing the self-efficiency of electrical equipment and avoiding its unnecessary operation, thus making it “smart”. One of the most significant energy consumers is lighting. About 19% of the electrical energy produced over the world is spent to lighting.

In this report, we’re trying to introduce an efficient way for driving the LED and controlling its brightness level, in order to benefit from high efficiency, and improved light quality as well. It’s called the PW-AM method, which is a novel combination of two driving methods. By applying a light intensity sensor and Wi-Fi modules, the compact circuit can simply be used in smart environments, communicating with user through a cellphone application, and simultaneously being able to adjust the ambient light in a smart way.

3. Astratto

La crescente domanda di energia elettrica e le prospettive del tutto discutibili di nuove sorgenti di energia rendono il problema dell’efficienza energetica di grande attualità al giorno d’oggi.

Ci sono principalmente due modi per rendere più efficiente il consumo energetico: aumentare l’efficienza dei dispositivi elettronici ed evitare il loro funzionamento quando non necessario, ovvero renderli intelligenti (“smart”).

Una delle fonti di maggior consumo è energetico è l’illuminazione. Infatti, circa il 19% dell’energia elettrica prodotta nel mondo è utilizzata per tale scopo.

In questo lavoro viene introdotto un modo efficiente per pilotare lampade a LED e controllare la loro luminescenza nell’ottica di aumentarne l’efficienza senza degradare la qualità dell’illuminazione. Questo metodo innovativo, chiamato AM-PWM, è una combinazione efficiente dei due metodi classici di pilotaggio delle sorgenti luminose a LED.

Inoltre, utilizzando un sensore luminoso e un modulo WiFi, viene creato un circuito completo che rende il sistema di illuminazione “smart”. Attraverso uno smartphone è possibile, infatti, fissare la luminosità dell’ambiente facendo in modo che il sistema reagisca per aggiustare la luce emessa dal LED ed evitare sprechi di energia. Ciò è utile nel caso in cui via sia una sorgente luminosa esterna, come per esempio una luce che penetra da una finestra, che renda naturalmente l’ambiente più luminoso. In tal caso, il circuito riduce la potenza fornita al LED con ovvio risparmio energetico ma mantenendo la stessa illuminazione nell’ambiente.

4. LED and Energy

One of the most significant energy consumers is lighting. About 19% of the electrical energy produced over the world is spent to lighting. For particular objects this percentage is even higher. For example, lighting consumes about 30–40% of electrical energy in commercial buildings. So it is quite reasonable to improve efficiency of lighting system. Like it was previously mentioned there are two ways: utilization of the lighting technologies that produce more light per power unit and making lighting systems smart.

Utilization of Light Emitting Diodes (LEDs) successfully combines these two ways. On the one hand, modern LEDs have efficiency of several tens of lumens per watt (for instance, W724C0 from "Seoul Semiconductor" ensures 700lm at l0W or 701m/W), which is comparable with high pressure sodium lamps (up to 1401m/W). Of course, these data are given for stand-alone LEDs. LED luminaries produce less light, but they are still good. On the other hand, it is possible to effectively dim (adjust) light of LED lamps with no negative impact on LEDs.

We can compare three common kinds of lights (Incandescent Bulb, CFL[1] Bulb, and LED Bulb) in terms of power, life time, and light intensity in Fig. 1. It can be noticed that in general, an LED light has lower power consumption and higher life time. Although it costs more, it's compensated by the costs of replacing a lamp and electrical power consumption. In Fig.1 all the three bulbs have equal lumens. For using these lamps in 20 years, we need one LED bulb, 3 CFL bulbs, or 21 incandescent lamps. In terms of consumed power, incandescent lamp uses 4.8 times and CFL uses 1.12 times an LED bulb.

[1] Compact Fluorescent Lamp

Figure 1 Comparison of three light generations: Incandescent, CFL, LED.

5. Brightness Characteristics of a Light Source

Studying the light characteristics, such as light quality and efficiency, plays an important role in choosing a light source. According to comparison between different light generations, we can select the proper light type depending on the demands for designing the desired light system.

5.1. Light Quality

Two measurable parameters for light quality are CCT[2] and CRI[3]. CCT represents the light temperature, which means the color of a blackbody at this temperature. For instance, yellow light temperature is higher than red. CRI is a quantitative measure of the ability of a light source to reveal the colors of various objects faithfully in comparison with an ideal or natural light source. The closer the light source spectrum to the visible spectrum of sunlight, the higher the CRI value. The best light has the CRI value equal to 100.

Sunlight has a CCT of 6500K around noon. Light sources with a CCT rating below 3200K are usually classified as "warm", while those with a CCT rating above 4000K are usually classified as "cool" in appearance. For a common incandescent lamp, CCT=2850K, and CRI above 95, and for a CFL with same CCT, CRI=62. White LEDs are available in broad bin selection ranges with CCTs from 2500 to 10000K (warm, neutral, or cool in appearance). White LEDs are typically manufactured by placing a blue LED in a package internally coated with a light converting phosphor. Most LED lights have a CRI between 80 and 90.

5.2. Light Color

For quantifying the light color, x,y, and z components are used. These components represent red (R), green (G), and blue (B) respectively. Incident light power is evaluated for each color and light color is shown as a point on the axis. Notice that the light is a combination of only these three components, which are expressed as a value in the range of 0-1, with a sum equal to 1, so we use only two of the components, x and y. For white light, the tree components are almost equal. These components are usually reported in a figure similar to Fig. 2.

[2] Correlated Color Temperature
[3] Color Rendering Index

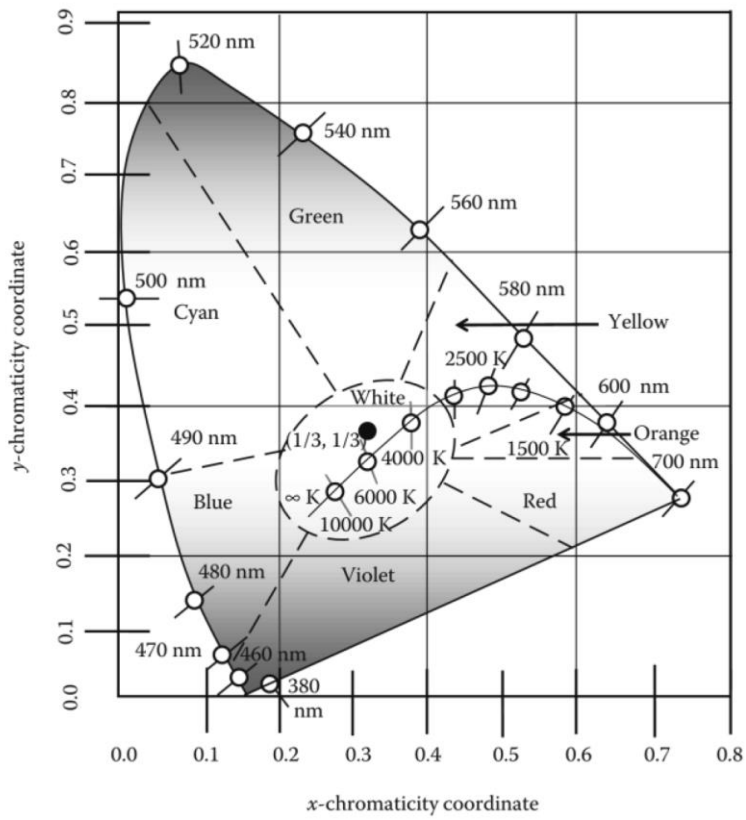


Figure 2 Light Color Components

5.3. Luminous Efficiency

In order for an object to be seen, the light should radiate from its surface toward the eye. The more the light radiated to the surface, the brighter the object. Light is measured with different techniques, and therefore there is a handful of related, but different, units of measurements. The light intensity on a surface is represented in luxes. This unit expresses the radiated lumen to a surface. The candela (unit cd) has its origin in the brightness of a "standard candle", but it has received a more precise definition in the International System of Units (SI) —and at that time the unit was also renamed from "candle" to "candela". The candela measures the amount of light emitted in the range of a (three-dimensional) angular span. Since the luminous intensity is described in terms of an angle, the distance at which you measure this intensity is irrelevant. The angular span for candela is expressed in Steradian, a measure without unit (like radian for angles in a two-dimensional space). One Steradian on a sphere with a radius of one meter gives a surface of one m^2. To summarize, the light intensity a candle radiates is equal to one candela, and one lumen is equal to 1 cd/sr. Considering the candle light uniformly radiated in the space, radiated power of a candle is equal to 4π.

