Study of High Brightness RGB Light-Emitting Diode Color Control Systems

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***Abstract*-This article is related to development of modern lighting systems, based on LEDs. There are several methods, how to get white color light using LED technology. This article considers RGB method, so careful attention paid for the control of light color. In this article existing solutions of RGB LED light control systems are compared in order to identify better of them and to adapt it for high brightness high power LEDs.**

I. Introduction

Light-emitting diodes (LEDs) are becoming more popular as general lighting solution due to reliability, excellent energy efficiency and color rendering index [1]. It looks that other artificial light sources have reached their capabilities for improvement, while LED technology continues to develop in field of efficiency rising.

Working separately, researchers at North Carolina State University (NC State) and the U.S. Department of Energy's National Renewable Energy Laboratory (NREL), respectively, have proposed a method for improving general LED efficiency and a technique for making RGB-process white light better [2].

Scientists from NC State and NREL have proposed introducing “voids” into semiconductor materials like gallium-nitride (GaN) films, trying to compensate for defects in these materials. This improves quality of the material that emits light, so that the efficiency of LED can be increased by factor of two.

In the same time scientists at NREL found a potentially new approach to producing truly green-emitting LEDs [2], which in turn could make producing white light even more efficient.

There are several approaches to making white light with LEDs. Relatively less efficient method is to uses yellow-green phosphorescent substances with blue LED (today most popular technology) or three color phosphorescent substances with ultraviolet LED. The problem is that with using of phosphor additional energy conversion stage appears, leading to additional losses.

Using of RGB LEDs theoretically is a most efficient approach to get white light. To date some problems hindered the development of white light RGB LEDs. RGB research has not produced high-quality white light because of lack of deep green LEDs (‘Green Gap’, inability of current LEDs to produce light in the wavelength range of 530 to 570 nanometers).

NREL researchers were able to produce an LED that emits light at a wavelength of 562 nm i.e. deep green light [2].

Assumption may be done that in future with new researches in this area RGB LEDs can be a major source of artificial white light. So this article considers on high power RGB LED light color control systems, which may be actually in near future.

II. RGB LED Spectral Distribution

Fig. 1 shows spectral distribution of RGB LED, used in experiments. This figure shows described above problem – lack of deep green. This leads to the fact that it is difficult to get good quality white color light with today available RGB LEDs.

In the ideal case white color light consists of all visible wavelength radiation.

III. RGB LED Current-Voltage Curves and Fitting Curves

For experiments single chip high brightness LEDs were used. Current-voltage curves for each color chip were detected (Fig. 2).

During data processing was revealed that 3rd order polynomial function best fits to this data (Fig. 2). Then fitting function of volt-ampere curve for red color chip looks as:

$$I_{FR} = 3.005 \cdot 10^{-7} V_{FR}^{\;3} - 1.393 \cdot 10^{-3} V_{FR}^{\;2} + \\ + 2.119 V_{FR} - 1.053 \cdot 10^{3}, \quad (1)$$

where I_{FR} is red chip forward current in mA and V_{FR} is red chip forward voltage in mV.

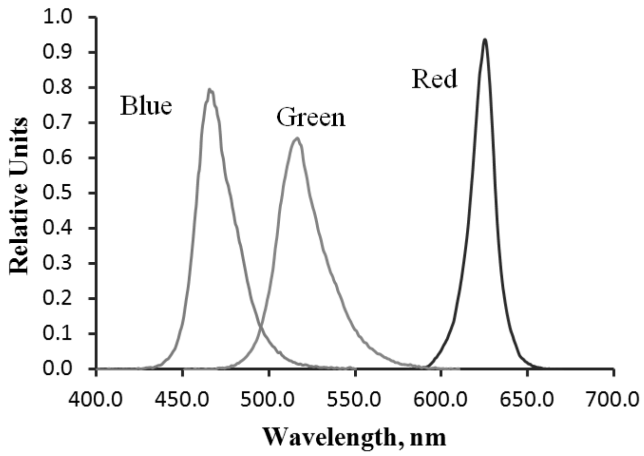

Fig. 1. Spectral distribution of RGB LED used in experiments.

