High Efficiency Multi-Channel LED Driver IC with Low Current-Balance Error Using Current-Mode Current Regulator

Seong-Jin Yoon*, Je-Kwang Cho** and In-Chul Hwang†

Abstract – This paper presents a multi-channel light-emitting diode (LED) driver IC with a current-mode current regulator. The proposed current regulator replaces resistors for current sensing with a sequentially controlled single current sensor and a single regulation loop for sensing and regulating all LED channel currents. This minimizes the current mismatch among the LED channels and increases voltage headroom or, equivalently, power efficiency. The proposed LED driver IC was fabricated in a 0.35-μm BCD 60-V high voltage process, and the chip area is 1.06 mm². The measured maximum power efficiency is 93.4 % from a 12-V input, and the inter-channel current error is smaller than as low as ±1.3 % in overall operating region.

Keywords: High power efficiency, Multi-channel LED driver, Inter-channel current error, DC-dimming, Current-mode current regulator

1. Introduction

Recently, fluorescent, incandescent, and other traditional lightings have been rapidly replaced with light-emitting diodes (LEDs) because of their advantages of high optical efficiency, long lifetime, small size, wide operating temperature range, etc. [1, 2]. To arrange a large number of LEDs for lighting applications with high power efficiency, a configuration of mixed series/parallel connections is typically preferred because the use of only series connection requires a high drive voltage and that of only parallel connection demands a large current driving and may causes a current imbalance among the LED channels. The driver circuits for such multi-channel LEDs can be grouped into several categories in terms of current regulation techniques. First, a linear current regulator, composed of operational amplifiers (op amps) and a current-sensing resistor, can be used for providing the desired LED currents [1-6]. This scheme offers excellent current accuracy with simple structure, and achieves high immunity to voltage variation due to its high output impedance. However, the output voltage range of such a linear current regulator can be limited because of the voltage drop across the sensing resistor. The power dissipated in the resistor also degrades the overall power efficiency of the LED driver IC. This situation becomes even worse when multiple LED channels need to be driven, because a pair of an op amp and a resistor is required in each channel resulting accordingly a high power dissipation and a large area.

To overcome the issue of power consumption and voltage headroom, current-mirror based current regulators have been used in several LED drivers [7, 8]. A simple CMOS current mirror can deliver the large amount of current required for an LED channel by sensing and multiplying a much smaller reference current. In this scheme, voltage headroom constraint imposed by the use as a sensing resistor in linear current regulators is relaxed, and thus the overall power efficiency can be improved. However, device mismatch and finite output impedance of the mirror transistors can cause severe current mismatches among the LED channels. Although a cascode transistor with an op amp can increase the output impedance [7], the increased voltage headroom degrades power efficiency as in the case of the resistor-based linear current regulators. To achieve high power efficiency and good inter-channel current matching without such an issue of the reduced voltage headroom, a single-inductor multi-output (SIMO) converter topology can be used for a multi-channel LED driver [10, 11], where all LED channel currents are precisely regulated in a time-multiplexed manner by sequentially sensing individual channel current using a single resistor. Since all LED channels share a single voltage sensing network in this scheme, the overall power efficiency can be greatly reduced with a good current matching among the LED channels. Moreover, if the output voltage of the regulator is designed to be an optimum value for each channel, the overall power dissipation can be further reduced. However, a drawback of this approach is that the overall area can be significantly increased due to the use of large-sized stabilization capacitors and switching elements used in each LED channel.

Another disadvantage of this SIMO converter based multi-channel LED driver is that current regulation does not operate when the converter input source energy is
charged onto the inductor. This can result in a significant current droop in the LED channels because all LED channels are not connected to the inductor and stay in an open loop configuration during that period.

In this paper, we propose a multi-channel LED driver IC with a current-mode current regulator (CMCR). To maximize power efficiency and voltage headroom, each LED channel current is controlled by a dedicated current-mirror transistor, rather than a resistor. The bias conditions of the mirror transistors in all LED channels are determined by a single CMCR in a time-multiplexed manner to minimize current mismatch among the LED channels. In addition, since the proposed LED driver uses a single-inductor single-output (SISO) topology for the boost converter, refresh operation of the LED channel currents is independent of current storing operation in the converter inductor, thereby reducing current droop in the LED channels and improving inter-channel current mismatch.