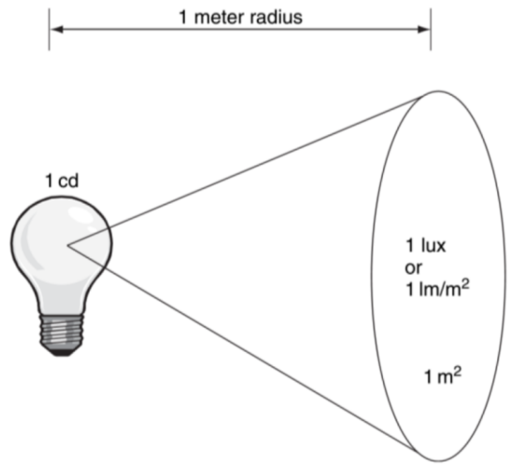


Figure 3 Illustration of light parameter: lux

One of the important characteristics of a light source is the Luminous efficiency, which is the generated light intensity with respect to the consumed power. It is the ratio of luminous flux to power, measured in lumens per watt in SI. A 60-Watt incandescent lamp generates 830 Lumen brightness, equal to 14 Lumen/Watt. A T8 fluorescent lamp generates 2700 Lumen, with the consumed power of 32 Watt, equal to 84 Lumen/Watt. For LED lamps, this efficiency is in the range of 50-100 Lumen/Watt.

Luminous efficiency is a measure of how well a light source produces visible light. Artificial light sources are usually evaluated in terms of luminous efficiency of the source, also sometimes called wall-plug efficiency. This is the ratio between the total luminous flux emitted by a device and the total amount of input power (electrical, etc.) it consumes. The luminous efficiency of the source is a measure of the efficiency of the device with the output adjusted to account for the spectral response curve (the luminosity function). When expressed in dimensionless form (for example, as a fraction of the maximum possible luminous efficiency), this value may be called luminous efficiency of a source, overall luminous efficiency or lighting efficiency.

The main difference between the luminous efficiency of radiation and the luminous efficiency of a source is that the latter accounts for input energy that is lost as heat or otherwise exits the source as something other than electromagnetic radiation. Luminous efficiency of radiation is a property of the radiation emitted by a source. Luminous efficiency of a source is a property of the source as a whole. To compare this efficiency for different types of light sources, we can refer to figure 4.

Bulb Information	60 Watt Incandescent	40 Watt, 4'-0" Fluorescent T-12	50 Watt Halogen Bi-Pin Base	13 Watt CFL Bulb	32 Watt, 4'-0" Fluorescent T-8	9.5 Watt LED Bulb
Lumens	850	2,600	1,200	800	2,800	800
Watts	60	40	50	13	32	9.5
Lumens per Watt (LPW)	14	65	24	62	88	84
Life Span (hrs)	1,000	20,000	2,000	8,000	20,000	25,000
Price per Bulb	$0.50	$2.00	$2.50	$5.00	$2.50	$10.00

Figure 4 A Comparison of Several Light Sources Specifications

6. An Introduction to LED Lamps

LED part name represents its diode behavior at first. Diode passes the current in one direction with a low voltage drop, and prevents the current to flow in the other direction. A 1N4148 has a 700mV voltage drop while an LED can have a 3.6V drop. This is due to the fact that an LED is not made of Si and another types of semiconductor; such as GaAsP/GaP and GaN/InGaN; are used for fabricating an LED. All kinds of diode radiate a little light but LED lights are designed in a way to enhance this capability and have an efficient optical behavior. LED lamps belong to two main categories: small and power LEDs. Small LEDs have been popularly used since 1970 in a variety of colors. A common small LED is shown in Fig.5. Such diodes were employed in monitor backlights, electronic parts keys, alarms, flash lamps, traffic lights, and cellphones. What distinguishes these elements is their power consumption, or from an industrial point of view, the driving current. A small red LED draws 20mA driving current for a forward bias of 2.2V. Consumed power is equal to 44mW. For small white LED, forward bias is 3.6V with 72mA current. In this way, for replacing a light bulb, one should employ hundreds of small LEDs.

Figure 5 Different Colors of Small LEDs

Power LEDs usually operate in 1-3V, 50-1000mA voltage and current range. The chip in power LEDs is much wider than the small LEDs. Power LEDs are nowadays employed in lamps, projectors, city lights, etc. They're supposed to replace the old light sources soon.

LED current has the same relationship with its voltage as a normal diode. The difference is in bias voltage, which in an LED reaches up to several times the normal diode. Eq. 1 shows the voltage-current relationship of a diode. At room temperature, KT/e value is almost equal to 25-26mV.

$$I = I_s \left(e^{eV/_{KT}} - 1 \right) \qquad (1)$$

For voltage values close to turn-on voltage of diode, which is much higher than 26mV, we can assume:

$$I = I_s e^{eV/_{KT}} \qquad (2)$$

After introducing new materials as semiconductors, GaAsP was employed for fabrication of LEDs. The band gap energy in GaAsP is higher than GaAs, so its wavelength would be shorter. Such diodes produce red light. Blue LEDs are made from InGaN. After discovery of blue light, the main colors were complete and white LED production became possible. Power LEDs were used to increase the radiated light power. Yet, for providing sufficient light, using several power LEDs is required.

A law similar to Moore's has been raised in light diodes industry, named Haitz's law [17]. Haitz's law is an observation and forecast about the steady improvement, over many years, of light-emitting diodes. It states that every decade, the cost per lumen (unit of useful light emitted) decreases by a factor of 10, and the amount of light generated per LED package increases by a factor of 20, for a given wavelength (color) of light. It is considered the LED counterpart of Moore's law, which states that the number of transistors in a given integrated circuit doubles every 18 to 24 months. Both laws rely on the process optimization of the production of semiconductor devices.

7. A Study on LED Driving Circuit

Due to the voltage-current characteristic of LEDs (Fig. 6), the best method for driving them would be to control their current, and using a current feedback, generating the required current.

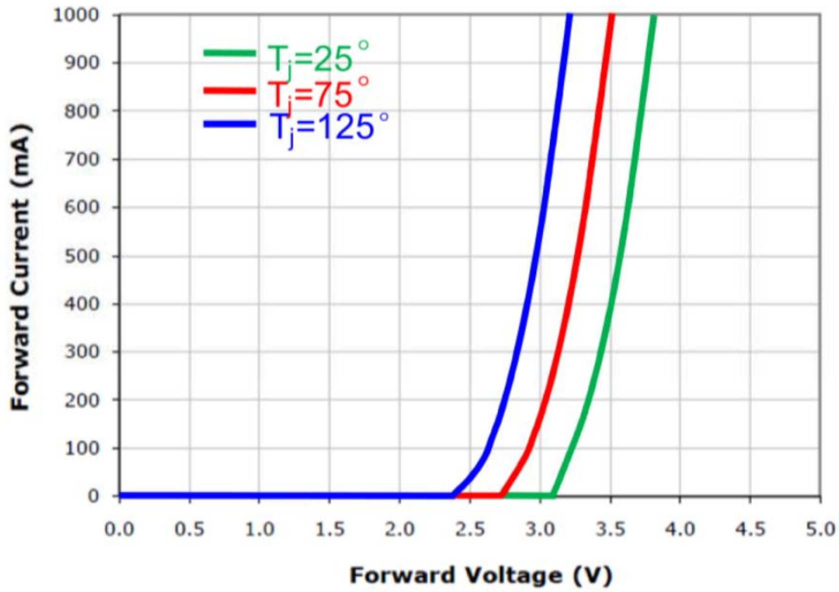


Figure 6 Ambient Temperature Impact on LED I-V characteristics

Driving LED lamps needs DC supply considering their I-V curve. The slope of the curve becomes steep after turning on the LED. Hence the current is so sensitive to voltage changes (around 700mA/V). The main difference between an LED driver and a DC power supply is in the output current.

In the driving circuit, current should be fixed on the value determined by the manufacturer. Reducing the current leads to reduction of LED brightness, and increasing it more than the nominal value results in reducing the lifetime and burning the LED.

Current is measured in the sensing part of the circuit, and using a feedback, the effective voltage on the load is regulated. For measuring the load current applying a feedback, a series resistor is normally employed. If the resistance value is low, feedback loop gain should increase, while increasing the resistance value leads to increased loss of the power circuit. Feedback resistance should have a high thermal stability so that by thermal changes, the circuit current remains constant.

8. LED Brightness Adjustment

Brightness adjustment means the ability of dimming the light intensity from the nominal value to turning off. LED brightness has an almost linear relationship with its current (Fig. 7). Hence, by adjusting the input current of the LED in the driving circuit, we can control its light intensity.

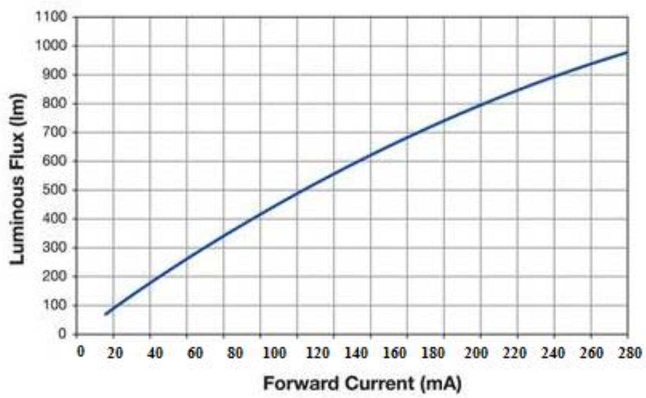


Figure 7 Luminous Flux vs Forward Current of LED

For decreasing the current flowing into an LED, two current modulation methods are proposed: AM[4], PWM[5]. An introduction to both methods is reported in the following.