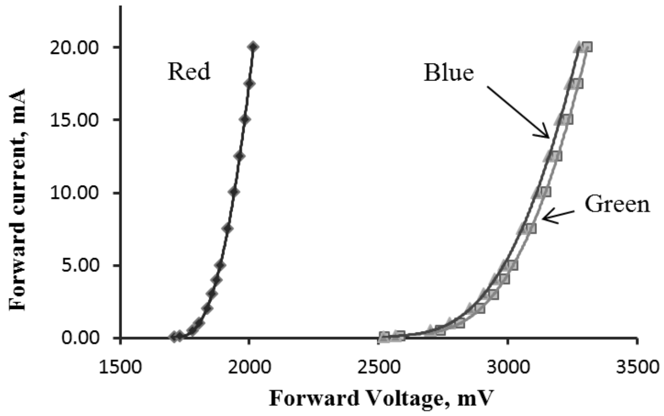

Fig. 2. Current-voltage curves of RGB LED for separate color chips (utilized in experiments LED).

In the same way fitting functions for green (2) and blue (3) color chips were determined.

$$I_{FG} = 4.206 \cdot 10^{-8} V_{FG}{}^{3} - 3.181 \cdot 10^{-4} V_{FG}{}^{2} + \\ + 8.012 \times 10^{-1} V_{FG} - 6.722 \cdot 10^{2} \quad (2)$$

$$I_{FG} = 4.048 \cdot 10^{-8} V_{FG}{}^{3} - 3.010 \cdot 10^{-4} V_{FG}{}^{2} + \\ + 7.453 \times 10^{-1} V_{FG} - 6.146 \cdot 10^{2} \quad (3)$$

Current-voltage fitting functions (1), (2) and (3) are true for range of voltage or current of considering current-voltage curve in Fig. 2 because fitting functions were constructed from these experimental data.

IV. LED Light Output Regulation by Forward Current

Today in lighting industry more popular are becoming "smart" solutions because it leads to significant energy savings. It means to use lighting control solutions, which give opportunity to produce light when and where it is needed. For this purpose smooth light flux should be provided.

Luminous flux of LED is proportional to the forward current. Also the light produced by LED follows its current at a very high rate [4].

There are several methods, how to regulate brightness of LED produced light, such as LED fluent current regulation, LED current pulse mode regulation and control by switching groups of LEDs in luminary (step mode luminous flux regulation) [3].

LED fluent current regulation is preferable for "smart" lighting systems as this method is the most flexible. In LED current pulse mode regulation method flickering may appear as produced light follows LED almost immediately [4].

LEDs are low voltage elements, so they usually are connected in series. In this case current for all LEDs is the same. The problem is that single chip LEDs produce relatively small amount of light, but number of series connected LEDs is limited by voltage across this string of LEDs. Also greater number of series connected LEDs decrease reliability of system, because failure of the one LED leads to failure of whole system.

High power LEDs can solve small light amount problem. High power LED consists of several LED chips, which are located in single case. In such a way LED manufacturers get rid from several problems, appearing in production of LED chips. Even one type LED chips have significant forward voltage variations, which makes it difficult to connect LED chips in parallel. Connecting LEDs in parallel leads to unequal division of current between these chips. Also with temperature variations changes parameters of LED current-voltage curve. Voltage variation problem solve by sorting of LED chips. Temperature variation problem solve by using of single case for parallel connected chips.

Depending on manufacturer, chips in high power LEDs are connected in parallel (increasing current) or in series-parallel forming matrix of chips (increasing current and voltage, Fig. 3).

So for calculations it is possible to use high power LED current-voltage curve created from single chip current-voltage curves (Fig. 2).

To get fluent current regulation i.e. fluent light regulation it is necessary to use DC/DC convertor, which operates in current mode. So the current control feedback must be investigated. There are several topologies available for those converters: buck, boost and buck-boost. There also several control methods of those topology converters: pulse width modulation (PWM) and frequency modulation (FM), which is divided in two subtypes. These subtypes are constant pulse frequency modulation (CPFM) and constant pause frequency modulation (CZFM) [5].

