A LED Driver Based on Pulse Current Modulator

Ming-Shian Lin Chern-Lin Chen
Department of Electrical Engineering and Graduate Institute of Electronics Engineering
National Taiwan University
Taipei, Taiwan

Abstract—**This paper presents a LED driver based on pulse current modulator. The proposed pulse current modulator consists of a voltage-controlled oscillator (VCO), a pulse generator, a series buffer, a single stage amplifier, a power transistor, and a sense resistance. A complete analysis and introduction of the proposed pulse current driving technique and the conventional driving technique will be presented in this paper. The LED driver used in the pulse current modulator driving technique supplies pulse driving current between 0mA~250mA and operates between 500k-Hz~1M-Hz. The LED driver is fabricated with CMOS 0.35-µm 2P4M technology. The chip area with pads is 935µm×956µm.**

I. Introduction

The significant improvements recently achieved in LED technology in terms of lifetime, luminous efficacy, energy-conversion efficiency, and color property make LED become one of the most promising candidates to replace conventional light sources in various residential and industrial applications. In the view of global warming and environmental protection, power saving and sustainable development have become some of the main requirements in research and development tasks. In a lighting system, these requirements may be achieved by developing new light sources (high-brightness LEDs,) using enhanced control techniques (adaptive control) and optimizing the system operation (current driving technique).

LEDs are a good choice for lighting applications due to its good luminous efficiency and long operating life. The rapid progress in LEDs has simultaneously stimulated interests in developing highly efficient LED drivers with optimized control circuits. To attain such operating life levels, the temperature of the LEDs must be controlled [1]-[5].

The main conventional driving techniques widely used in most LED drivers, the amplitude-mode driving technique and pulse width modulation (PWM) mode driving technique. LEDs are current-driven devices where the luminous intensity varies with the forward current. For above reason, the operation of the LED control mainly is decided by regulating the forward current pass through the LED, which are the conventional driving techniques used in most LED drivers serviceable in the market. The differences between the lightness of LEDs produced by these two techniques are introduction here. After that, a new driving technique is being proposed in this paper, the pulse current driving technique.

The amplitude-mode driving technique controls the luminous flux emitted by the LEDs by changing the dc current through the LED. This amplitude modulation method can be easily implemented with feedback loop in a current regulator, as shown in Fig. 1. The current regulator functions by sensing the LED current using sensing resistance R_{sense}, and the cross voltage of the sense resistor is sent to an error amplifier that adjusts the output voltage of the current regulator to a voltage value that provides regulated current to LEDs. In other words, the LED brightness is adjusted by adjusting the current flowing through the LED. The amplitude of the LED current in Fig. 1 can be regulated by the modulating voltage V_{ref} as

$$I_{LED} = \frac{V_{ref}}{R_{sense}} \tag{1}$$

In order to secure a steady LED current, a highly stable output voltage of an ac-dc converter and a current regulator are required. Because of the small sense resistance of the current regulator, small ripples will cause large variations in the LED current. Therefore, high power supply rejection ratio (PSRR) and fast load regulation are important for a good current regulator. Nevertheless, this architecture suffers from poor operating efficiency because of the dropout voltage across the power transistor of the current regulator. Another concern of the issue is the stability and compensation of current regulator[6][7].

Another driving method called the PWM driving technique uses a pulsed current to drive the LED. The fact that LEDs show instant response to the driving current makes PWM current a suitable driving technique. As shown in Fig. 2, the current passing through the LED switches periodically and the PWM current is controlled between a high and a zero level by a switch and a sense resistance connected in series with the LED. The average current of LED with PWM driving technique is obtained from

$$\overline{I_{LED}} = DI_{LED} \tag{2}$$

$$D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T} \tag{3}$$

Where I_{LED} is the high level of PWM current, D is the duty cycle of the switching period, and t_{on}, t_{off} and T are the turn on time, turn off time and switching period, respectively.Due to the rapid switching in the load current, the current regulator is required to have rapid load transient response. A number of related methods have been proposed to improve load transient response of a current regulator, such as dual control loop and high slew rate amplifier, etc. Since the peak current of PWM

