

A PFM-controlled LED Driver To Achieve Consistent Illuminance

Pang-Yen Lou

Department of Electrical Engineering
National Sun Yat-Sen University,
Kaohsiung, Taiwan 80424
lou0105cat@vlsi.ee.nsysu.edu.tw

Chen-Cheng-Hung Hung

Department of Electrical Engineering
National Sun Yat-Sen University,
Kaohsiung, Taiwan 80424
chenghung@vlsi.ee.nsysu.edu.tw

Chua-Chin Wang[†]

Department of Electrical Engineering
National Sun Yat-Sen University,
Kaohsiung, Taiwan 80424
ccwang@ee.nsysu.edu.tw

Abstract—This investigation demonstrates a LED driver with PFM control to generate consistent illuminance, where Illumination Equalizer circuit, PFM Control Circuit, Voltage Limiter, Zero Current Detector, Level Shifter, Clock Generator, and Delay Cell are included. Fabricated using 0.5 μm HV CMOS process, the prototype occupies a chip area of 3.2 mm^2 . The proposed LED driver is also featured with a novel illuminance equalizer, which is able to achieve the accuracy as high as 99% under 20 mA LED output current, and the efficiency is as high as 93% by all-PVT-corner post-layout simulations.

Keywords— LED driver, high accuracy, illuminance equalizer, high efficiency, HV CMOS

I. Introduction

LED has been developing at an unexpected foot pace since 1990s. New breakthroughs in LED process technology have continuously increased the luminous efficiency. For the sake of environmental protection, LEDs are now often made of semiconductors. The basic theory is the combination of holes and electrons to lower the energy level and release light energy. Many LED driver designs have been proposed recently [1] [2]. Compared with traditional light bulbs with high heat loss and easy burnout, LED lamps attain low energy consumption, small volume, and hard to break. They also can reduce energy consumption and heat waste such that it is an excellent light source in line with modern trends. A good LED system requires not only high luminous efficiency, but also high conversion efficiency. Referring to Fig. 1, it shows that the LED illuminance is linearly proportional to forward current. What's more is that the brightness of the LED is proportional to the current. It then indicates that the illuminance is highly sensitive to the LED current. Therefore, the LED driver needs a stable current to generate consistent brightness. A current difference by 5 mA can make the illuminance rise up to 30~40 Lux in Fig. 1, which not acceptable in certain application, e.g., medical instrument.

[†] C.-C. Wang is the contact author. He is also with Institute of Undersea Technology (IUT) of NSYSU, Taiwan.)

Fig. 2 shows another issue that the I_d - V_d curve of the LED will be seriously affected by temperature variations. When the temperature is high (T_{High}), the curve shifts to the left, and vice versa. Therefore, even if the driving current (I_d) is the same, the temperature (T) results in the variation of voltage (V_d). Another problem is that the longer working time, the higher temperature of LED. Thus, it will affect the illuminance. Even if the LED driver is designed to supply a high-precision current, the inaccurate illuminance happens. In this investigation, to achieve illuminance stability and correctly, the proposed LED driver proposes an illuminance equalizer by sensing the temperature and auto-adjusting the output current to stabilize illuminance on time.

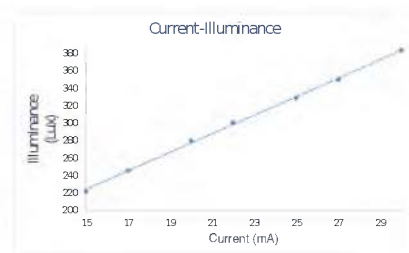


Fig. 1. Current-Illuminance curve.

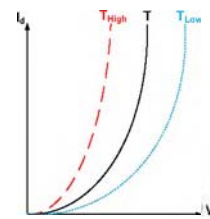


Fig. 2. I_d - V_d curve of diode at different temperatures.

II. LED Driver with Consistent Illuminance

Fig. 3 shows the block diagram of the proposed LED driver. It consists of an Illumination Equalizer, a PFM control circuit, a Zero Current Detector (ZCD), a High Level Shifter, a power PMOS, a power NMOS, a Clock Generator, a Delay Cell, and a LED string. The details of

each sub-circuit are given in the following text.

A. Illumination Equalizer

A thermistor (Rt) detecting the temperature of the LEDs is used as shown in Fig. 3 and 4. The temperature variation is converted to a voltage, V_{rt} , through the resistor divider composed of Rt and R1. V_{rt} would be coupled to Voltage Limiter for further conversion.

