

ANALYSIS OF A FEEDBACK DRIVER FOR SEMICONDUCTOR LIGHT SOURCES

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Abstract – The paper presents analysis of an electronic system of a driver with the feedback optical loop used for stabilization of radiation power of a semiconductor light sources such as CW laser diodes (LDs) or light-emitting diodes (LEDs). The analysis has permitted derivation of the strict form of static equation describing the relation between the optical output power and the electrical driving signal. The considerations are based on general feedback analysis procedures. A detail metrological analysis of the influence of instabilities in the parameters of the driver system on the value of the optical power of light source is presented

Keywords: laser driver, stabilized source of light, automatic optical power control

1. INTRODUCTION

In many measuring applications, the use of semiconductor sources of light e.g. light-emitting diodes (LEDs) and laser diodes (LDs) is a promising alternative to conventional light sources such as filament lamps, xenon lamps and lasers [1]. In particular the technology of high-power LEDs has progressed rapidly in recent years and currently LEDs can successfully replace high-power conventional light sources in many optoelectronic applications.

The light sources used for measuring purposes must meet the requirements of high stability of the power of the emitted radiation. On the other hand, it is well known that radiant output power of these semiconductor sources of light is strongly dependent on temperature. It is worth noting that the stabilization of the emitted optical power is especially important for the proper operation of the laser diodes because the temperature increases can stop functioning of the laser diode and on the other hand the temperature decreases may cause catastrophic damage of laser diode [2-4]. Thus, an important problem is to work out the design of construction of the semiconductor light source driver system to minimize influence of disturbing factors on output power radiation. One solution of the problem to maintain a constant radiant power of the light source involves the use of a system consisting of a photodiode monitoring the intensity of the light source and a system of feedback loop which can adjust the current supplied to the light source. These systems are called the automatic power control [2] or light source drive circuit with optical feedback loop and

generally their principle of operation is well known [2-7]. Many interesting constructions of driver systems with optical feedback loop dedicated to stabilization of intensity of semiconductor source of light have been reported widely in literature [2-7]. However, the authors of these papers have not been concerned with the analytical side of the problem aimed at derivation of the equation expressing the relation between the input signal of the driver (command signal) and the output signal (emitted optical power of the light source). They have used the approximated form of the equation describing this relationship. Such an approach is possible, but only assuming that the controller gain in the feedback driver system achieves very high value. In practice, in many feedback drivers the gain controller does not exceed the value of a few dozen and then it is recommended to use the accurate form of the transfer equation.

This paper presents a design and analysis of the feedback driver system for LEDs source of light. In the intention of the author, the driver system designed with the optical feedback and a controller of proportional type (P) is an exemplary object for more accurate studies of this system based on feedback control analysis procedures. The main goal of the study was to derive the exact form of the static equation describing the relation between the optical output power and the electrical driving signal (command signal). This equation is expected to enable detail metrological analysis of the influence of instabilities in the parameters of the driver system on the value of optical power of the light source.

2. SYSTEM OF THE LEDS DRIVER WITH OPTICAL FEEDBACK LOOP

The designed LEDs driver system allows both setting the optical power level and maintenance of a constant value of the optical power of LEDs connected in series. In topology of this driver system, a controller of proportional type (P) is implemented. The scheme of the LEDs driver system is shown in Fig. 1.

The radiation-emitting element is the head comprising from a few to a few ten LEDs connected in series (LEDs array), depending on the technical version applied. The LEDs are controlled by a current supplied with negative feedback based on the operational amplifier *M3* and the power amplifier on a unipolar transistor made in the IFET technology (voltage-current converter). In the presented

scheme of driver, stabilization of the LEDs radiation power is realized by the automatic control system with the optical feedback loop. The optical power of LEDs is monitored by the photodiode $D1$ (the feedback sensor). Since the photodiode is linear, the photoelectrical current I_F of this photodiode is directly proportional to the LEDs optical power P_{LED} . The photodiode current I_F causes the voltage drop across the resistor R_F . This voltage signal via the voltage follower $M1$ is applied to the inverse input of the difference amplifier $M2$, operating as a proportional controller.

