V

Publication [V]

P. Pinho, E. Tetri and L. Halonen, "Synergies of controller-based LED drivers and quality solid-state lighting," in *Proceedings of the 2nd Conference on Ph.D. Research in MicroElectronics and Electronics - PRIME 2006*, 2006, pp. 405-408.

Synergies of Controller-Based LED Drivers and Quality Solid-State Lighting

Paulo Pinho, Eino Tetri, Liisa Halonen
Department of Electrical and Communications Engineering, Lighting Laboratory
Helsinki University of Technology
Espoo, Finland
paulo.pinho@tkk.fi

Abstract—**The present paper emphasizes the importance of electronics and microelectronics towards the future entrance of high-power light emitting diodes (HP-LEDs) in the general lighting market. Electronic controller-based drivers have a key role on the successful and rapid acceptance of solid-state lighting (SSL) products. This paper describes as an example of the SSL potentialities, a LED-base prototype luminaire with adjustable correlated color temperature (CCT) control.**

I. INTRODUCTION

The electroluminescent effect has been firstly reported 100 years ago by Henry Josef Round [1]. His experiments with SiC (silicon carbide), also known as carborundum, resulted in the first practical implementation of a light emitting diode (LED). In spite of the important scientific breakthrough, the technological development of LED was relatively slow until the mid-20th century. Red LEDs were firstly used in commercial applications as on-off light indicators. Since then the speed of development has gradually increased over the last 40 years. The main improvements have been related with light extraction, internal and external quantum efficiencies, conversion efficiency and with the compound semiconductor's structure. Consequently, besides a light indicator LEDs have become also a promising light source.

Nowadays, the entrance of LEDs in general lighting market is one of the main goals of the LED industry. Solid-state lighting (SSL), as it is commonly referred, offers new possibilities and advantages for the end-user. By providing the appropriated controls and LED types, the qualitative and quantitative aspects of the light produced can be fully controlled. Increase in work productivity, in physical and physiologic comfort or in control of metabolic cycle together with better light utilization and improved energy efficiency are just a few of the benefits which can be attained with SSL.

Good-quality white light can be achieved by appropriated control of the spectral power distribution of the light. Color mixing using colored LEDs is the ideal way to do it. By applying correct control strategies to drive the different color LEDs is possible to control or select the light level, the correlated color temperature (CCT) with the highest color rendering index (CRI) possible for proper reproduction of the colors.

Nowadays the applications involving LEDs are innumerable and its varieties impose a clear demand on design of controllable LED drivers. In most of today's applications power converters, power conditioning, controllers and microcontrollers are in the great majority of the cases indispensable components of an LED system. As the LED technology evolves, the possibilities for new and more intelligent products enlarge the demand for more specific features from the controller-based LED drivers.

Here are presented the key features and more significant advantages of SSL, its development trajectory, emphasizing the importance of controller-based drivers in the present and in the future. The control strategy used to adjust and control the CCT and light level of a prototype LED fixture is described as a case example to demonstrate the potentialities of the SSL technology.

II. SOLID-STATE LIGHTING

A. *Energy Efficiency*

The entrance of LEDs in the lighting market it is dependent on future improvements in conversion efficiency and optical power per package. Although most of the high-power LEDs (HP-LEDs) nowadays convert between 15 to 20% of the input power into light, their efficiency potential is far better. In fact the best AlInGaP (aluminum indium gallium phosphide) red LED and InGaN (indium gallium nitride) green and blue LEDs can have internal quantum efficiencies which can reach almost 100% and 50%, respectively. To achieve external quantum efficiencies close to that magnitude, the light extraction has to be improved. By allowing more photons to escape from the LED chip without been absorbed by the surrounding structure, is one of the main design challenges which has to be addressed in order to increase the device conversion efficiency and the radiant power per device.

Considering that approximately 20 to 25% of the total energy produced in developed countries is consumed by lighting, places LEDs in general and SSL in particular, between the main potential energy-efficient technologies in the future. OIDA (Optoelectronics Industry Development Association) roadmap on LEDs for general illumination produced in collaboration with US Department of Energy, predicts that by the year of 2025 the total amount of energy used for lighting will be reduced in 50% due to SSL [2]. By that time a white LED with warm CCT similar to incandescent lamps, will produce 50% light and 50% heat and will have a luminous efficacy of 160lm/W. Nowadays, traditional white light sources such as incandescent, halogen, fluorescent and high-pressure sodium lamps have luminous efficacies of approximately 15, 25, 80 and 150lm/W, respectively. Due to technical and material limitations those efficacies are likely to remain the same in the future. Conversely, the two main techniques commonly used to produce white light with LEDs, by color mixing and by phosphor down-conversion, still have large space for improvements. However, the development and advantages that SSL might bring has to be supported by efficient and reliable electronic drivers with appropriated control strategies. The development of LED drivers, which are capable of responding to the increasing and more demanding applications, are definitely essential for the successful arrival of LEDs to the general lighting market.