The schematic of Voltage Limiter is shown in Fig. 5. When LEDs are turned on, the working current starts to increase so that the temperature of the LED will increase as well. To avoid over-heating, a limiting circuit is needed. The voltage limiter consists of a comparator and two transmission gates. If V_{rt} doesn't exceed the limit (V_{lim}), V_{rt} will be output. Otherwise, the V_{lim} will be selected as the output. The output would be coupled to PFM Control Circuit which consists of a RS latch, a comparator, and a Clock Generator. PFM will then be in charge of tuning LED illuminance.

The tuning of the illuminance would be 10.6 Lux per 1 mA based on Fig. 1. The formula of illuminance equalization are shown as follows:

Referring to [3], a Steinhart–Hart equation of Rt is derived.

$$R_t(T) = R_0 \cdot e^{\beta(\frac{1}{T} - \frac{1}{T_0})} \quad (1)$$

where T means current temperature, and T_0 means the initial temperature.

$$V_{rt} = \frac{R_1}{R_1 + R_0 \cdot e^{\beta(\frac{1}{T} - \frac{1}{T_0})}} \cdot V_{in} \quad (2)$$

Thus, V_{rt} will be very sensitive with temperature variations.

$$V_{fb} = \frac{R_3}{R_3 + R_2} \cdot V_{out} \quad (3)$$

Referring to Eqn. (1)-(3) and PFM Control Circuit, we can get the V_{com} as Eqn. (4).

$$V_{com} = \begin{cases} 0 & \text{if } V_{fb} > V_{rt} \\ 1 & \text{if } V_{rt} > V_{fb} \end{cases} \quad (4)$$

The PFM adjusts duty cycle during off time. When the duty cycle of PFM becomes larger, V_{out} and I_{in} would also being larger, and vice versa. The relationship between duty cycle, V_{out} , and I_{in} is shown in Eqn. (5).

$$\text{duty cycle} = \frac{V_{out} - V_{in}}{V_{out}} = \frac{I_{in} - I_{out}}{I_{in}} \quad (5)$$

The timing sequence diagram of PFM Control Circuit is shown in Fig. 6. In an extreme state of off time, when the off time is much larger than on time, PFM is equalized as a pulse signal in Eqn. (6).

$$\begin{aligned} \text{PFM}(t) &= \delta(t) \\ \mathcal{L}\{\text{PFM}(t)\} &= 1 \end{aligned} \quad (6)$$

The Laplace transform is converged for all s . In the other extreme state of off time, when the on time is much larger than off time, PFM becomes a unit step function in Eqn. (7).

$$\begin{aligned} \text{PFM}(t) &= u(t) \\ \mathcal{L}\{\text{PFM}(t)\} &= \frac{1}{s} \end{aligned} \quad (7)$$

The Laplace transform is converged under $\Re(s) > 0$. Thus, $\text{PFM}(t)$ is proved to be stable so that the proposed LED driver can achieve the consistent illuminance.

B. Zero Current Detector (ZCD)

The ZCD in Fig. 3 is shown in Fig. 7. To prevent the power PMOS from reversely biased to cause power lost and reduce efficiency, a detection circuit is needed. When ZCD senses the reverse current from M2, it will cut-off power PMOS M2.

C. Delay Cell

When the power PMOS is turned on before the power NMOS is completely turned off, a large DC current will flow to the ground causing serious efficiency loss and even damage to the entire circuit. Therefore, it is necessary to ensure the driving signals of power devices to turn on the power PMOS longer than the power NMOS to prevent the possible large DC current.

III. Simulation and verification

This proposed design is realized using TSMC 0.5 μm HV CMOS process. The layout of the entire LED driver is shown in Fig. 8, where the core area is $1120 \times 677.2 \mu\text{m}^2$, and the total chip area is $1831 \times 1754 \mu\text{m}^2$.

Post-layout simulation of proposed LED driver at TT corner is shown in Fig. 9. In the initial state, the LED driver is working without illuminance equalization. When Rt senses the temperature of the LEDs over the limit, the illuminance equalization is enabled. The PFM frequency increases with the temperature. The output voltage (V_{out}) and output current (I_{out}) start to increase to enhance the illuminance of LEDs. Finally, the voltage will be limited to stop the equalization. The worst case post-layout simulation of LED driver is shown in Fig. 10. After the equalization, the target I_{out} is 21 mA, comparing with the simulation result, 21.2 mA, the current error is 1%. Table I tabulates the performance comparison of the proposed design and several recent LED driver works indicating that we attain the highest accuracy and the best FOM among all LED driver works in 2011-2020. Moreover, the proposed LED driver also shows the least chip normalization area in Table I.