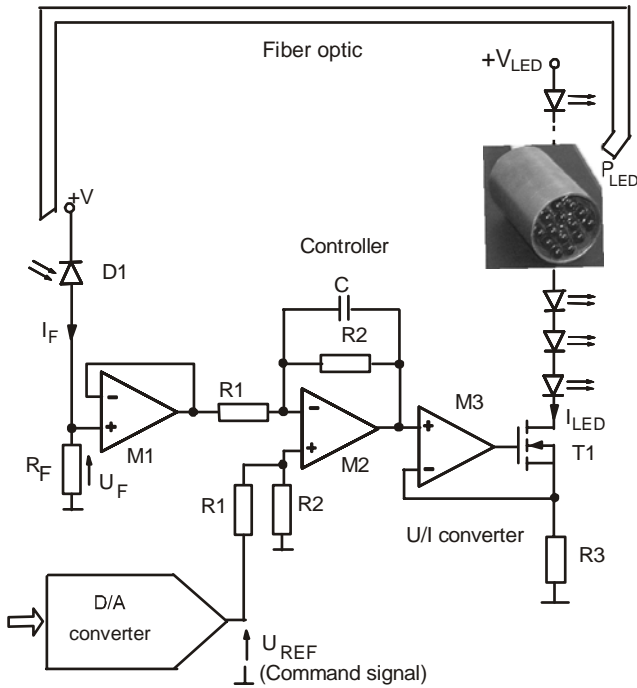


Fig. 1. Circuit diagram of the LEDs driver

The non-inverse input of the amplifier $M2$ is connected to the output of a digital to analog converter which provides DC voltage reference signal U_{REF} . The controller compares the actual voltage signal U_F from the voltage follower output with the reference voltage U_{REF} and generates the output signal directly proportional to the difference of these signals. The voltage output signal of the controller sets the LEDs current via the voltage-current converter so that the value of the voltage drop U_F across the resistor R_F , caused by the photocurrent I_F is nearly equal to the value of the reference voltage U_{REF} . In the result the emitted LEDs power is proportional to the value of reference voltage U_{REF} (command signal).

3. ANALYSIS OF DRIVER SYSTEM

Fig. 2 shows a block diagram in the form of a closed loop control system corresponding to the circuit diagram of the LEDs driver given in Fig. 1. The control system of the LEDs driver shown in Fig.2 includes three main blocks - the controller, the LEDs array and the feedback sensor. The proportional controller (difference amplifier $M2$ shown in Fig.1) and the voltage-current converter

(the operational amplifier $M3$ and the transistor $T1$ shown in Fig.1) are connected in series so we can to locate these blocks in a common block marked in Fig. 2 as “controller”.

The transmittances for each of the function block of the block diagram shown in Fig. 2 can be described by the Laplace transfer functions.

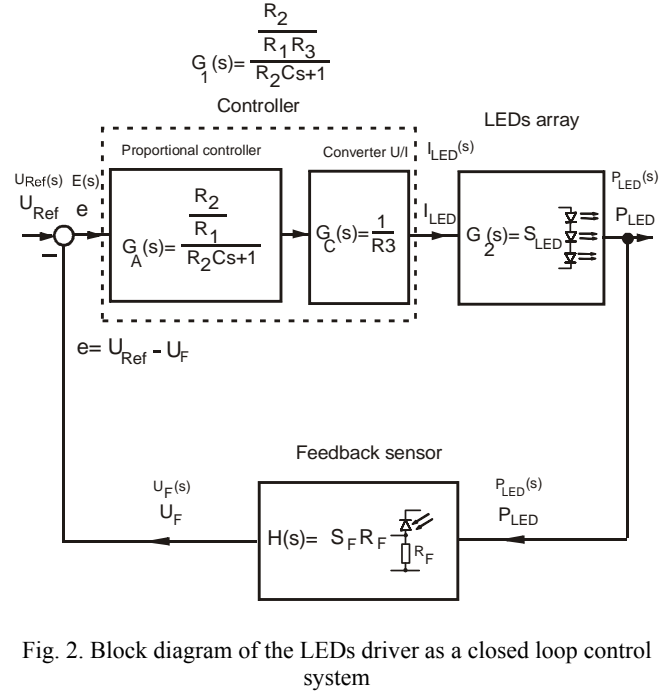


Fig. 2. Block diagram of the LEDs driver as a closed loop control system

The controller block consists two blocks connected in series. The first one is the proportional controller described by Laplace transfer function $G_A(s) = (R_2 / R_1) / (R_2Cs + 1)$ and the second one is the voltage-current converter described by Laplace transfer function $G_C(s) = 1 / R_3$. According to the rules of the block diagram algebra the equivalent transfer function $G_1(s)$ of the controller is a product of the transfer functions $G_A(s)$ and $G_C(s)$ and is given by