8.1. AM Method

In amplitude modulation, the current amplitude is the controlled parameter, thus the brightness is controlled by changing the operating point. By modulating the current, we mean changing the current level, not its pattern. The current level is determined in the feedback unit of the circuit. Such circuit needs a constant-current switching converter with the ability of feedback control.

[4] Amplitude Modulation
[5] Pulse Width Modulation

8.2. PWM Method

Because LEDs are semiconductor devices they can be turned on and off much quicker than other lighting technologies. This high switching speed makes LEDs suitable for use with pulse width modulation (PWM) methods for dimming. Using PWM the intensity is controlled by adjusting the duty cycle, the ratio of the time the device is on to the overall switching period. Dimming in this manner allows for a large range of dimming levels. Also with this type of control, intensity is independent of color making it suitable for many applications

Human's eye cannot detect fast changes of the light source and observes its mean effect. For instance if an LED turns on and off with time interval of 100ms, the eye can recognize the LED flickering. If the time interval changes to 1ms, the eye observes a continuously on LED. However, in this case the LED brightness would be half the nominal level. By adjusting the duty cycle and keeping the total interval short enough, we can control the mean brightness value and the dimming level.

$$I_{AVG} = I_{PEAK} \times D \qquad (3)$$

Where:

D: duty cycle $=t_{on}/T$

t_{on}: switch on time

T: switching period

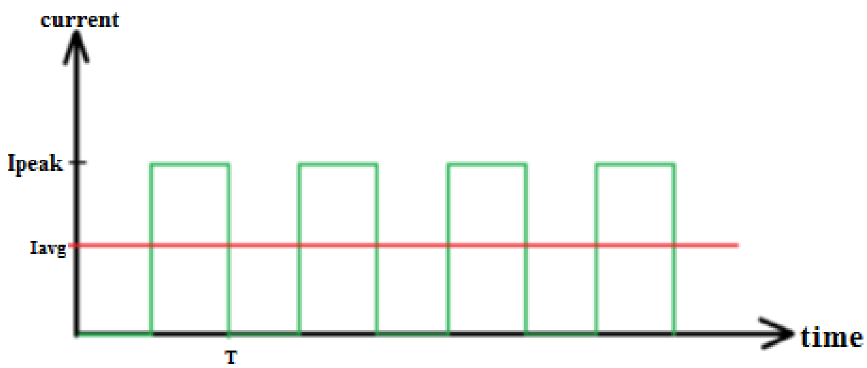


Figure 8 the Average Current Change in PWM Method

The low frequency in PWM leads to detection of LED flickering by the eye and it gets annoying. So the switching frequency should be higher than 100Hz. The only limit for increasing the frequency would be the switching frequency of the driving circuit. Considering the PWM frequency equal to 1kHz, for having the light level of 10%, pulse width would be 100us. 10 switching periods would be enough for reaching the nominal current and staying on.

In addition to high switching frequency, the driving circuit in PWM method should have a fast output filter. If the driving circuit has high output capacity, the LED would turn on and off slowly, and the brightness level would not be equal to light controlling pulse average.

8.3. PW-AM Combinational Method

As mentioned before, for dimming an LED lamp we can make use of PWM or AM methods. In amplitude modulation, the current amplitude is the controlled parameter, thus the brightness is controlled by changing the operating point. Due to the exponential current-voltage relationship, current decrease leads to voltage decrease. But it also leads to reduced energy of the photons emitted from the LED PN junction. On the other hand, light color changes while adjusting the brightness. This is one of the main problems in amplitude modulation method, which we try to prove experimentally in the next chapter.

Applying the pulse width modulation method, we can adjust the average brightness by controlling the switching speed and the duty cycle. In this procedure, the operating point is in one of the on/off states, thus the electrical efficiency over time is constant. Since the average value of current and voltage are fixed and the only changing parameter is the duty cycle, the overall electrical efficiency would be constant. On the other hand, energy consumption and LED brightness have an almost linear relationship with work cycle. So in all cases other than the nominal lux of LED, amplitude modulation method is more efficient. Each of these methods has its pros and cons. By combining the two mentioned methods (AM and PWM), an innovative light controlling method is suggested (PW-AM). The main idea of the proposed approach, is to create a balance between efficiency and brightness changes; in order to benefit from the higher efficiency and color quality at the same time.

For reducing power loss, electrical efficiency plays a more important role near to nominal current value rather than near to zero(off) current, because increasing the efficiency at nominal current value results in more power saving. In AM method, higher efficiency is reached at the cost of losing the light color quality. Light quality change is more noticeable by getting far from the nominal current. PWM method prevents light color change by keeping the operating point constant.

For reducing the brightness from the nominal level (ON), we first apply AM method. Since the power consumption reduces at a higher rate with respect to the brightness, the LED efficiency would increase near the nominal operating point by reducing the current level, in which the power consumption is high. Getting closer to the off level results in color change, so we stop reducing the current level (AM method) before the color quality changes, and instead we apply PWM method to dim the LED brightness near off level. This means keeping the current level constant but starting to switch the output current and reduce the duty cycle. To summarize, for dimming an LED in PW-AM method, the LED current is reduced from its nominal value with a linear, uniform pattern, up to a certain point in which we switch between the two methods. Then the current level remains constant and for reducing the brightness, the current is pulse width modulated and we act on the duty cycle. The switch point between the two methods should be selected in a way to be able to hold the balance between the efficiency and the light quality.

8.4. Studying the Effect of PW-AM Method on LED Functionality

Evaluating the performance of PW-AM method is possible only by comparing it to AM and PWM methods. To this aim, LED characteristics are studied by driving the LED with these methods. In addition to the relations governing the LEDs, we use a practical example for comparing the methods.

1. **Luminous efficiency**

   As mentioned before, luminous efficay, or efficiency is a measure of how well a light source produces visible light. It is the ratio of luminous flux to power, measured in lumens per watt in SI. Not all wavelengths of light are equally visible, or equally effective at stimulating human vision, due to the spectral sensitivity of the human eye; radiation in the infrared and ultraviolet parts of the spectrum is useless for illumination. The luminous efficiency of a source is the product of how well it converts energy to electromagnetic radiation, and how well the emitted radiation is detected by the human eye. Luminous efficiency, denoted K, is defined as:

$$K = \frac{\Phi_V}{\Phi_e} = \frac{\int_0^\infty K(\lambda)\Phi_{e,\lambda} d\lambda}{\int_0^\infty \Phi_{e,\lambda} d\lambda}$$

   where

   Φ_V is the luminous flux;

   Φ_e is the radiant flux;

   $\Phi_{e,\lambda}$ is the spectral radiant flux;

   $K(\lambda) = K_m V(\lambda)$ is the spectral luminous efficiency.

AM method increases the LED efficiency by moving from operating point and getting close to zero current. Considering the exponential current-voltage relation, LED voltage is reduced by current reduction. Diode power consumption is equal to the current multiplied by voltage. Assuming the linear relationship between LED current and brightness, in AM method the efficiency increases.

For performing a quantitative analysis on efficiency change and comparing different brightness control methods, we use a 2W Osram LED and its charts. This LED is designed as multichip which is shown in Fig. 9. The nominal operating point of this LED in room temperature is 700mA, 3.45V for current and voltage respectively. The color specifications of this LED is derived from the datasheet as follows:

$$C_x = 0.46, C_y = 0.41 \text{ acc. to CIE 1931 (warm white)}$$

We can observe the Osram LED current-voltage curve in Fig. 10. As expected, we can notice the exponential relationship. Voltage drop is much lower with respect to current decrease.

Figure 9 LE CWUW Diode of Osram Co.