IV. Conclusion

An energy-efficient LED driver is proposed with a illuminance equalization mechanism. The efficiency of the proposed LED driver is as high as 93%. Post-layout

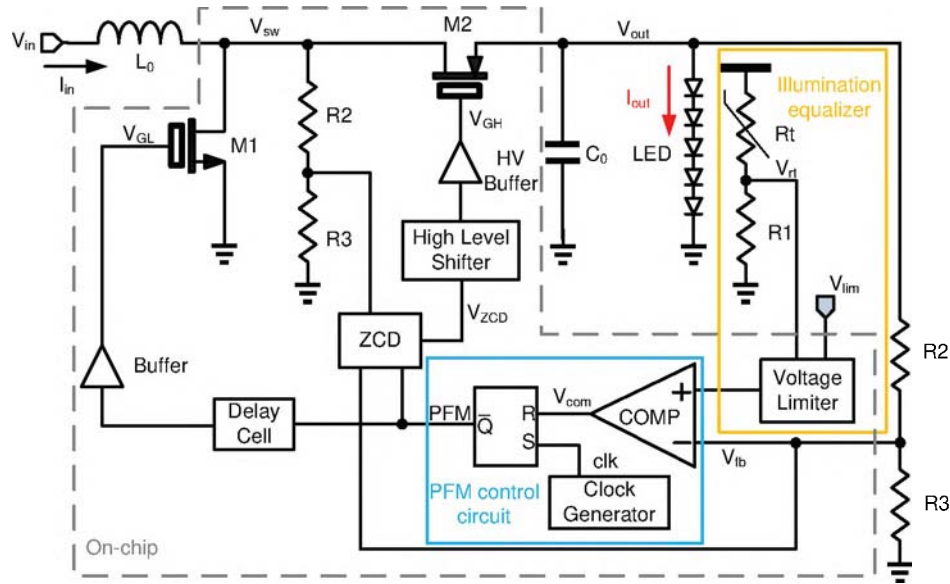


Fig. 3. Block diagram of the proposed LED driver.

TABLE I
Comparison with Prior Works.

	TSCII [4]	JSSC [5]	TENCON [6]	JSSC [7]	TCSI [8]	This work
Year	2011	2011	2012	2014	2018	2020
Process (nm)	250	500	350	350	500	500
Switch Frequency (kHz)	1100	10000	600	1000	2200	600
Input Voltage(V)	3~5	3~5.5	2.7~4.2	10~40	5~115	4.5~6
Output Current (mA)	20	600	27	345	350	20~21
Current Error (%)	1	2.8	1.2	2.8	2.7	1
Efficiency (%)	86.7	86	85	93	92.6	93
Chip Area (mm ²)	1.125	5	5.45	3.47	7	3.2
Chip Area (Normalization)	18	20	44.49	28.34	28	12.8
Converter Type	Boost	Buck-Boost	Boost	Buck	Buck	Boost
FOM*	4.82	1.54	1.59	1.17	1.22	7.27

$$*FOM = \frac{\text{Efficiency}}{\text{Current Error} + \text{Chip Area (Normalization)}}$$

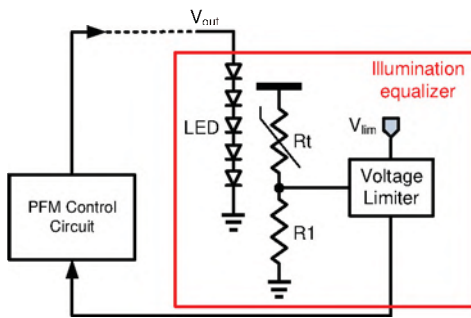


Fig. 4. Simplified architecture of Illumination Equalizer.

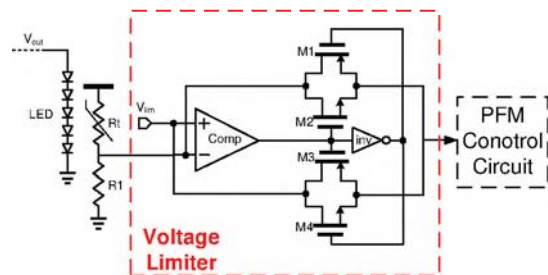


Fig. 5. Schematic of Voltage Limiter.

simulations justify the illuminance equalization is able to elevate the accuracy as high as 99%.