B. *White Light from blue and ultraviolet LEDs*

The advent of solid-state lighting has become feasible when the first viable blue LED has been demonstrated by Shuji Nakamura in mid-90th [3]. Nowadays blue LED-based white light is produced by covering the chip with a yellow phosphor such as YAG:Ce (cerium-doped yttrium aluminum garnet). The combination of the blue light emitted directly from the LED chip and the yellow light resulted from the blue light down-converted by the phosphor, results in white light. A similar approach based on phosphor down-conversion uses UV (ultraviolet) LED together with triphosphors emitting in the blue, green and red region of the electromagnetic spectrum. In this situation the UV light is totally converted into visible white light by the triphosphors layer. Other phosphor-based combinations are possible but their main disadvantage is the additional losses created by the phosphor layers reducing the LED's overall efficiency. Further efforts are been done in order to improve the conversion efficiency of phosphors. Especially, efficient red phosphors are essential to effectively and efficiently compete with our well known incandescent lamps, which have CCTs around 3000K and CRI of 100. Recent developments on phosphor-converted white LEDs (pc-WLEDs) have revealed luminous efficacies raging between 70 and 100lm/W in laboratory conditions with CRI over 80. In future, nanoparticles or quantum dots can be a viable, efficient and versatile technological solution to substitute conventional phosphors on LEDs.

C. *White Light from Color Mixing*

White light can be produced by mixing the radiant emission of different color LEDs. The advantages in terms of efficiency and controllability of the white light quality of such type of multi-wavelength LED (MW-LED) fixture are superior comparing to white pc-WLEDs. Fig. 1 shows a MW-LED fixture with dimming and CCT (correlated color temperature) control using the LED's forward voltage as feedback variable [4].

Figure 1. MW-LED fixture with adjustable CCT control

MW-LED fixtures can provide good quality white light with excellent energy performance potential. Theoretical maximums for the luminous efficacies can in some cases be superior to 400lm/W [5].

Although LEDs can be easily controlled, in arrays composed of different color LEDs such as in MW-LED fixtures, the situation is more complex. The main difficulty results from the control complexity due to the different binning and thermal behavior of the LEDs composing the cluster. Due to technical limitations during the epitaxial growth of the semiconductor wafer, the LEDs yielded have differences in their spectral and radiant power. Moreover, LEDs are temperature-dependent devices. The optical and spectral emission of different compound semiconductor materials from which color LEDs are made-of, behave differently with the temperature. AlInGaP LEDs such as red and amber are more sensitive to temperature than InGaN-based such as royal blue, green, white, blue and cyan LEDs. Fig. 2 shows the evolution of light output of colored LEDs in respect to the p-n junction temperature.

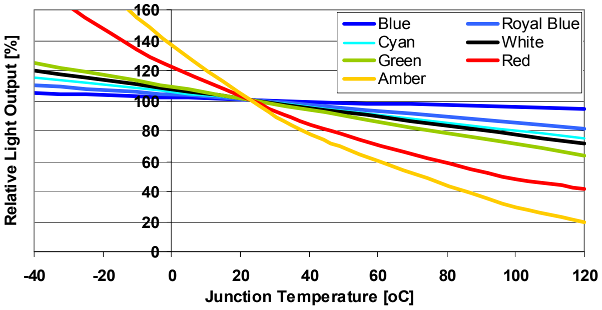

Figure 2. Relative light output of different colored LEDs in fuction of the junction temperature.

The spectral changes resulting from the dissimilarities of AlInGaP and InGaN-based LEDs can be even more severe if the thermal management is not properly taken into account. Therefore, the optical emission of the different group of LEDs composing the array has to be compensated in function of its p-n junction temperature. This will allow maintaining the whiteness of the light produced as close as possible to the required operation point.

III. MW-LED Fixture With Ajustable CCT Control

Different techniques are possible to control the white light produced by a MW-LED fixture. Here, a control strategy used to adjust and control the dimming levels and the CCT with high CRI is presented as a case example.