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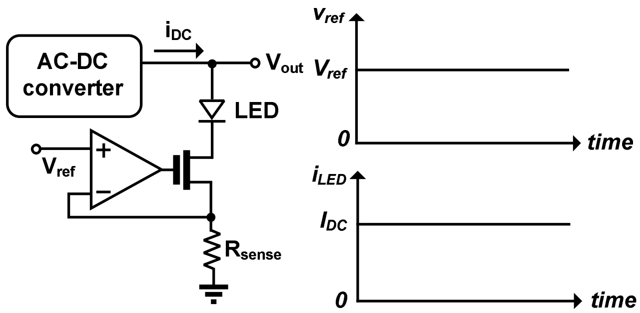
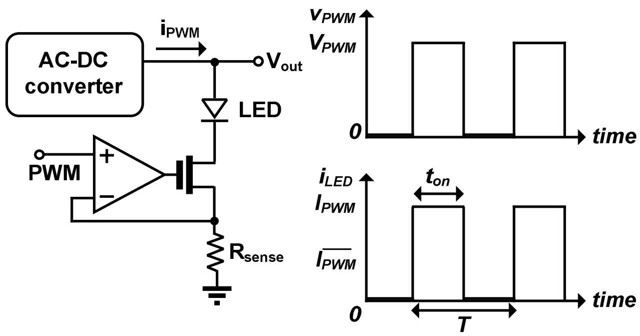
driving technique is fixed and driving is achieved by varying the duty ratio of the pulsed current which determines the average values of both the current and the luminous flux.



(a) (b)

Fig1. Conventional amplitude-mode driving technique [6]. (a) Schematic representation. (b) Associated driving waveforms.



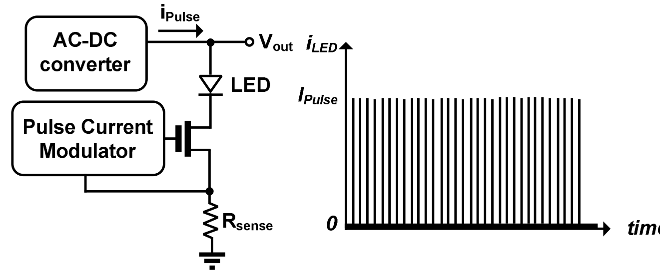
(a) (b)

Fig. 2. Conventional pulse width modulation (PWM) mode driving technique [6]. (a) Schematic representation. (b) Associated driving waveforms.

However, using the two conventional driving techniques and operating the LED at high dc current value, the illumination of the LED continues to increase but at a decreasing rate and shows a tendency to saturate. This means that the part of the driving current is not used for light generation. In other words, the luminous efficiency decreases as the dc current increases.

Having considered the drawback of the two conventional techniques, therefore, we propose using a LED driver based on a pulse current modulator to generate a series of pulse current to drive the LED. Therefore, with the new pulse current driving technique, a series of pulse current is generated from a pulse current modulator.

This pulse current modulation method can be implemented by a closed loop in a pulse current modulator, as shown in Fig. 3, where the pulse current modulator functions by sensing the LED current using sensing resistance R_{sense}, and the cross voltage of the sense resistor is sent to the modulator to produce the next pulse current sent to the LED. In other words, the LED brightness is adjusted by adjusting the frequency of the pulse current flowing through the LED.



(a) (b)

Fig. 3. The proposed LED driver based on a pulse current modulator. (a) Schematic representation. (b) Associated driving waveforms.

In this paper, the circuit descriptions of the proposed pulse current modulator will be included in Section II. The measurement results and specification of the proposed LED driver are introduced in Section III. Finally, the conclusion is presented in Section IV.

II. CIRCUIT DESCRIPTIONS

The function block of the LED driver is shown in Fig. 4. It consists of a voltage-controlled oscillator (VCO), a pulse generator, a series buffer, a single stage amplifier, a power transistor, and a sense resistance, which are described in the next paragraphs.

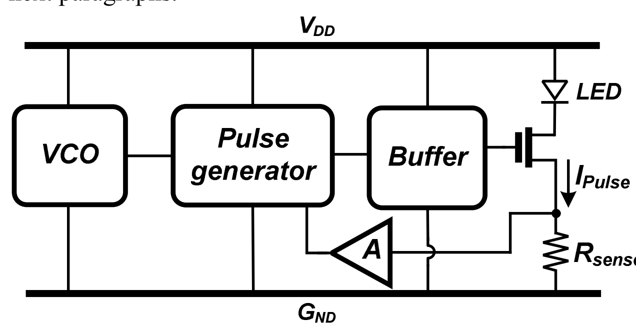
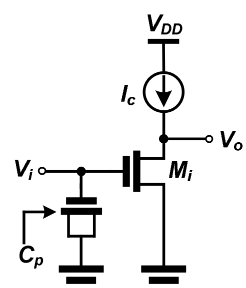
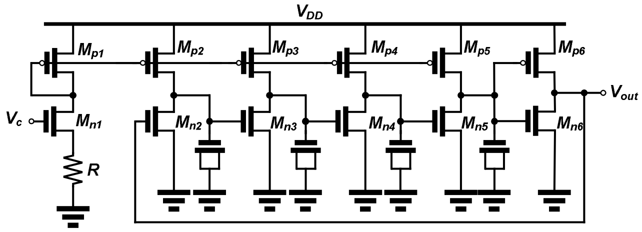