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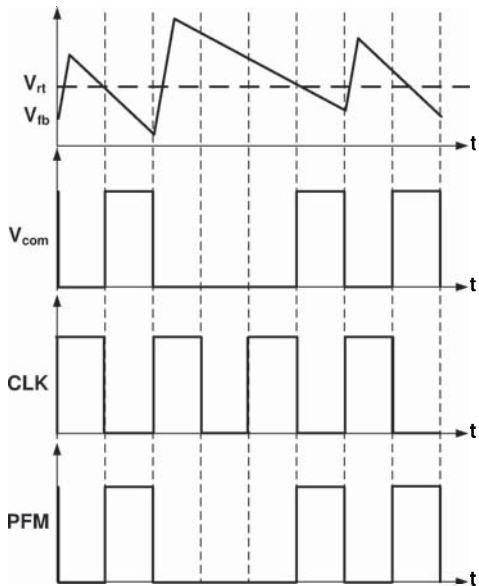


Fig. 6. Sequence diagram of PFM Control Circuit.

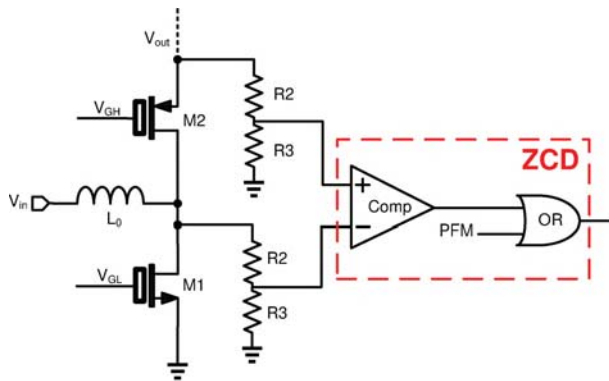


Fig. 7. Architecture of ZCD.

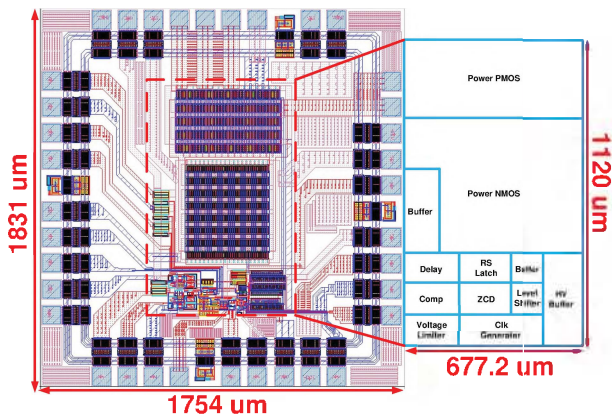


Fig. 8. LED driver layout.

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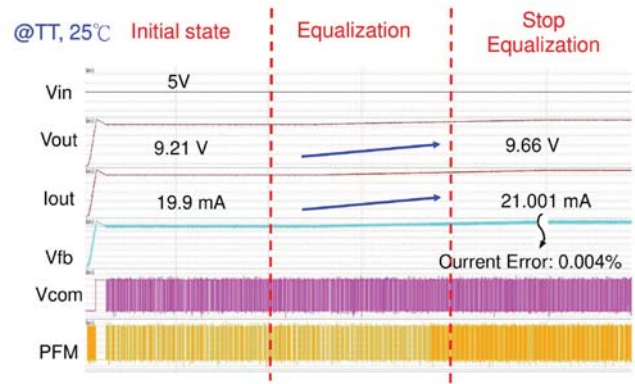


Fig. 9. Post-layout simulation of proposed LED driver at TT corner.

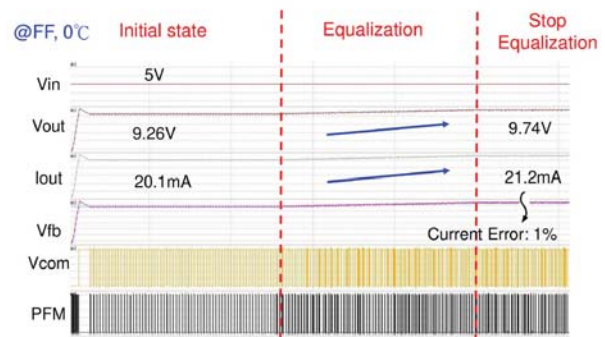


Fig. 10. Worst case post-layout simulation.

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