A > 89% Efficient LED Driver with 0.5V Supply Voltage for Applications Requiring Low Average Current

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I. ABSTRACT

A modified boost converter topology is proposed to achieve better than 89% efficiency as an LED driver for applications in which low supply voltage and low average current are desired such as in a photoplethysmographic (PPG) heart rate (HR) monitor device. The approach embraces pulsing of the LED current, and allows a highly digital implementation for varying LED brightness based on Pulse Density Modulation (PDM). Measured results indicate that the LED driver, which is implemented in 180nm CMOS along with an external inductor, achieves an output current range of 28uA to 1.3mA with 6 current settings while maintaining >89% efficiency over a supply voltage range of 0.5 to 0.6V.

II. INTRODUCTION

Wearable sensors have recently become a topic of high interest since they can be paired with smart phones which offer a convenient platform for processing and display of information. In this application realm, we consider wearable HR monitoring devices based on PPG techniques in which light is passed through tissue in order to sense blood flow variations due to HR. The PPG approach offers the advantage of ease of usability compared to ECG based approaches due to the fact that a single detection location can be utilized (such as on a finger) and no contact electrodes are required. Achieving low cost and very low power PPG devices [1] could provide tremendous benefit to society by improving health and fitness and helping to prevent cardiovascular disease, which leads to more than 1/4th of the deaths around the globe [2].

This work focuses on an LED driver suitable for such PPG devices, and complements previously published work in which a low power, highly sensitive HR sensor has been developed which runs on a 0.5V supply as shown in Fig. 1 [3]. The advantages of using such a low supply voltage are that it offers the possibility of direct charging from a photovoltaic (PV) cell without additional power conversion circuits and that it lowers power consumption of the primarily digital architecture of the sensor [3]. However, red LEDs, which are chosen as the light source due to the fact that the 660nm wavelength offers the maximum difference in absorption between oxygenated versus non-oxygenated hemoglobin [4][5], typically have a turn-on voltage of around 1.8V. Therefore, the LED driver circuit must boost its output voltage compared to the 0.5V supply voltage in order to enable light emission.

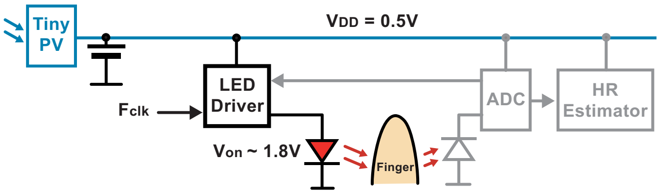

Fig. 1 Block diagram of a PPG based heart monitoring system [3]

Since the LED driver is the dominant source of power consumption in this system [4], it is critical to achieve high power efficiency in its design. However, running off of a 0.5V supply in 180nm CMOS is challenging as it is close to the threshold of the CMOS devices, and supporting low average current is also challenging since it demands a design with low fixed power consumption. Here we present a highly efficient LED driver topology that meets these demands with a simple implementation.

III. PROPOSED ARCHITECTURE

There are two main approaches to realize an efficient LED driver capable of boosting the supply voltage: a switched capacitor based DC-to-DC converter or an inductor based boost converter. Each of these methods carries challenges in achieving high efficiency under very low supply voltage since such low voltage often leads to high resistance during the turn-on state of the switches and therefore an increase in switching loss. In the case of the switched capacitor based design, another key issue is that several stages may be required when striving for a voltage boost by a factor of 4 (i.e., 2V/0.5V). For the inductor-based boost converter, a key challenge is that the turn-on voltage of the rectifying diode used within its structure may contribute substantial power loss. While this issue can be somewhat mitigated by using a MOS device rather than diode to perform such rectification, the additional loss introduced by the MOS device is still problematic when seeking high efficiency with low supply voltage. SPICE simulations reveal significant challenges in achieving >80% efficiency for either of these approaches when operating with 0.5V supply voltage in 180nm CMOS.