According to [5] using of buck converter is the most efficient solution, if difference between input and output voltages is quite a small. So in this section calculation of necessary for regulation duty ratio changes and frequency changes will be considered.

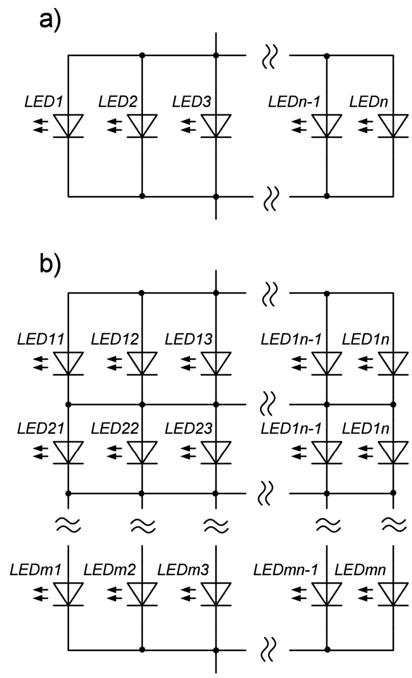

Fig. 3. Principal schematics of chip connections in high power LED: a) parallel connection; b) matrix connection.

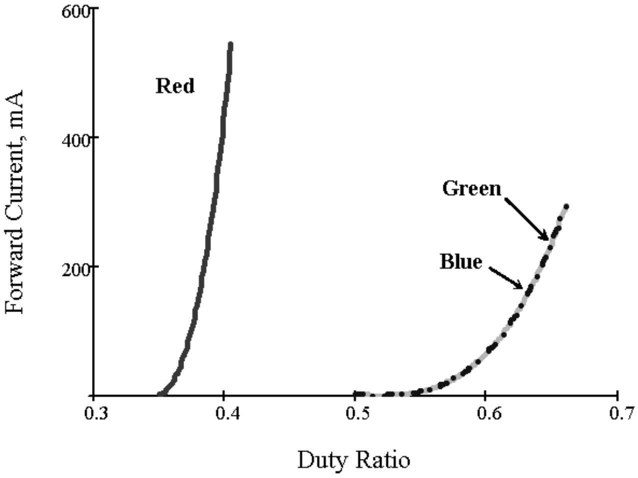

Fig. 4. Different color LED forward current dependence from duty ratio for PWM control method at 5V input voltage and constant frequency.

Making assumption that buck converter operates at continuous current mode (as current driver) and components are ideal, relation of output voltage to duty ratio in PWM case looks as follows:

$$\frac{V_{LED}}{V_{in}} = D\,, \qquad (4)$$

where V_{LED} is converter output voltage i.e. LED string forward voltage V_F, V_{in} is converter input voltage and D is duty ratio – the ratio of positive pulse of the control signal to the period of this control signal.

Relation of output voltage to control signal frequency f in CPFM case describes following equation (assumptions the same as in case with PWM):

$$\frac{V_{LED}}{V_{in}} = t_{on} \times f\,, \qquad (5)$$

where t_{on} is time of positive pulse of control signal in seconds and f is frequency in hertz.

Relation of output voltage to control signal frequency f in CPZM case describes following equation

$$\frac{V_{LED}}{V_{in}} = \frac{(1 - t_{off})}{f}\,, \qquad (6)$$

where t_{off} time of control signal zero state.