Fig. 4. Proposed LED driver system block diagram.

The VCO is based on a ring oscillator composed of single-ended delay cells, as shown in Fig. 5(a). The implemented VCO consists of 5 delay cells, as show in Fig. 5(b). The output current buffer stage which consists of M_{p6} and M_{n6}, converts the small amplitude of VCO output signal into a rail to rail square signal. This single stage inverter structure of delay cell has lower power consumption compared to fully differential structure.



(a)



(b)

Fig. 5. (a) Delay cell (b) Ring oscillator based VCO circuit

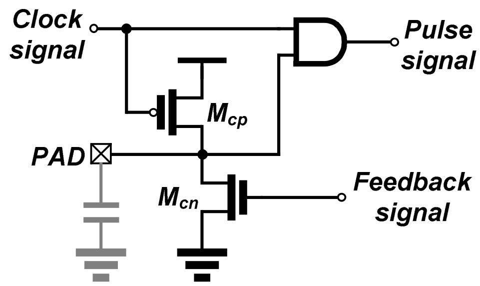


Fig. 6. Pulse generator circuit

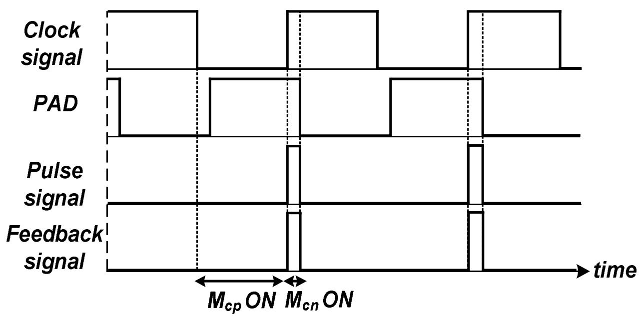


Fig. 7. Operational timing diagram of the pulse generator circuit.

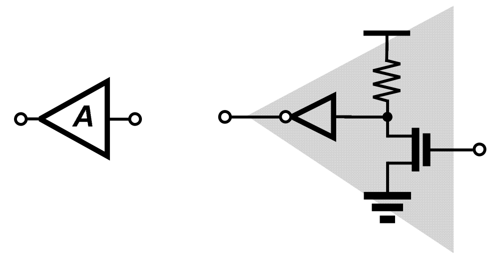
The pulse generator circuit is composed of the transistors M_{cp}, M_{cn}, and a logic AND gate. These components are interconnected. The timing diagram of the pulse generator is shown in Fig.7. When the clock signal of VCO is low, the transistors M_{cp} is turned on and operated in the triode region as a current source charging the capacitor C_L with the power supply. When the clock signal of VCO is high, the transistors M_{cp} is turned off and the feedback signal becomes high. The transistors M_{cn} is turned on and operated in the triode region as a current source discharging the capacitor C_L to the ground. The discharge period can be expressed as follows

$$t_{discharge} = 0.7 \times R_n \times C_L \tag{4}$$

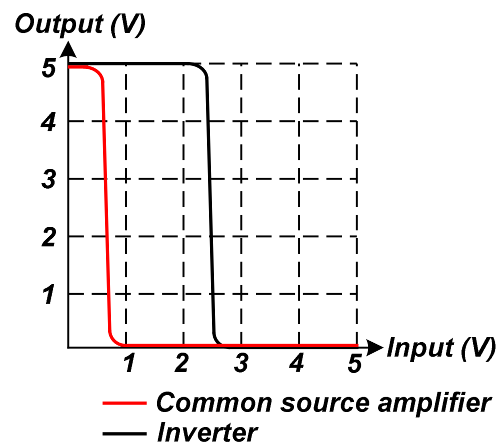
$$R_n = \frac{1}{\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{th})} \tag{5}$$

The equations above show that the discharge pulse width is determined by capacitance.