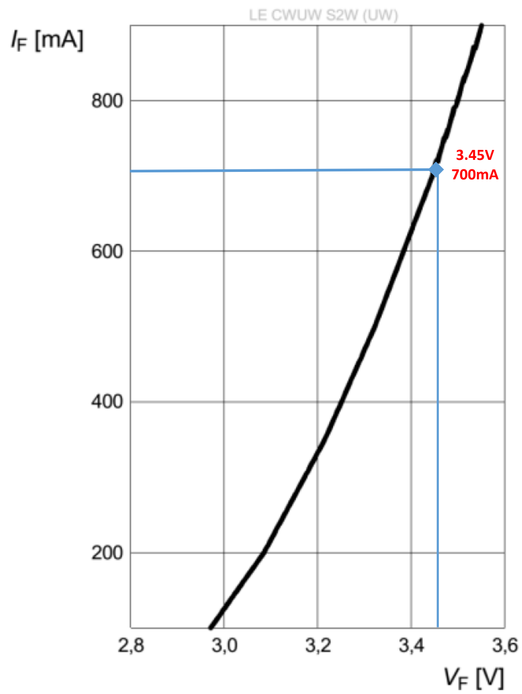


Figure 10 I-V Characteristics of the LED at Room Temperature

The expected condition for increased efficiency is not met completely. In Fig. 11 we can observe the normalized chart of brightness-current. We can notice that the relationship is not linear and by getting close to the operating point, brightness increase rate reduces. The main reason is the electron-hole recombination before the photon emission. In this situation the electrical energy is not converted to lighting and is wasted as heat. Increasing the current leads to increased probability of recombination and the brightness chart takes more distance from the linear status. We can consider this reduction in brightness increase rate as the supplement of voltage drop for increasing the efficiency in AM method. Close to operating point, reducing the current makes small difference in voltage but results in the chart getting closer to linear state. By getting far from the operating point, the effect of brightness enhancement is decreased and the effect of voltage drop becomes noticeable.

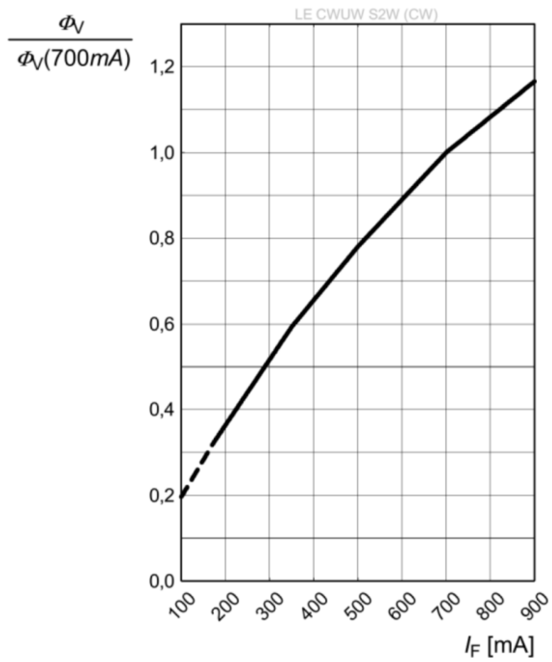


Figure 11 Normalized Diagram of LED Luminous Flux vs. Current

The efficiency is more important near the operating point since the power consumption is higher at this point. In Fig. 12 we can see the rate of efficiency increase with respect to operating point. Current reduction leads to increase of the ratio of LED lumen to electrical power.

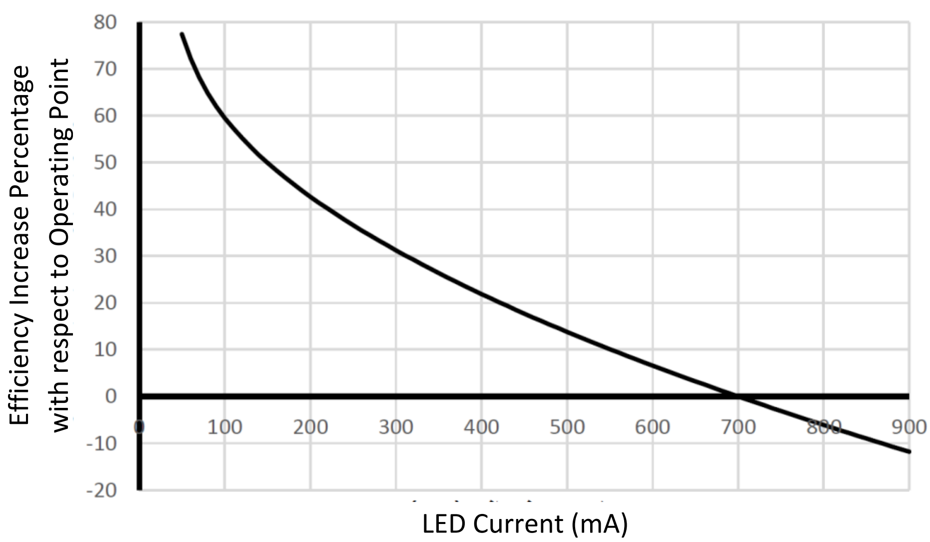


Figure 12 Efficiency Increase Percentage with Respect to the Operating Point (700 mA)

AM method decreases the efficiency by moving along the curve. In PWM method, by reducing the duty cycle, the average power consumption reduces but at the same time the brightness is decreasing. In the next chapter, we're trying to study which parameter is dominant by measuring the efficiency changes. However, we can remark that by fixing the operating point, the color quality of the light would not be impaired in this method. PW-AM method first increases the efficiency by applying the AM method, and then after a special point, moves to turning off with PWM method.

For analyzing the energy loss, we study the power loss at different brightness levels. PW-AM method can benefit from the efficiency improvement advantage in AM method region and after switching to PWM method, try to gain the benefit of LED color quality.

2. Temperature Variations Effect

In the exponential current-voltage equation of diode, KT/q factor is proportional to the temperature. So diode voltage and current are dependent on temperature. Increasing the temperature leads to LED voltage decrease at constant current, which results in decreased power consumption. However, this cannot be considered as increasing the efficiency since the luminous efficiency decreases as the temperature increases.

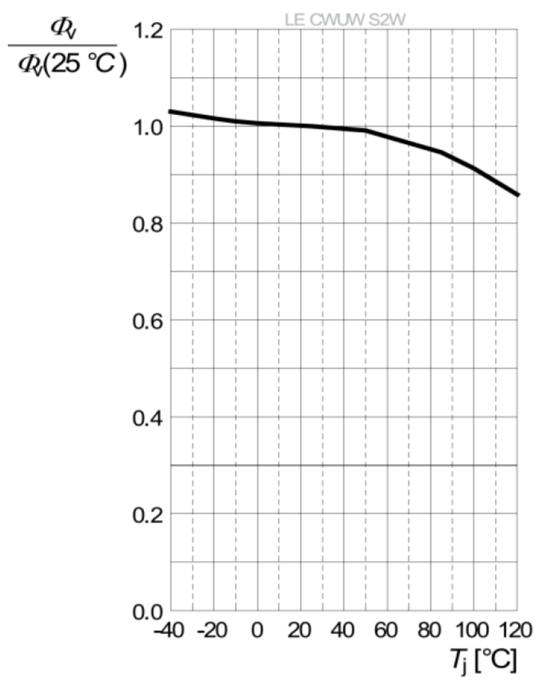
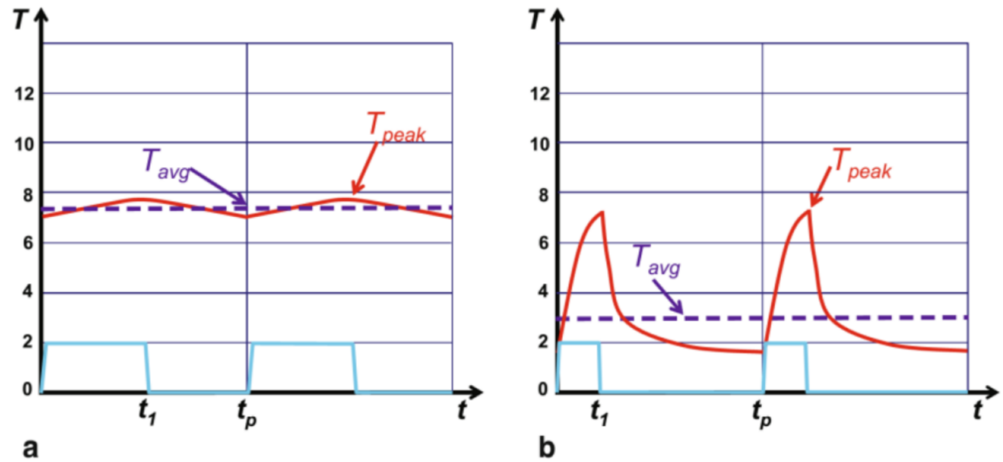


Figure 13 Temperature Change Impact on LED Efficiency

Fig.13 shows that for improving the lighting efficiency we should reduce the LED temperature. Heat-sink optimum design has an important role in LED fabrication process.

Other than the efficiency, the lifetime parameter is also related to temperature. AM method reduces the temperature of the LED body by reducing the power loss. However, by switching the current of LED in PWM method, increased current leads to increased power loss and heating the part. The LED body should transfer the generated heat to the heat-sink and cool the LED. The thermal resistance leads to the change in LED temperature in PWM method, such as in Fig. 14.