$$G_1(s) = \frac{I_{LED}(s)}{E(s)} = G_A(s)G_C(s) = \frac{R_2}{R_1 R_3 (R_2Cs + 1)} \quad (1)$$

where $I_{LED}(s)$ and $E(s)$ are the Laplace transforms of the current signal of LEDs $I_{LED}(t)$ and the signal of the feedback error $e(t)$, respectively. Resistors R_1, R_2, R_3 refer to the resistors shown in the block diagram in Fig. 1.

The transfer function $G_2(s)$ of LEDs array is given by

$$G_2(s) = \frac{P_{LED}(s)}{I_{LED}(s)} = S_{LED} \quad (2)$$

where $P_{LED}(s)$ and $I_{LED}(s)$ are the Laplace transforms of the emitted power signal $P_{LED}(t)$ of LEDs and the current signal $I_F(t)$ of LEDs, respectively and the coefficient S_{LED} is the emissivity of LEDs defined as $S_{LED} = P_{LED} / I_{LED}$.

• The transfer function $H(s)$ of the feedback sensor is given by:

$$H(s) = \frac{U_F(s)}{P_{LED}(s)} = \frac{I_F(s)R_F}{\alpha P_{LED}(s)} = S_F R_F, \quad (3)$$

where $I_F(s)$ is the Laplace transforms of the photodiode current $I_F(t)$, $U_F(s)$ is the Laplace transforms of voltage signal $U_F(t)$ induced by the current flow $I_F(t)$ through the load resistor R_F , α is a coefficient characterising fraction of the output LEDs power absorbed by the photodiode and S_F is the sensitivity of photodiode DI defined as $S_F = I_F / \alpha P_{LED}$.

According to the rules of the block diagram algebra (negative feedback block reduction), the equivalent transmittance $G(s)$ of the block diagram shown in Fig.2 is given by

$$G(s) = \frac{P_{LED}(s)}{U_{REF}(s)} = \frac{G_1(s)G_2(s)}{1 + G_1(s)G_2(s)H(s)}. \quad (4)$$

Taking the relevant relations describing the transmittances $G_1(s)$, $G_2(s)$ and $H(s)$, the equivalent transmittance $G(s)$ is given by

$$G(s) = \frac{\frac{R_2}{R_1 R_3 (R_2 C s + 1)} S_{LED}}{1 + \frac{R_2}{R_1 R_3 (R_2 C s + 1)} R_F S_{LED} S_F}. \quad (5)$$

In general, the relation between the response signal $P_{LED}(s)$ and the input signal $U_{REF}(s)$ (command signal) can be expressed as

$$P_{LED}(s) = G(s)U_{REF}(s) \quad (6)$$

The relation of the response signal $P_{LED}(s)$ to the step input signal $U_{REF}(s) = U_{REF} / s$ with the amplitude U_{REF} is given by:

$$P_{LED}(s) = \frac{\frac{R_2}{R_1 R_3 (R_2 C s + 1)} S_{LED}}{1 + \frac{R_2}{R_1 R_3 (R_2 C s + 1)} R_F S_{LED} S_F} \cdot \frac{U_{REF}}{s}. \quad (7)$$

Employing the final value theorem one can determine the behaviour of the signal $P_{LED}(t)$ for time approaching infinity. In other words, when the input signal is of the step type then final value theorem allows derivation of the static equation of the driver analysed. The general form of the equation following from the final value theorem is:

$$P_{LED}(\infty) = \lim_{t \rightarrow \infty} P_{LED}(t) = \lim_{s \rightarrow 0} s P_{LED}(s). \quad (8)$$

Substituting formula (7) describing $P_{LED}(s)$ into equation (8) one can determine the exact form of static equation (9) describing the relation between the optical output power