This paper is organized as follows. Section II describes the basic operation of the proposed LED driver from a system point of view. The detailed circuit implementation of the CMCR is explained in Section III, followed by the experimental results in Section IV. Section V summarizes and concludes the results of this work.

2. Overall LED Driver IC with CMCR

The proposed LED driver is shown in Fig. 1. It consists of two major functional blocks: a current-mode boost converter for regulating output voltage $V_{OUT}$ and the proposed CMCR for regulating LED channel current $I_{LED1}$ and $I_{LED2}$. The boost converter control loop, composed of an external LC filter ($L_0, C_0$) and a current-mode pulse width modulation (PWM) controller, adjusts $V_{OUT}$ so that the lower voltage of $V_{CH1}$ and $V_{CH2}$, drain voltage of the transistors $M_1$ and $M_2$, is equalized to a reference voltage $V_{REF}$ [1, 2]. With a properly chosen $V_{REF}$, the voltage headroom of the overall system can be maximized. To avoid the sub-oscillation problem in the current-mode PWM controller, a compensation ramp current signal $I_{Saw}$ is generated from an oscillator in addition to a square pulse $V_{CLK}$ [5]. Then, the $I_{Saw}$ is converted to a ramp voltage signal ($V_{sense}$) multiplied by $R_f$.

The proposed CMCR sets the LED current, $I_{LED1}$ and $I_{LED2}$, to some multiple times of a predefined reference current $I_{REF}$ by a single current-mode feedback. The negative feedback operates for the two LED channels in a time-multiplexed manner with the switches $SW_D$ and $SW_G$. When the channel-1 is in the feedback loop, a high-gain current-mode error amplifier (CA) forces the $I_{LED1}$ to be equal to a desired value, which is determined by $I_{REF}$ and the aspect ratio of $M_{SEN}$ and $M_1$. Then, during the next period, $I_{LED2}$ is regulated to a desired value in the same manner. Observe that the use of the switch $SW_D$ is to minimize the effect of finite output impedance of the transistors $M_1, M_2$, and $M_{SEN}$ on the accuracy of the LED channel current. It senses $V_{CH1}$ (or $V_{CH2}$) when $M_1$ (or $M_2$) is in the regulation loop and feeds the voltage to the drain of $M_{SEN}$ thereby guaranteeing perfect current mirroring from $M_{SEN}$ to $M_1$ (or $M_2$). The sequential regulation of $I_{LED1}$ and $I_{LED2}$ continues repeatedly and, since the two LED channels share a single feedback loop, the current ratio error between $I_{LED1}$ and $I_{LED2}$ is minimized. For the same reason, the driver IC consumes less power and occupies smaller area, compared with the case where each channel is individually controlled.

A drawback of the proposed scheme is that the LED
channel current may change from the desired value by the leakage current at the gate of \( M_1 \) and \( M_2 \) when it is disconnected from the CMCR loop. With steady-state linear approximation, we can expect the maximum deviation of LED channel current as

\[
\Delta I = G_m \cdot \Delta V_G = G_m \cdot I_{\text{leak}} \cdot t_{\text{dis}} / C_G ,
\]

(1)

where \( G_m \) is the transconductance of \( M_1 \) (or \( M_2 \)), \( \Delta V_G \) is gate voltage deviation, and \( I_{\text{leak}} \) and \( C_G \) are the total leakage current and the capacitance at the gate of the transistor, respectively. \( t_{\text{dis}} \) is the time duration while each channel is disconnected from the current regulation feedback loop. The capacitance \( C_G \) is determined by the dedicated sample-and-hold capacitor \( C_{\text{S\&H1}} \) (or \( C_{\text{S\&H2}} \)) and gate parasitic capacitance of \( M_1 \) (or \( M_2 \)). Here, the duration of channel disconnection from the feedback loop, \( t_{\text{dis}} \), can be expressed as

\[
t_{\text{dis}} = (N - 1) / f_{\text{clk}} ,
\]

(2)

where \( f_{\text{clk}} \) is the switching frequency and \( N \) is the number of the LED channels.