Junction temperature waveform at different heating pulse series:
a $t_1 = 0.1$ ms, $t_p = 0.2$ ms, $\delta = 0.5$, $f = 1/t_p = 5$ kHz, $dT_{peak} = 7.8$ K, $dT_{avg} = 7.3$ K
b $t_1 = 1$ ms, $t_p = 5$ ms, $\delta = 0.2$, $f = 1/t_p = 200$ Hz, $dT_{peak} = 6.9$ K $dT_{avg} = 2.9$ K

Figure 14 Temperature Changes of LED by PWM Current

3. LED Color Change

The LED emits blue or ultraviolet rays and converts it to white light. The white color is generated after colliding with the phosphorous cover on the LED lens. The light color depends on two parameters: the cover material and the radiation frequency of the diode. The radiation frequency represents the radiated photon energy. The energy is determined by the diode voltage. By increasing the voltage, the photon energy is increased and the light color becomes blue. Voltage reduction changes the color to green and red. Fig. 15 shows the light color change of the discussed LED at room temperature. Symbols x, y correspond to chromaticity coordinates parameters according to CIE 1931. We can notice that by reducing the current and the voltage drop of the diode, the red and green components of the light increase. The chromatic aberration is low at the beginning but increases as getting far from the operating point.

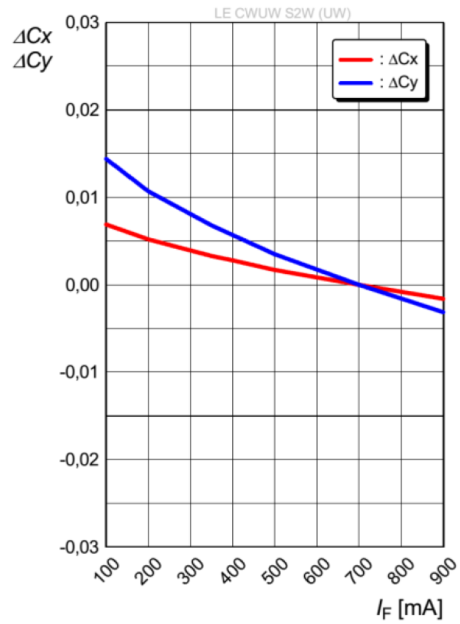


Figure 15 LED Chromaticity Coordinate Shift vs Forward Current at Room Temperature

X, y, and z components changes result in light color change. Osram has published its white LED categories, which can be found in Fig. 16. We can notice that x and y changes lead to changing the light color from warm white (reddish), to cool white (bluish). Each of the specified parts shows the range of white LED variations at different conditions.

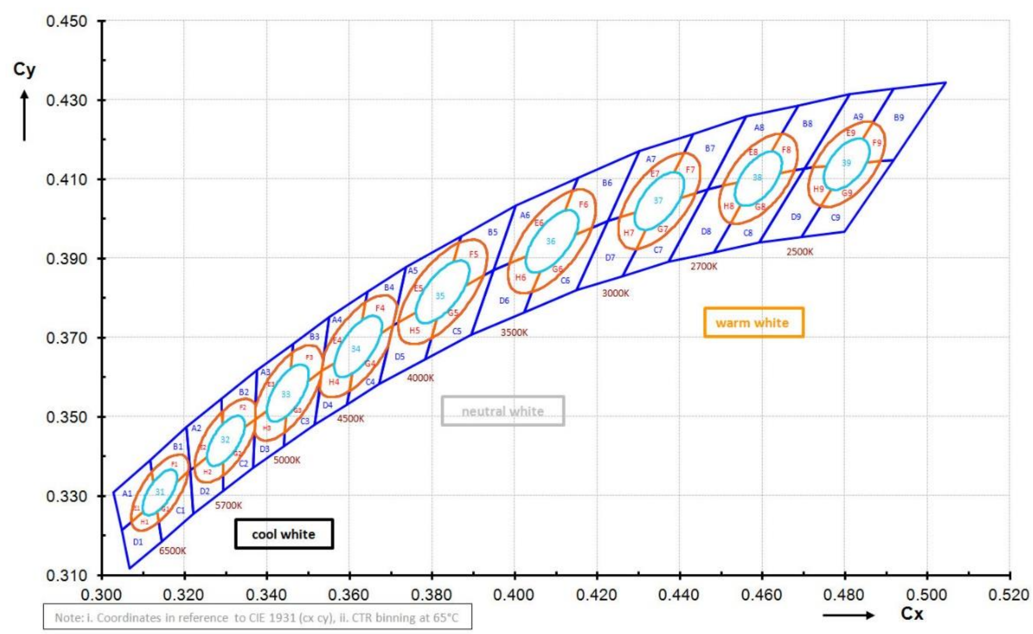


Figure 16 White LEDs Color Characteristics of Osram Co.

White color and its temperature changes leads to different object colors seen. Fig. 17 shows the object color difference in two cases: warm white light and cool white light. Color changes can be annoying in long time periods.

Figure 17 Colors Changes in Warm White Light (Above), Cool White Light (Bottom)

PWM method uses the operating point of the LED, so is preferred to AM method for dimming the LED. However, in this method the light color changes too. The reason is the temperature change of the LED package. As said before, temperature raise results in LED voltage reduction, which leads to the reddish white light. To conclude, in PWM method, the current reduction makes the light color bluish. In AM method, the impact of two parameters- temperature and voltage decrease- on the light color is in opposite direction. The voltage drop due to the current decrease has a bigger role with respect to the temperature reduction. Close to the operating point, the two effects cancel each other. By moving towards off status and low currents, the effect of reduced current overcomes and the light color becomes reddish.

To summarize, PWM method has a good condition in brightness quality. AM method, although having lower light quality, proves to have better performance near operating point. Applying PW-AM method, we can benefit from good light quality and higher efficiency at the same time.

9. Designing PW-AM LED Dimming Circuit

For designing a driving circuit with the LED dimming ability, we need a power supply at first. This supply should be able to provide the output power required for LEDs with respect to the desired voltage and LED layout. Then by designing the feedback circuit, we fix the output current and implement the desired brightness control method. The main difference between a driving circuit and a power supply is in the feedback unit. In Fig. 18 we can see a schematic design of the PW-AM driving circuit units.

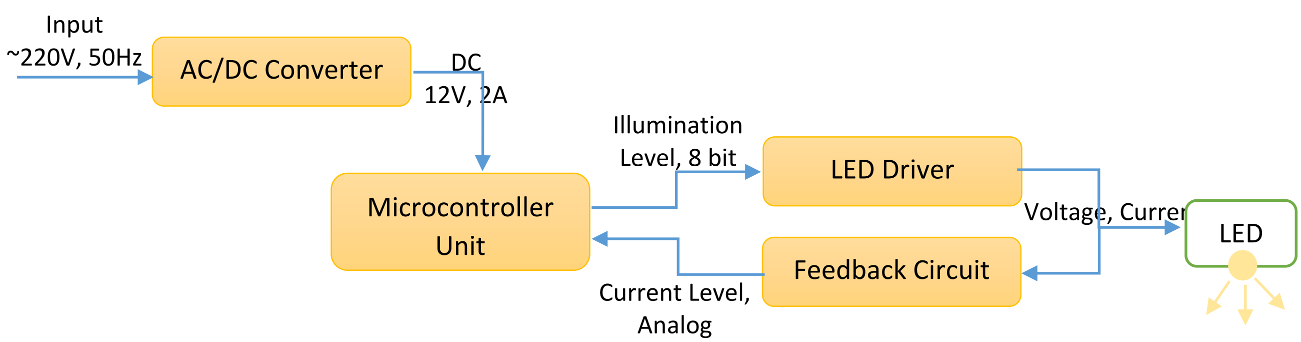


Figure 18 PW-AM Method Dimmable Driving Circuit Units

Implementing PW-AM method is possible using amplifier ICs and logical operator; but since for connecting to smart environments, a microprocessor is required, implementation of this circuit becomes easier. The microcontroller can both receive the desired brightness level and control the driving circuit.

The complete circuit includes another sensing part, which is for measuring the ambient light level, and also a Wi-Fi connection, for being able to control and monitor the light status. The schematic design can be found in Fig. 19. In the schematic introduced, we can observe two separate circuits, which are communicating through Wi-Fi. The circuit that leads to driving the LED is called Smart WiLi and the one containing the light intensity sensor module (Lux Meter) is called Smart Sensor. The user can set the desired ambient light value through an Android application, the Smart WiLi circuit tries to produce the light value by controlling the LED either in PWM control region or in AM control region, depending on the operating point. Then an external feedback loop, consisting of the LED light, the ambient light, the light intensity sensor, and the Wi-Fi module, tries to decide the LED operating point in a smart way, considering the other lights presence in the environment, in order to produce the user preferred overall brightness value. It's called "Smart", first of all because of its huge application in Smart

Home and Internet of Things fields, and also because of being able to adjust the ambient light level by considering the combination of several light sources. It's monitoring the ambient light level constantly, and by changes in other light sources, such as sunrise or sunset, it modifies the LED light level to reach the user desired light level. PW-AM method implementation enables us to control the output current by programming the microcontroller.