A. LED Cluster Composition

The LED cluster is composed by 61 LEDs placed in form of a circle. Royal blue, green, amber and red LEDs were the chosen colors to produce the white light. Fig. 1 shows the LED array of the MW-LED fixture. The dominant wavelengths and number of LEDs of each color composing the cluster are presented in table I.

TABLE I. Dominant Wavelengths of the LEDs and Their Respective Quantities

Color	Wavelength (nm)	No. of LEDs
Royal Blue	455	12
Green	530	25
Amber	590	17
Red	652	7

B. Control and Operation

The block diagram shown in Fig. 3 and flowchart in Fig. 4, represent the general control scheme of the luminaire and its operation, respectively. In this application the CCT and the dimming levels can be set by the user on a PC which is connected to the microcontroller (µC) via a PLN (power line communications) modem. An 8-bit PWM is used for dimming the LEDs.

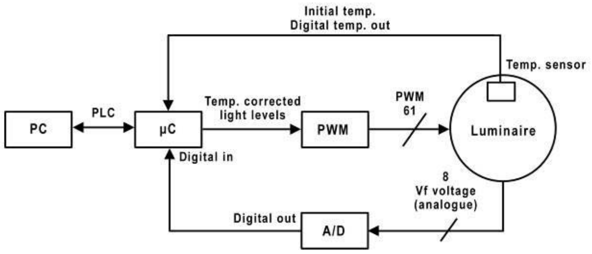

Figure 3. Control scheme the MW-LED fixture with controllable CCT and light level.

For each CCT selected by the user, within a 50-K step interval, there are pre-calculated intensities to each group of color LEDs. The computer selects the right values and multiplies those with the dimming level. The data is sent to the control system where the p-n junction temperature Tj has been calculated based on the measured forward voltages using (1).

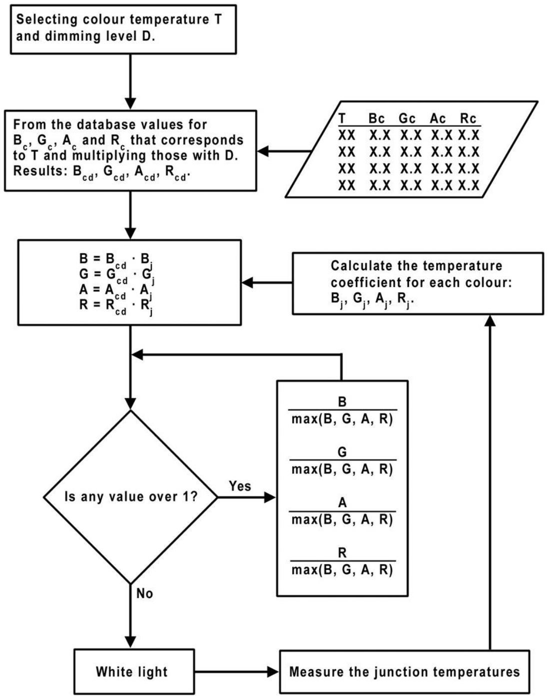

Figure 4. Flowchart showing the operational principle of the MW-LED fixture's control.

$$Tj \approx (Rj\text{-}b \bullet Vf \bullet If) + Tb \tag{1}$$

Where Rj-b is the thermal resistance from the junction to the board, Vf is the forward voltage, If is the forward current and Tb is the board temperature.

When the luminaire is turned on it will initialize itself. In the first five milliseconds it will measure the temperature of the combination of the (metal-core printed circuit board) MCPCB and the heatsink with the temperature sensor installed on the circuit board. Simultaneously, the system measures the forward voltages of the eight LEDs. From these initial the initial values for Tj are calculated according to (1). The previous measurements and calculations provide the reference value to each LED, the junction temperature from where the corresponding forward voltages are obtained overcoming in that way the problem of different forward voltages in various LEDs.

After the initialization the forward voltage measurements are taken within every 100 ms. For each LED, a junction temperature-dependent luminous flux characteristic has been assigned. Based on such characteristics given by the manufacturer's datasheet the luminous flux expressions are derived and scaled so that the reference flux should be the one obtained at junction temperature equal to 70 ºC.