P_{LED} and the electrical driving signal U_{REF} of the driver analyzed:

$$P_{LED} = \frac{\frac{R_2}{R_1 R_3} S_{LED}}{1 + \frac{R_2}{R_1 R_3} S_F R_F S_{LED}} \cdot U_{REF}. \quad (9)$$

If the gain value of the system controller i.e., $R_2 / R_1 R_3$ is sufficiently high, then the so-call loop-gain i.e. $(R_2 / R_1 R_3) \cdot S_F R_F S_{LED}$ can satisfy the inequality

$$\frac{R_2}{R_1 R_3} S_F R_F S_{LED} \gg 1. \quad (10)$$

If this condition is satisfied then the value of the static error (steady-state error) is very small and the equation (9) can be given in a simpler form

$$P_{LEDest} \approx \frac{U_{REF}}{S_F R_F}, \quad (11)$$

where P_{LEDest} is the output power of LEDs calculated for very large value of loop-gain (see equation (10)).

This estimated form of the static equation describing the dependence between the optical output power and the electrical driving signal U_{REF} (command signal) is commonly used in literature by many authors. It should be emphasised that the use of a too high gain of the controller unit leads to undesirable effects, which can even cause the loss of the system's stability. Thus, the driver controller gain should be optimal in value to avoid the risk of the system's instability. In practice, in many feedback drivers the gain controller does not exceed the value of a few dozen and then the static system error can achieve substantial values. The relative value of this error is defined as

$$\delta_S = \frac{|P_{LEDest} - P_{LED}|}{P_{LED}}, \quad (12)$$

where P_{LEDest} and P_{LED} are LEDs power described by equations (11) and (9) respectively. Substituting both formula (9) and (11) into equation (12) one can obtain formula (13) expressing the relative static error as

$$\delta_S = \frac{1}{\frac{R_2}{R_1 R_3} S_{LED} S_F R_F}. \quad (13)$$

Metrological analysis should also investigate the influence of the instabilities in the driver parameters on the output optical power signal of LEDs. The analysis of the approximate form of the static equation (11) of the driver gives important information that the relative variations in the parameters reference voltage U_{REF} , sensitivity of photodiode S_F and feedback resistor R_F , marked as δU_{REF} ,

δS_F and δR_F , are responsible for the relative error δP_{LED} of the power of the LEDs emitted radiation. Using the Taylor series expansion one can obtain a simple relationship (14), which allows determination of the value of the relative error δP_{LED} .

$$\delta P_{LED} = |\delta U_{REF}| + |\delta S_F| + |\delta R_F| \quad (14)$$

If it is necessary to use the exact form of the static transfer function (9) of the driver analysed, the Taylor series expansion should be used to obtain relationship (15), which allows exact determination of the relative error δP_{LED} :

$$\begin{aligned} \delta P_{LED} = & |\delta U_{REF}| + \left| \frac{\delta S_F}{1 + \frac{1}{KR_F S_{LED} S_F}} \right| + \\ & + \left| \frac{\delta S_{LED}}{1 + KR_F S_{LED} S_F} \right| + \left| \frac{\delta R_F}{1 + \frac{1}{KR_F S_{LED} S_F}} \right| + , \\ & + \left| \frac{\delta K}{1 + KR_F S_{LED} S_F} \right| \end{aligned} \quad (15)$$

where K is the controller gain defined as

$$K = \frac{R_2}{R_1 R_3} . \quad (16)$$

4. CONCLUSIONS

This paper presents the design and analysis of an electronic system of a driver with the feedback optical loop used for stabilization of the radiation power of the LEDs light source. In the intention of the author, the designed driver system with the optical feedback and controller of type proportional (P) is an exemplary object for more accurate studies of this system. It should be noted that the driver systems of laser diodes are in practice identical to the designed LEDs driver system, so the results of these studies are useful for all family of semiconductor light source drivers. As a result of this analysis the exact form of the static transfer function describing the relation between the optical output power and the electrical driving signal was derived. The considerations were based on the feedback control system analysis procedures. A detail metrological analysis of the influence of the instabilities in the parameters of the driver system on the value of the optical power of the light source was presented.

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