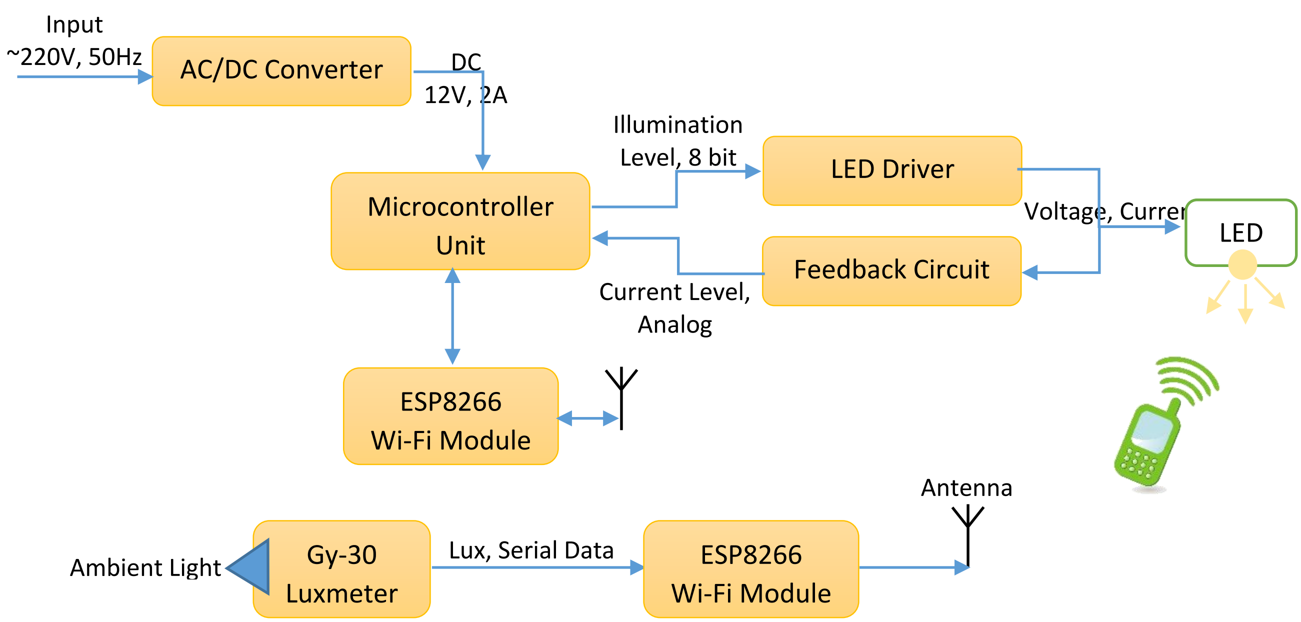


Figure 19 Schematic Design of the Whole Dimming Circuit

For evaluating the LED characteristics we use a measuring setup. We can monitor the required data in the Android application, connected to the system through WiFi. For this aim, we use a 1W Osram LED. We can see the LED on its test board in Fig. 20.

Figure 20 Osram 1Watt LED Test Board

In Fig. 21 we can observe the schematic belonging to the Smart Sensor circuit, and its test application. The picture in the right side is the same circuit, printed, assembled, and used in the whole Light Controlling circuit.

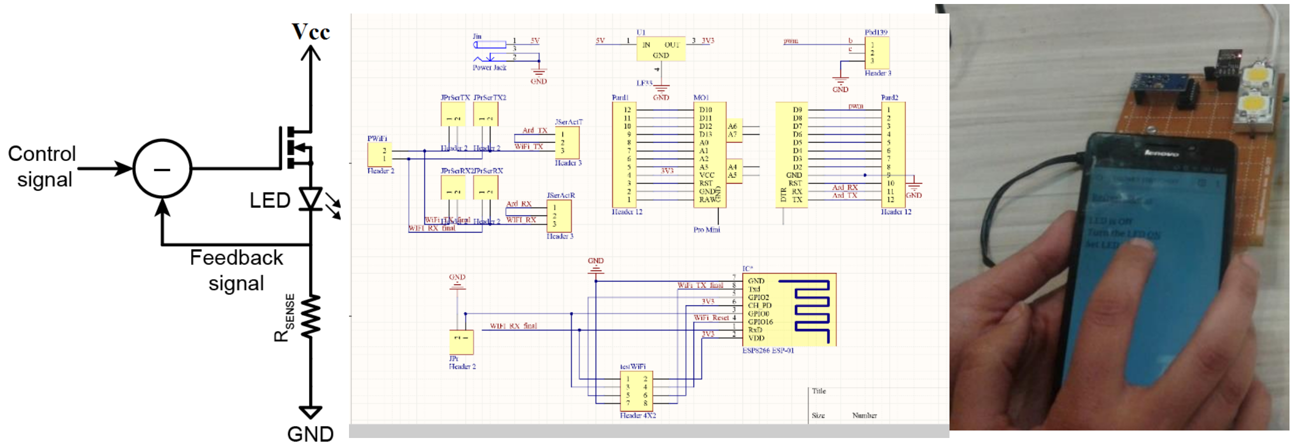


Figure 21 the Schematic Design of the LED Driving Circuit (Left), Test Circuits and Application (Right)

The second circuit, which is the Smart Sensor part, is also shown in Fig. 22. This circuit is responsible for closing the optical loop, and monitoring the ambient light level constantly, and reporting the ambient light level changes through Wi-Fi to the Smart Driver circuit, in order to adjust the LED light level, regarding the user-set light value.

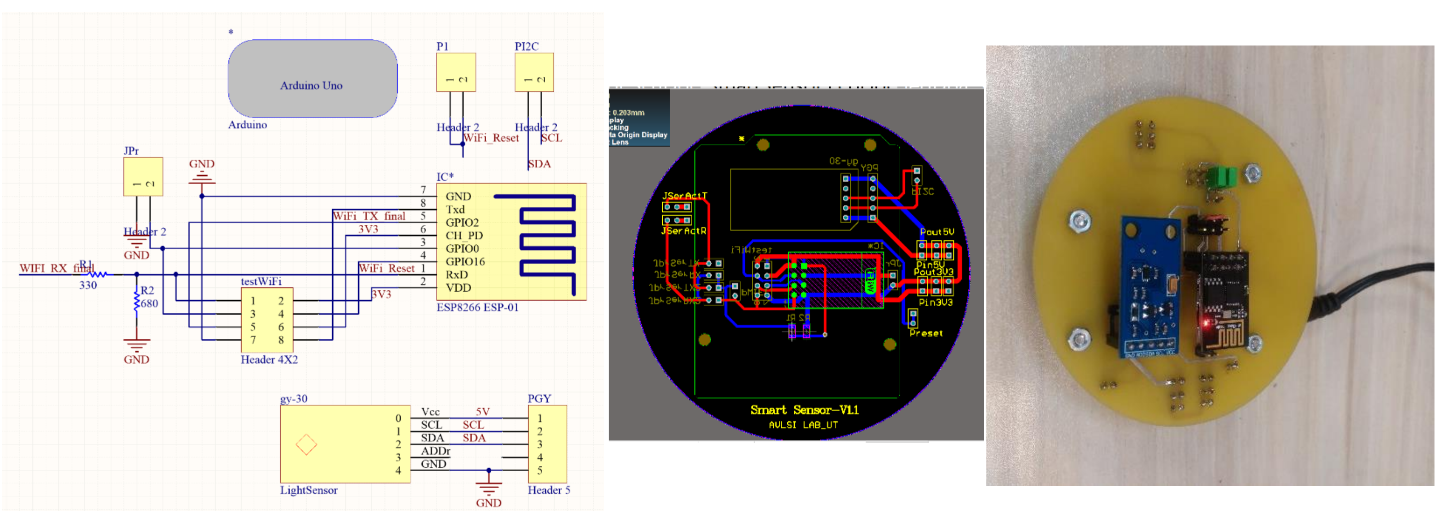


Figure 22 Smart Light Sensor with WiFi, Schematic Design (Left), PCB Design (Middle), Fabricated Circuit (Right)

Using a smart sensor configuration, connected to WiFi network, we can monitor the light status of each LED module. This network is connected to the LED driver network, so the light is constantly adjusted based on the ambient light variations.

10. Measurements

For measuring the LED characteristics and operating the experiments, we use an industrial light meter, which has a large lumens dynamic range for LEDs, extracts the spectral power distribution, performs light quality measurement, and calculates the illuminance. It's a MAVOSPEC BASE light meter from Gossen Co. Cooperating with its software, we can import all the required data to an EXCEL file.