The temperature coefficients for all color LEDs are determined using the above referred expressions. The control system multiplies the values send by the computer with the temperature coefficients. After that it checks if any value is over 100 %. If some value is over 100 %, all the values are scaled so that maximum value would be 100 %. The results of the calculation are intensities for each color and resulting light should be white light with the desired color temperature.

C. Performance Evaluation

Fig. 5 shows the temporal evolution of the spectral power distribution and consequently the CCT, of the white light produced by the MW-LED fixture. Spectral measurements were taken at 5 s and 10 min after turned on the luminaire at room's ambient temperature of 25 ºC. The control scheme based on the measurement of the LEDs' forward voltage has shown an acceptable but not ideal CCT control. Certain grade o controllability has been achieved by controlling the CCT within a 33K interval. Therefore further improvements have to be done namely, by using exponential expressions instead of linear ones for the temperature-depend luminous flux characteristic of red and amber LEDs.

No spectral measurements were taken at different ambient temperature because it is expected that the control system will have a similar performance and control behavior, resulting from the fact that the junction temperature and consequently the forward voltage of the LEDs will vary proportionally to the ambient temperature. This means that ideally the light intensity ratio between the different group of color LEDs would be maintained in order to have as constant as possible the chromaticity coordinates, the CCT and the CRI of the light produced, independently of the external operation conditions.

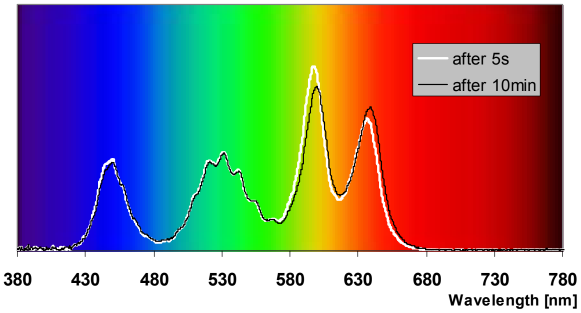

Figure 5. Spectral power distribution of a MW-LED fixture at 5 seconds and 10 minutes after switched-on at ambient temperature of 25ºC.

The maximum energy efficiency potential of the fixture without taken into account the driver stage, is approximately 330lm/W, with a CCT around 3400K and general CRI of 88.

IV. CONCLUSIONS

Due to the monochromatic nature of LEDs', spectral emission and its controllability, the qualitative aspects of the white light can be finally controlled by the end-user. Control strategies and the means to do it, will pave the way for intelligent and quality SSL. Such applications will have to integrate microcontrollers, power conditioning and LED arrays in order to make compact and practical fixtures for better market acceptance.

While solid-state light sources experiment rapid technological developments, the drivers and control strategies have also to be adapted to that. Microelectronics and electronics provide the means to do it and will be one of the key factors helping to develop and accelerate the penetration of solid-state lighting and related products on the market.

The LED drivers' controllers can be ideal interfaces for communication protocols such as DALI (digital addressable lighting interface) and DMX (digital multiplex) which will allow the end-user to have full control of the light source. Moreover, by using feedback control loops in the form of current, voltage, temperature or optical signals will furthermore enhance the capability of future intelligent solid-state light sources. Therefore, the sophistication of the drivers is likely to increase along with the increasing number of more demanding applications. The gradual inclusion of sophisticated electronic drivers in solid-state light fixtures will make the future of such light sources even brighter.

ACKNOWLEDGMENT

The author would like to thanks all participants in the LED-PLC project for their valuable work during the development of the MW-LED fixture with controllable CCT, which is partially described in this paper.

REFERENCES

[1] H. J. Round, "Discovery of electroluminescence - blue light emission from Silicon Carbide (SiC)," Electron World 19, 1907, p. 309.

[2] Optoelectronics Industry Development Association (OIDA), "The promise of solid state lighting for general illumination – Light emitting diodes (LEDs) and organic light emitting diodes (OLEDs)", 2001.

[3] S. Nakamura, G. Fasol, "The blue diode laser - GaN light emitters and lasers," Springer-Verlag, Berlin, 1997, p. 343.

[4] O. Moisio, M. Pajula, P. Pinho, E. Tetri, L. Halonen, R. Sepponen, "Use of junction temperature in control of CCT in LED luminaire," CIE Midterm Meeting and International Lighting Congress, Léon, Spain, 12.5.-21.5.2005, in press.

[5] Y. Ohno, "Color Issues of White LEDs", A section in "Solid state light emitting diodes for general illumination," OIDA Workshop Preliminary Report, October 26-27, 2000.