The single stage amplifier circuit is a non-inverter amplifier that consists of a common source amplifier and an inverter, as shown in Fig.8 (a). As Fig.8 (b) shows, it can be seen from the voltage transfer curves of a common source amplifier and an inverter that the common source amplifier has an advantage over the inverter in lower input range. Therefore the across voltage of the sense resistance can be lower and the sense resistance value can be smaller. In other words, across voltage of the LED will be large enough.



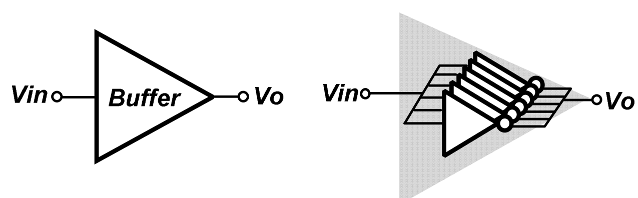
(a)



(b)

Fig. 8. (a) single stage amplifier circuit. (b)Voltage transfer curves of a common source amplifier and an inverter.

A series buffer is composed of CMOS inverters. In order to increase the driver ability to switch the power transistor we connect the CMOS inverters in parallel. The buffer connection is shown in Fig.9 (a) and (b).



(a) (b)

Fig. 9 (a) Buffer (b) Parallel connection inverters of the buffer

As shown in Fig. 10, when the pulse generator output signal is high, the buffer provides a push current to charge C_{GD} that is the parasitic capacitance of the power transistor. When the pulse generator output signal is low, the buffer provides a pull current to discharge C_{GD} to the ground. Consisting of CMOS inverters connected in parallel, the buffer is capable of providing a large push current and a large pull current to quickly switch the power transistor.

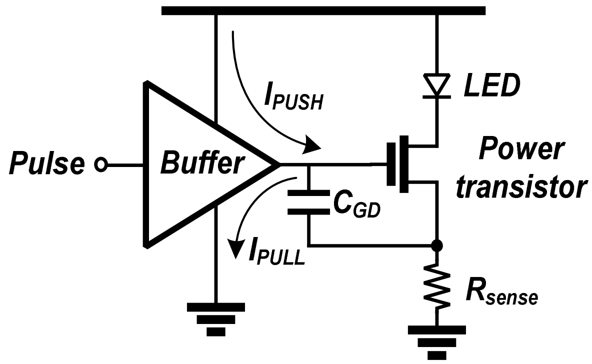


Fig. 10. Parasitical capacitance of power transistor

A feedback path is composed of a sense resistance and a non-inverter amplifier. The non-inverter amplifier converts the small amplitude that passes through the sense resistance into a rail to rail pulse signals. The pulse generator then merges the output clock of the VCO and the output pulse signal of the non-inverter amplifier to produce the next pulse current. In the above process, the LED driver generates a series of pulse current to drive the LED.

III. EXPERIMENTAL RESULTS

The proposed pulse current modulator based on LED drivers is fabricated with the 0.35-µm 2P4M CMOS technology. Fig. 11 shows the chip microphotograph of the proposed LED driver. The chip area with pads is 935µm ×956µm. The LED driver used in the pulse current modulator driving technique supplies driving pulse current between 0mA~250mA. Detailed specifications of the LED driver are listed in Table I.

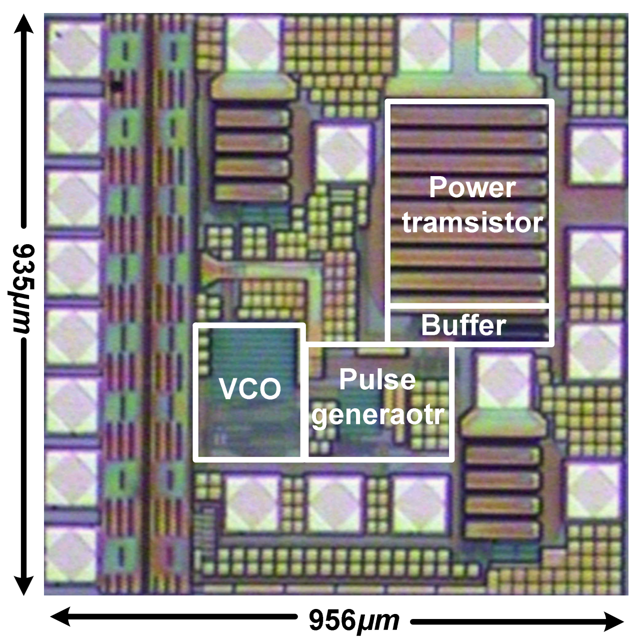


Fig. 11. Chip micrograph

Table I. Specifications of Measured Performance

	Measurement
Fabrication Process	0.35µm 2P4M CMOS
Chip area (with PAD)	935µm ×956µm
Input Voltage	4.5V~5.5V
Output Current Pulse	0~250mA
Pulse Width	90ns
Operate Frequency	500kHz~1MHz
Quiescent Current	10µA
Feature	Pulse current driving