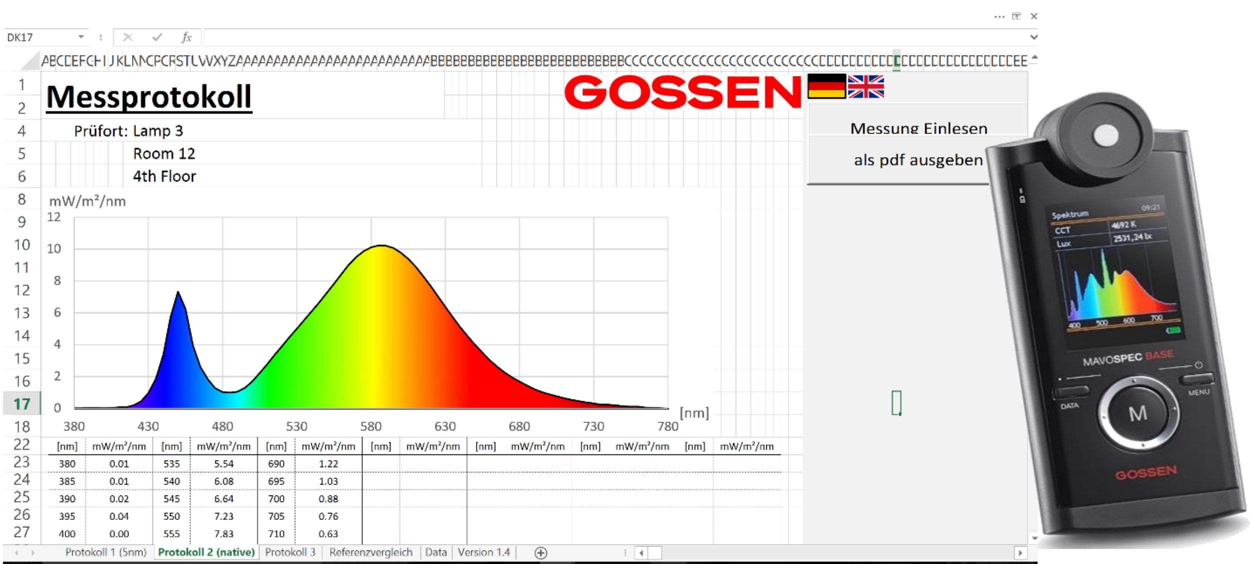


Figure 23 Gossen Measurement Equipment, the Software (Left), the MAVOSPEC Base Device (Right)

This equipment provides the following data of an LED:

- CRI, CCT
- Lumen
- x, y components of CIE1931, u, v components of CIE1960, and u', v' components of CIE1976
- CIE1931, CIE1960, CIE1976 charts
- dominant, peak wavelength

- flicker frequency, index, percentage
- effective power vs wavelength chart
- integration time
- data table of lumen, spectrum, and power

The measured current-voltage of the LED can be seen in Fig. 24. Notice that the operating point voltage of different LEDs is different. In addition, voltage to current drop rate does not have a similar pattern.

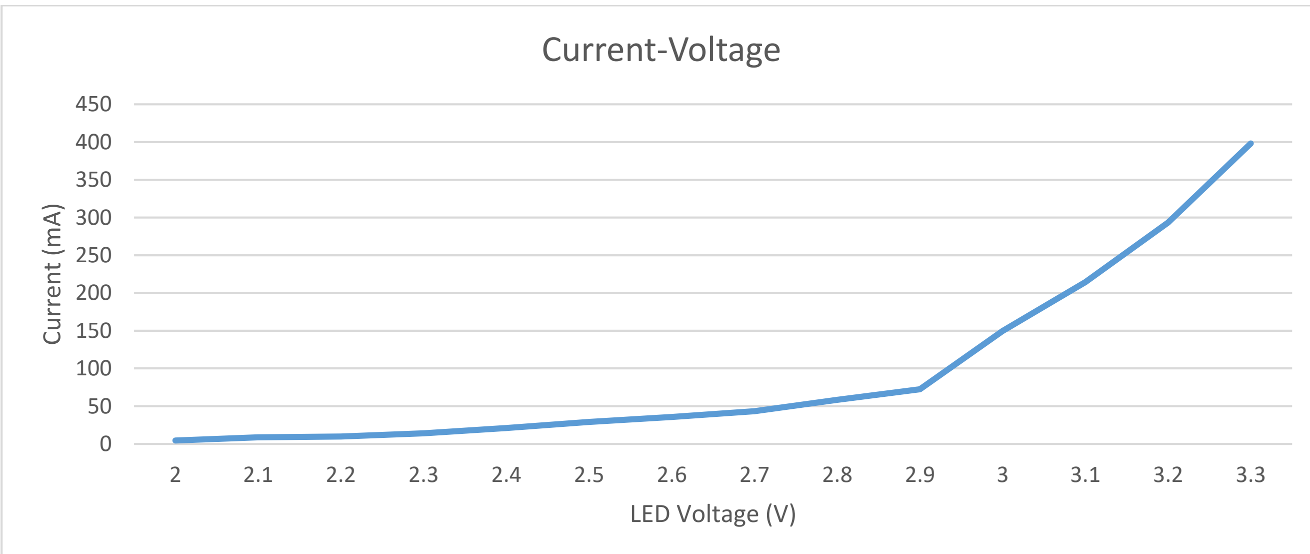


Figure 24 I-V Characteristics of the LED

In the first step, we try to prove the main assumption of this idea, which is the destructive impact of reducing the light on the light quality in AM method. By doing a simple measurement, we can compare the two AM and PWM methods in light quality. As mentioned before, CRI parameter is a parameter for comparing the light quality to the ideal or natural light source. By sweeping the light intensity in both methods, and finding the corresponding CRI in each point, we report the results in Fig. 25. It's obvious that by reducing the amplitude in AM method, and hence reducing the light level, the CRI is also reducing, while using the PWM method, since the operating voltage and current are fixed, the CRI remains almost constant.

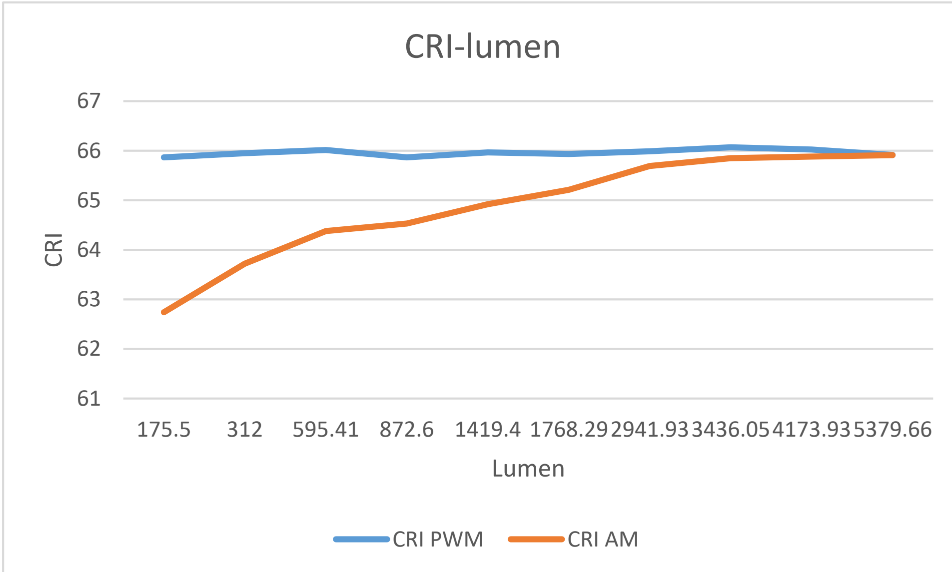


Figure 25 a Comparison between CRI Variations in PWM and AM Methods

In the second experiment, we sweep the current in AM method and we measure the power and the light intensity. By calculating the luminous efficiency, we can find the chart below. As expected, by reducing the current level from the nominal value, the luminous efficiency increases up to a certain point. Then the decrease in the light intensity becomes dominant and the overall efficiency decreases by reducing the current (Fig. 26).

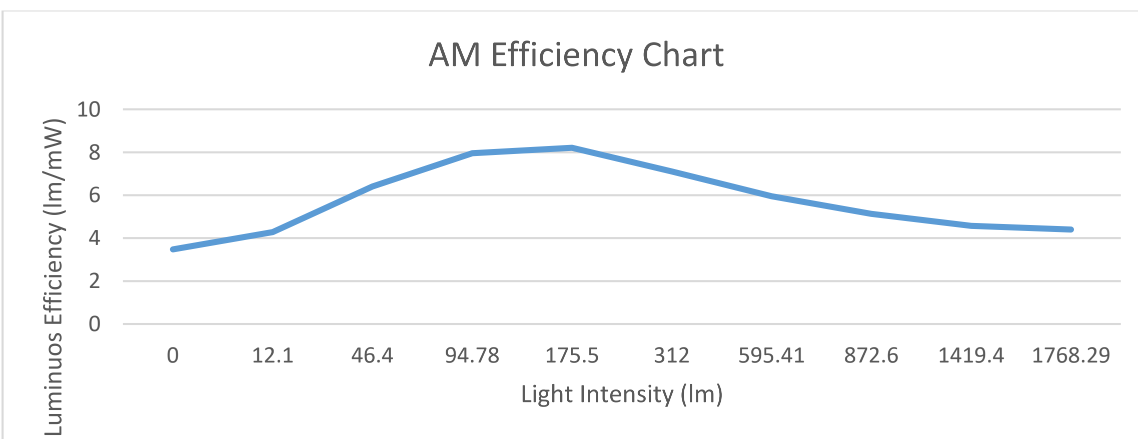


Figure 26 Evaluating the Luminous Efficiency in AM Method, with respect to LED Light Intensity

In the last step, we compare the efficiency of both methods for the same brightness value. The trend of PWM efficiency change is almost the same as AM, but the variation is lower. By finding the intersection point, we can decide the point in which we should switch between the two methods. As calculated, this point for this LED happens at the luminous efficiency of **6.02451**, **2648.52 lm**, voltage of **2.975V**, and current of **147.7728mA** (Fig. 27). Before this point (for lower light levels), we benefit from applying PWM method, its higher efficiency, and improved CRI. After this point, by applying AM method, we improve the efficiency as expected.