From (1) and (2), it is better to use a fast switching frequency in order to reduce the magnitude of \( \Delta I \). But, in this case the CMCR feedback loop must operate fast enough with an attendant high power dissipation. Additionally, it may result in larger glitch induced errors because such errors are typically proportional to the switching frequency. Another way to reduce \( \Delta I \) in (1) is to decrease \( G_m \) by using larger gate length and/or smaller gate width for \( M_1 \) and \( M_2 \). But, this can reduce the bandwidth of the CMCR feedback loop too much and require too high \( V_{\text{CH1}} \) and \( V_{\text{CH2}} \) for \( M_1 \) and \( M_2 \) to operate in a saturation region. Thus, the switching frequency and the size of \( M_1 \) and \( M_2 \) should be carefully chosen taking all the above constraints into consideration.

3. Circuit Implementation of CMCR

The circuit implementation of the proposed CMCR and its switching timing diagram are shown in Fig. 2 and Fig. 3, respectively. The CMCR consists of two circuit blocks: a sense-FET based current sensor [12-15] in the left dotted box and a current- mode amplifier in the right dotted box.
To simplify design and prove only the design concept, only two LED channels are included in the prototype driver IC.

In the sense-FET based current sensor, transistors $M_1$ and $M_2$ alternately regulate their respective LED channel currents, $I_{LED1}$ and $I_{LED2}$. This is performed by equalizing the drain voltage of $M_{sen}$ to $V_{CH1}$ or $V_{CH2}$ and feeding the gate voltage of $M_{sen}$ to $M_1$ or $M_2$. When the switch $S_{1d}$ is on during phase-1, the circuit composed of OP A1 and $M_3$ replicates the drain voltage of $M_{1}$, $V_{CH1}$, into $V_{C}$. The negative feedback formed through $M_{4}$, $M_5$, $M_6$, and $M_{SEN}$ forces $V_{e}$ to settle to the voltage such that $I_{SEN}$ is equal to $I_{REF}$. Then $S_{1g}$ is turned on after a short delay, and $V_{e}$ is transferred to $V_{G1}$. Because $S_{id}$ and $S_{ig}$ are turned on at different time instants, $V_{e}$ can settle fast and the final settled value of $V_{e}$ is fed to $V_{G1}$. The reason for the turn-on time mismatch of $S_{id}$ and $S_{ig}$ is to set up the $M_{SEN}$ drain current first and then regulate the LED channel current. This operation repeats in phase-2 in the same manner when $S_{2d}$ and $S_{2g}$ are turned on. Since $M_1$ and $M_2$ are sequentially controlled by the CMCR, their gate voltage and drain current can be independently customized to different values.

In this work, $I_{LED1}$ and $I_{LED2}$ are designed to be equalized and varies according to a 3-bit digital control from 50 mA to 370 mA. The gate width of $M_{sen}$ is 3000 times smaller than those of $M_1$ and $M_2$ in order to reduce power dissipated by the CMCR.

The gate length of $M_1$ and $M_2$ is set to 0.5 μm, a little larger than the minimum gate length of 0.35 μm, trading off the channel current droop $ΔI$ in (1) and the bandwidth of the current regulation loop. The transconductance of the transistors $M_1$ and $M_2$ ranges from 150 mS to 280 mS depending on the LED channel current.

To reduce the channel current deviation when the channel is not in the current regulation loop, metal-insulator-metal (MIM) capacitors are used for $C_{SH1}$ and $C_{SH2}$ at the gate of $M_1$ and $M_2$. The sample-and-hold capacitance is chosen to be 2 pF, which results in the channel current deviation of 0.28% or less with the driving current of 200 mA and the switching frequency of 200 kHz. The switches $SW_D$ and $SW_G$ are designed using transmission gates with minimum gate length and width to minimize the switch nonidealities such as channel charge injection and clock feedthrough. The operation of the feedback loop is stabilized by the compensation resistor ($R_C$) and capacitor ($C_C$).

### 4. Measurement Results

The proposed multi-channel LED driver was fabricated in a 0.35-μm BCD process. Fig. 4 shows the microphotograph of the prototype LED driver. The total active area is 1.06 mm², of which the power transistor and the CMCR occupy 0.64 mm² and 0.018 mm², respectively. The LED driver was tested using a 12-V input at a 200-kHz switching frequency.