Fig.12 shows that the continuous pulse current of the LED driver and amplitude is about 230mA in a system operating with 5V power supply. Fig.13 shows the results of the single pulse current of the LED driver and the amplitude is about 230mA with a pulse width of 90 nanoseconds at the frequency of 800k-Hz. The rise and fall times were 60 and 30ns, respectively. All measured results are obtained at room temperature. As mentioned above, the repetition rate of the LED optical output is the same as the electrical circuit oscillation, clearly demonstrating that the LED operation is controlled by the switching characteristics of the power transistor.

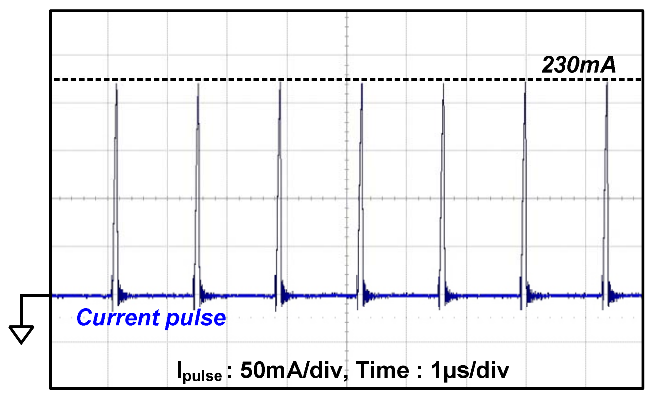


Fig.12. Experimental result of continuous current pulses of the LED driver for V_{DD}=5V (Horizontal scale: 1µs/div and 500mA/div.)

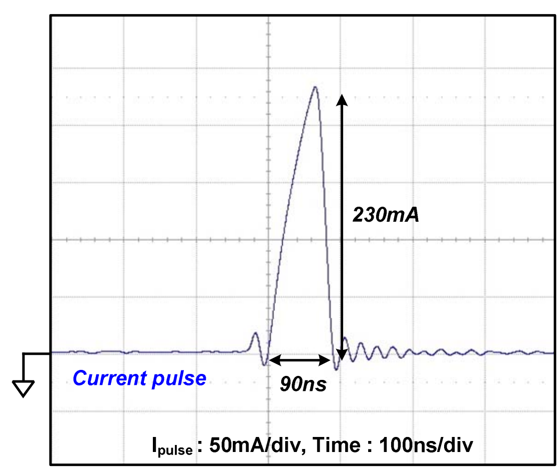


Fig. 13. Experimental result of a single current pulse of the LED driver (Horizontal scale: 100ns/div; vertical scale: 50mA/div.)

The the frequency of the LED driver is modulated to adjust its brightness, but low operating frequency results in insufficient brightness, while high frequency causes large switching loss, which leads to lower efficiency. Therefore, we limit the frequency range of pulse current between 500k-Hz~1M-Hz. The driver operates on relatively low voltage (5V), and demonstrates stable operation at continuous frequencies of at least 500k-Hz.

IV. Conclusion

An LED driver based on a pulse current modulator technique was proposed in this paper. The proposed topology provides a robust design when the process and temperature variations are considered. The pulse current driving technique can be extended to any existing LED driver architecture to improve heat dissipation problem. To our knowledge, this is the first LED driver that uses this method to drive LED. The proposed driving technique and as well as conventional driving techniques were also introduced and analyzed in this paper. The proposed simplified circuit with a cost effective drive system can achieve low power consumption, improve heat dissipation and increase standby time, which are essential for portable devices. This circuit demonstrates a successful application of pulse current technology in resolving certain practical problems of LEDs. The driver has been implemented with 0.35-μm 2P4M CMOS technology and occupies an area of 0.893mm^2. Measurement results showed that the maximum amplitude of the pulse current is 250mA, and the entire driver with protection circuits consumed an average quiescent current of 10μA.

Acknowledgment

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