Let's assume that it is necessary to get 1W LED current-voltage curve for red color. One red color LED chip provides about 40mW then it is necessary to use about 25 red color LED chips, to provide 1W power. In this case fitting function (1) must be rewritten as:

$$25 \times I_{FR} = 3.005 \cdot 10^{-7} V_{FR}{}^{3} - 1.393 \cdot 10^{-3} V_{FR}{}^{2} + 2.119 V_{FR} - 1.053 \cdot 10^{3}. \qquad (7)$$

Combining expressions (4) and (6) we obtain relationship of red color 1W LED current from duty ratio (PWM control method):

$$I_F = [3.005 \cdot 10^{-7} (D \cdot V_{in})^3 - 1.393 \cdot 10^{-3} (D \cdot V_{in})^2 + 2.119 (D \cdot V_{in}) - 1.053 \cdot 10^3] \cdot 25. \qquad (8)$$

In the same way relationship of current from duty ratio (Fig. 4) for green (8) and blue (9) color 1W LED can be written:

$$I_F = [4.206 \cdot 10^{-8} (D \cdot V_{in})^3 - 3.181 \cdot 10^{-4} (D \cdot V_{in})^2 + 8.012 \times 10^{-1} (D \cdot V_{in}) - 6.722 \cdot 10^2] \cdot 15, \qquad (9)$$

$$I_F = [4.048 \cdot 10^{-8} (D \cdot V_{in})^3 - 3.010 \cdot 10^{-4} (D \cdot V_{in})^2 + 7.453 \times 10^{-1} (D \cdot V_{in}) - 6.146 \cdot 10^2] \cdot 15. \qquad (10)$$

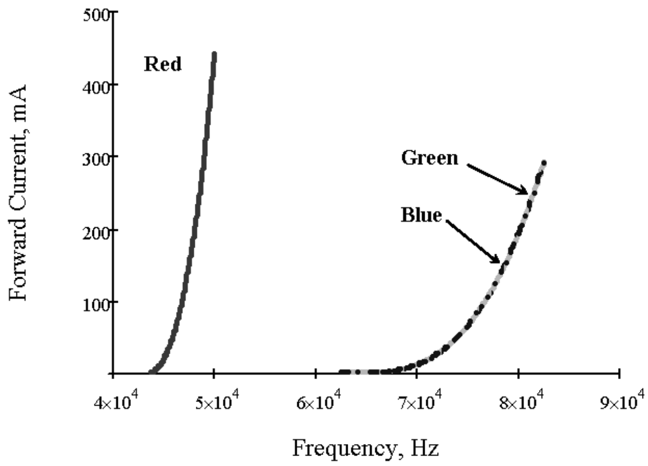

Fig. 5. Different color LED forward current dependence from frequency for CPFM control method at 5V input voltage and constant positive pulse time $t_{on}=8\mu s$.

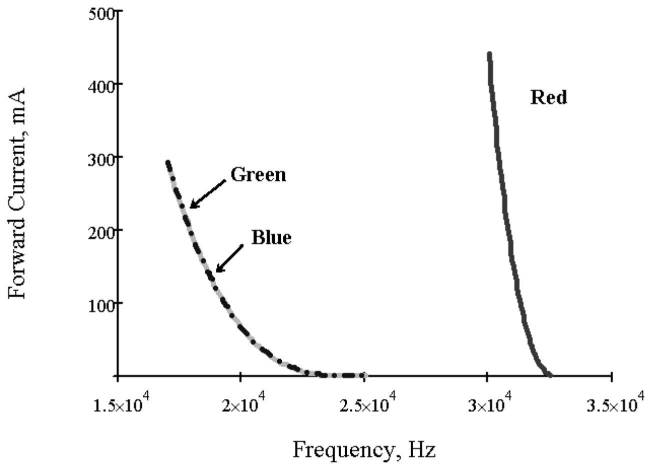

Fig. 6. Different color LED forward current dependence from frequency for CZFM control method at 5V input voltage and constant zero state time $t_{off}=20\mu s$.