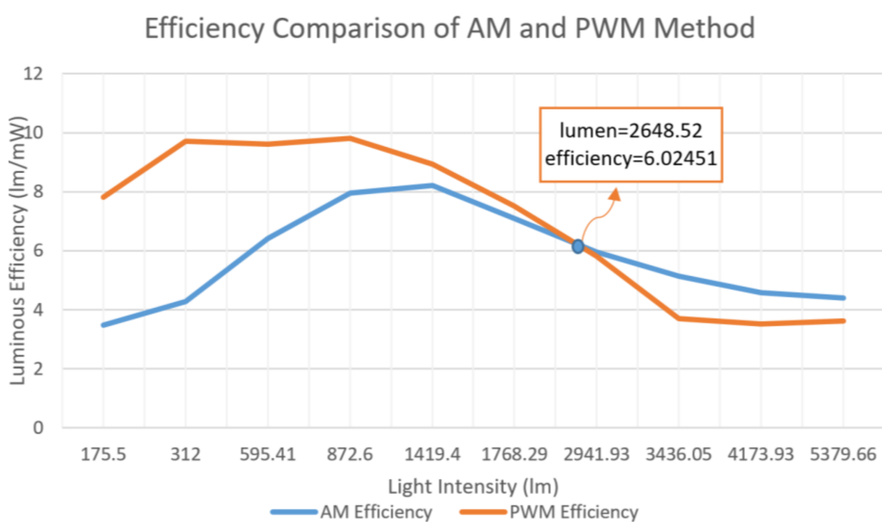


Figure 27 Finding the Switching Point of the Two Methods, by Comparing Their Luminous Efficiency

10.1. Applying PW-AM Method

After finding the switching point, in the C++ code of the Arduino processing unit, we fix the switching point between the two methods, and by writing a look-up-table in the code, we can assure that for every current, lumen value, what is expected from the output pins of the Arduino unit.

In Fig. 28, we can observe the effect of applying the PW-AM method. It's compared to the case of PWM and AM methods in the left and right parts, respectively. All the comparisons are done in the points with the same light intensity.

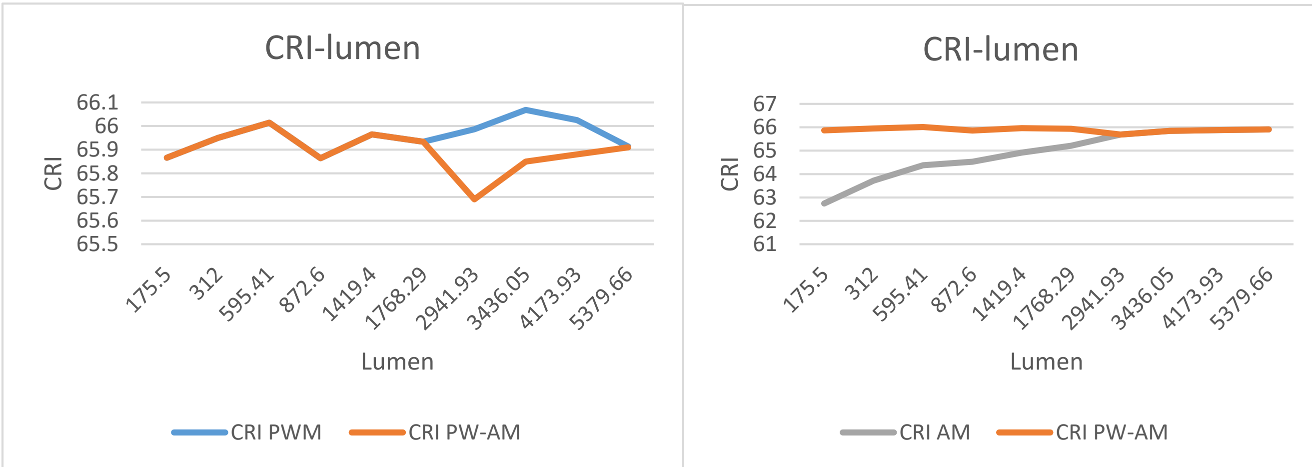


Figure 28 Comparing the CRI Value after Applying PW-AM Method to PWM Method (left), AM Method (right)

We can notice the improved CRI value with respect to AM method is 5.3% at the maximum level and 2.38% in average. However, we can also notice that this is done at the cost of reduced CRI near the maximum LED light intensity, with respect to PWM method, but at the maximum level this reduction is near 0.454% and 0.341% in average. We can conclude that the overall impact of applying PW-AM method is definitely positive for CRI enhancement.

The other important parameter, which was the luminous efficiency is improved as well. Considering Fig. 29, we can observe that by switching at the optimum point, we take advantage of both AM and PWM methods peak efficiencies. We can state that the efficiency is increased about 1.3% in the average with respect to PWM method, and 18.2% with respect to AM method.

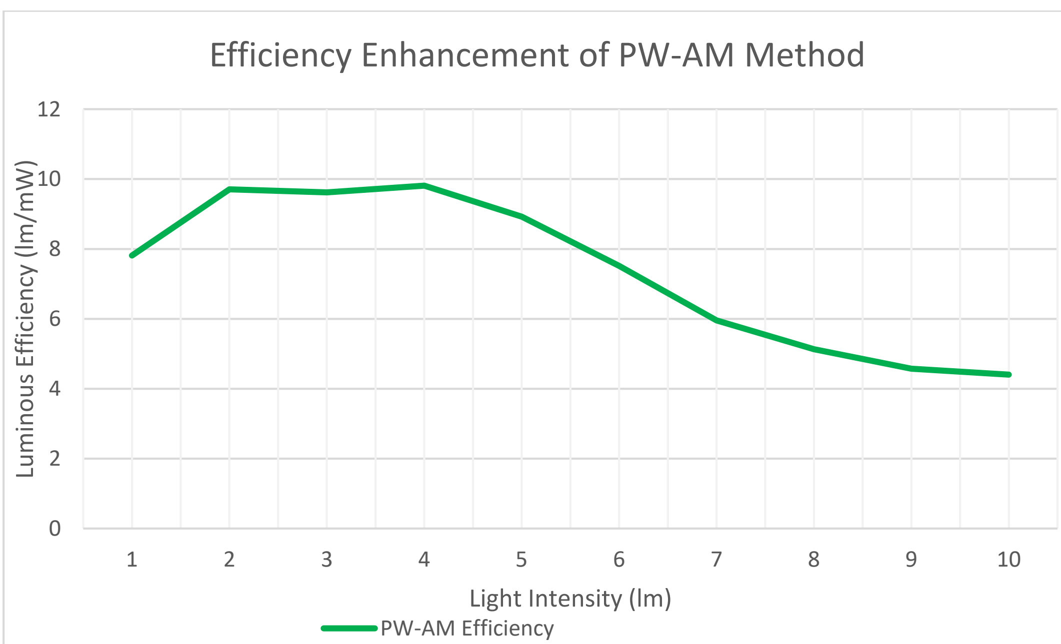


Figure 29 Luminous Efficiency of PW-AM Method vs Light Intensity

11. Conclusion

Lighting is a large and rapidly growing source of energy demand and greenhouse gas emissions. At the same time the savings potential of lighting energy is high even with the current technology, and there are new energy efficient lighting technologies coming on the market. Currently, more than 33 billion lamps operate worldwide, consuming more than 2 650 TWh of energy annually.

Any attempt to develop an energy efficient lighting strategy should, as the first priority, guarantee that the quality of the luminous environment is as high as possible. The results presented in this report demonstrate that this is achievable, even with high savings in electricity consumption. Through professional lighting design energy efficient and high quality lighting can be reached. Better lighting quality does not necessarily mean higher consumption of energy. While it is important to provide adequate light levels for ensuring optimized visual performance, there are always light levels above which a further increase in the light level does not improve performance.

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