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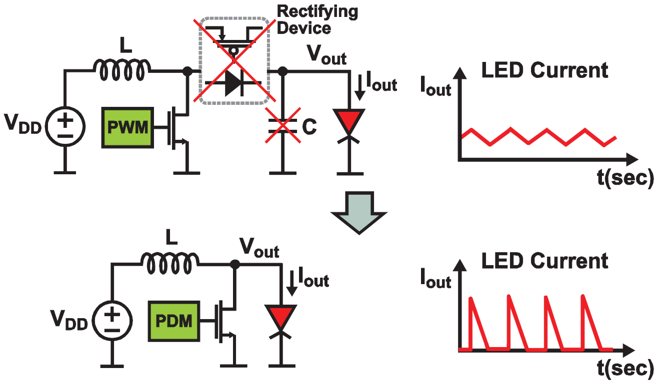


Fig. 2 Proposed LED driver in which the rectifying device and output storage capacitor are eliminated and LED current is allowed to pulse

Fig. 2 presents a simplified view of the proposed LED driver circuit implementation, and compares it to a conventional inductor-based DC-to-DC converter. Rather than seeking a constant DC voltage with minimal ripple [6][7], the proposed LED driver leverages the rectifying characteristic of the red LED to achieve a simple structure that produces pulsed LED current. This approach allows elimination of the rectifying diode or MOS device and output storage capacitor as utilized in the conventional inductor-based boost converter topology. For this pulsed design, the inductor and the on-time of the switch are appropriately selected such that peak currents are sufficiently low to avoid long term reliability issues. Note that the HR sensor will filter out such pulsing due to the fact that it requires < 10Hz bandwidth to sense the HR signal [3].

An important factor in designing the LED driver for the PPG application space is to achieve the highest luminous efficiency possible for the LED. In the case of the red LED utilized in this application, the use of pulsed LED current leads to slightly improved LED luminous efficiency compared to using a small average DC current. Fig. 3 shows a simulated LED luminous intensity characteristic for pulsed versus DC current flowing into the LED. The pulsing action improves the LED lighting efficiency by producing higher luminous intensity for a given average current, especially when the average current is relatively low (i.e., < 2mA). Therefore, pulsed current exhibits higher optical-to-electrical efficiency, meaning more lumens for the same value of average current.

IV. DIGITAL CONTROLLER

Control of the average output current for a conventional boost converter is typically achieved using Pulse Width Modulation (PWM) with constant switching frequency. However, PWM control requires analog circuits that invite extra design complexity when working at 0.5 supply voltage. In contrast, the proposed pulsed LED driver design shown in Fig. 2 allows very simple digital control based on Pulse Density Modulation (PDM). As an example, Fig. 4 compares the LED current waveforms for pulse densities of 100% and 50%. In this design a 100% density is defined as the case when a pulse occurs at every period of the switching clock on the gate of the NMOS switch shown in Fig. 2. Reduction of the pulse density from 100% to 50% leads to reduction of the average LED current by a factor of two.

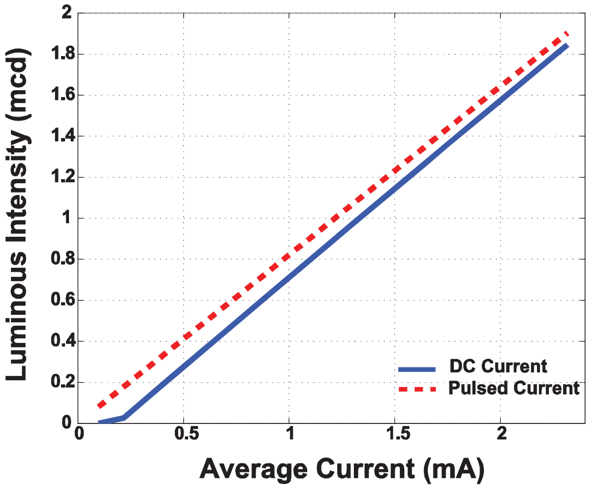


Fig. 3 Simulated luminous intensity of a red LED for DC versus pulsed current over a range of 0.1 to 2.3mA average LED current