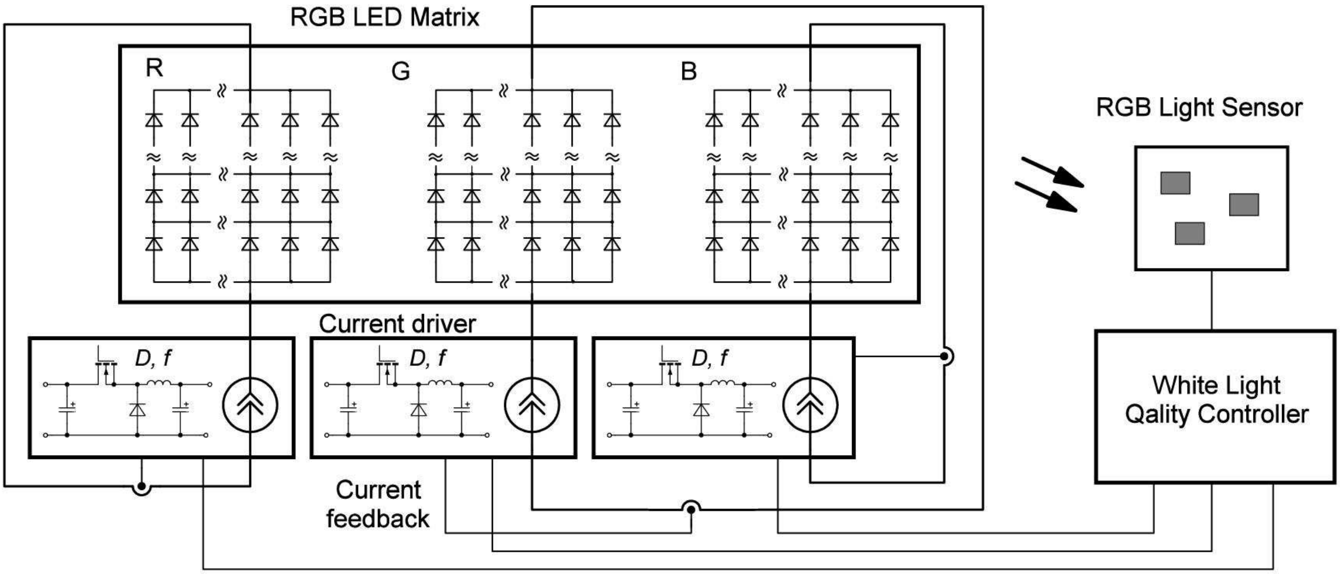

Fig. 7. Block schematics for control system of RGB high power LED.

Combining expressions (5) and (6) we obtain relationship of red color 1W LED current from control signal frequency (CPFM control method, Fig. 5):

$$I_F = [3.005 \cdot 10^{-7} \left(t_{on} \cdot f \cdot V_{in}\right)^3 - \\ -1.393 \cdot 10^{-3} \left(t_{on} \cdot f \cdot V_{in}\right)^2 + \\ +2.119 \left(t_{on} \cdot f \cdot V_{in}\right) - 1.053 \cdot 10^3] \cdot 25. \quad (11)$$

In the same way expressions for green and blue color 1W LEDs can be written.

Combining expressions (6) and (7) we obtain relationship of red color 1W LED current from control signal frequency (CZFM control method, Fig. 6):

$$I_F = [3.005 \cdot 10^{-7} \left((1 - t_{off} \cdot f) \cdot V_{in}\right)^3 - \\ -1.393 \cdot 10^{-3} \left((1 - t_{off} \cdot f) \cdot V_{in}\right)^2 + \\ +2.119 \left((1 - t_{off} \cdot f) \cdot V_{in}\right) - 1.053 \cdot 10^3] \cdot 25. \quad (12)$$

Also in this case expressions for green and blue color 1W LEDs can be written.

V. CONCLUSIONS

LED current control provides the best result of fluent light regulation, which is very important for modern "smart" lighting systems. DC/DC switching mode converters, which operates in current mode provides excellent luminous flux regulation.

In this paper calculations of control parameters for buck converter at different control methods were considered.

Management of such converter can be implemented using a microcontroller (MCU) with current feedback (Fig. 7).

In case of using MCU it is critical to choose correct control range for DC/DC switching mode converter. This allow to increase number of steps of regulation, because buck converter is voltage source, but LED current changes at a very high range with even small voltage variations. Especially it is critical for RGB LEDs, when regulation range depends of LED color.

Also experimental data is expected soon.

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