Only two LED channels are included for design simplicity, and each channel is designed with six series-connected LEDs.

Fig. 5(a) shows the evaluation board including our chip packaged with COB and two-channel six-series-connected LEDs. Fig. 5(b) shows its back side of the board, which includes an inductor and a capacitor for the boost converter. Fig. 6 shows the measured forward-biased current-voltage characteristics of the two LED strings in the experimental prototype.

When the same voltage was applied, the current mismatch is larger than 3.8% in the current range from 50 mA to 350 mA.
Observe that the current mismatch becomes larger as the LED current decreases from 200 mA to 50 mA. This current mismatch in the light-load condition is undesirable because such a large mismatch can cause visible difference in luminosity between different LED channels.

Fig. 7(a) shows the measured channel current when it is set to 50 mA. The inter-channel current mismatch is as small as 0.24 %. The corresponding channel voltages ($V_{CH1}$ and $V_{CH2}$ in Fig. 2(a)) is shown in Fig. 7(b). The voltage difference between $V_{CH1}$ and $V_{CH2}$ is determined by the forward-biased voltage difference of the two LED strings shown in Fig. 6. This voltage difference is maintained by $M_1$ and $M_2$ in Fig. 2(a) since the gate voltages difference of $M_1$ and $M_2$ forces the transistor drain currents to be equal to each other when the CMCR operates properly.

Fig. 8 shows the measurement results of the LED channel currents and their mismatch. The channel current is changed from 50 mA to 350 mA with a 50 mA step by adjusting reference current $I_{REF}$ in Fig. 2(a) with a 3-bit digital input. Unlike the case shown in Fig. 6 where current regulation is not applied, the inter-channel current mismatch reduces as current decreases being smaller than 0.5 % when the channel current is less than 100 mA. This in turn result in significant suppression of visible brightness imbalance in a light-load mode of DC dimming. The current mismatch of the LED channels increases as the current increases being maximized to 1.3 % at the maximum current of 350 mA.

The power efficiency of the overall system is shown in Fig. 9. It is as high as 93.4 % at the LED channel current of 100 mA and stays higher than 90 % as long as the channel current is less 250 mA. Table 1 shows the comparison of the prototype LED driver with the previously published

Table 1. Performance comparison

<table>
<thead>
<tr>
<th></th>
<th>[4]</th>
<th>[6]</th>
<th>[7]</th>
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<tr>
<td>Technology</td>
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<td>0.35μm process</td>
<td>0.35μm process</td>
<td>0.35μm BCD process</td>
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<td>Current mirror</td>
<td>Single inductor multi output</td>
<td>Current - mode current regulator</td>
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<td>Converter type</td>
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<td>Buck</td>
<td>Boost</td>
<td>Boost</td>
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<td>2</td>
<td>2</td>
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<tr>
<td>Supply voltage</td>
<td>4.5–48V</td>
<td>30V</td>
<td>3V</td>
<td>12V</td>
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<tr>
<td>Output voltage</td>
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<td>10–20V</td>
<td>3–4V</td>
<td>19V</td>
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<tr>
<td>Switching frequency</td>
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<td>1MHz</td>
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</tr>
<tr>
<td>Maximum power efficiency</td>
<td>89.3%</td>
<td>87%</td>
<td>N/A</td>
<td>93.4%</td>
</tr>
<tr>
<td>Maximum current mismatch</td>
<td>N/A</td>
<td>2%</td>
<td>1.7%</td>
<td>1.3%</td>
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<tr>
<td>Chip area</td>
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Fig. 9. Measured overall system power efficiency
works. The proposed LED driver achieves less inter-channel current mismatch while maintaining better power efficiency with a smaller area.

5. Conclusion

In this paper, a multi-channel LED driver IC with a current-mode current regulator has been proposed to achieve better current balance among the LED channels and low power consumption for lighting applications. It precisely regulates the currents of the LEDs using a shard single current regulator in a time-multiplexed manner, and thus eliminates the use of resistors. This enables low-voltage low-power design of multi-channel LED drivers with a small area. The experimental measurement results show that the maximum efficiency of the prototype LED driver is as high as 93.4% including the CMCR, and its inter-channel current mismatch is 1.3% or less.

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References


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