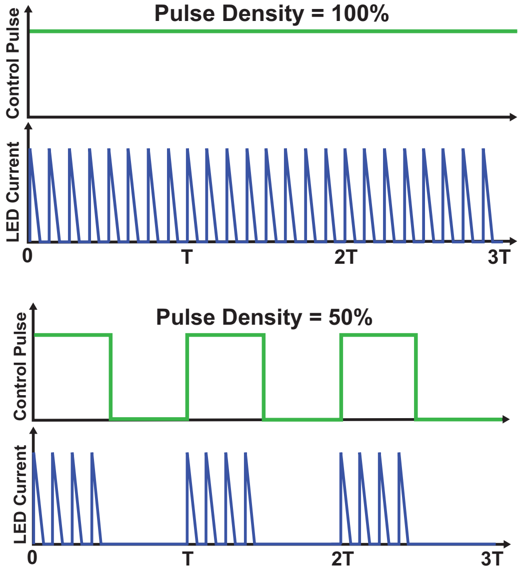
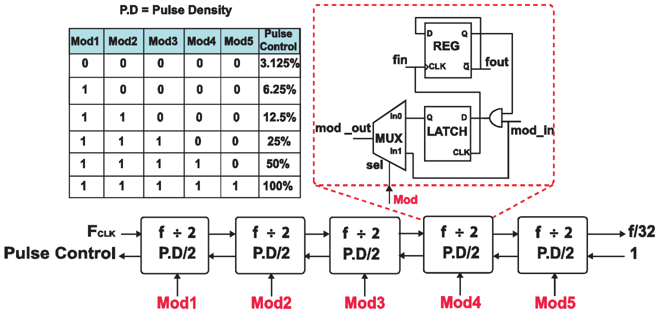


Fig. 4 Example of using pulse density to control the average current through the LED with the proposed LED driver

Digital control of PDM is achievable in a variety of ways. As an example, rather than taking the approach shown in Fig. 4, the 50% pulse density could be implemented by skipping every other pulse or by applying an algorithm that non-uniformly skips pulses subject to the constraint of maintaining a 50% average. The latter approach can be achieved using a digital Delta-Sigma modulator [8] to control the pulse gating, and has the advantage of providing very high resolution control of the average light intensity from the LED. However, for this work, which does not require fine light intensity control, we use a simple circuit based on a frequency divider to extend the pulse swallowing approach shown on Fig. 4 to accommodate a 32x pulse density range with values of 100%, 50%, 25%, 12.5%, 6.25% and 3.125%.

The divider architecture is shown in Fig. 5, and allows for change in the LED light intensity in steps of a factor of 2 according to the Mod input signals. Since the frequency is divided by 2 at each divider stage, the power consumption is progressively lowered for each stage in order to lower the fixed power of the overall LED driver. The overall PDM waveform is achieved by using digital gates to modulate the f/32 and pulse control signals as shown in Fig. 5, and the resulting signal then passes through a chain of buffers to the gate of the switch in the LED driver. The chain of buffers is progressively scaled such that it drives the large gate capacitance of the switch with minimum delay and power losses. The range of the pulse density control signal depends on the number of the stages in the frequency divider, with 5 stages providing a range from 3.125% to 100%.



Mod1	Mod2	Mod3	Mod4	Mod5	Pulse Control
0	0	0	0	0	3.125%
1	0	0	0	0	6.25%
1	1	0	0	0	12.5%
1	1	1	0	0	25%
1	1	1	1	0	50%
1	1	1	1	1	100%

Fig. 5 Pulse control using a simple frequency divider implementation with truth table

V. MEASUREMENT RESULTS

Fig.6 shows SPICE simulation results for the relationship between the switch width and the LED driver efficiency assuming a supply voltage in the range of 0.5V to 0.6V. In this system a large switch width is used to minimize the switch on-resistance in order to obtain high efficiency. The NMOS switch device is optimized with a width and length of 12mm and 180nm, respectively. Further increase of the switch width does not improve the driver performance since larger driving buffers are required that consume more power and degrade the performance. Gate bootstrapping could prove beneficial, but was not utilized in this work for the sake of simplicity. Fig. 7 shows the 0.18μm CMOS die photo of the proposed LED driver. The overall die area is 2.89mm^2, and the active area is 0.51mm^2 (including test circuits). The overall system employs a 15μH off-chip inductor and a switching frequency of F_{clk}=1MHz (which is derived from a 2MHz input clock in order to ensure even duty cycle).

Fig. 8 displays the measured LED voltage and current while operating with 100% pulse density. In this case, the switch is closed during half of the clock period, during which time the current in the inductor builds while the LED voltage is held close to zero. When the switch is opened, the LED voltage immediately increases to the LED turn-on voltage of ~1.8V. The LED current then ramps down as the inductor energy is progressively consumed by the LED. After the LED current goes to zero, the inductor and parasitic capacitance cause oscillations to appear on the LED voltage. These oscillations continue until damped out by loss or when the switch turns on again.

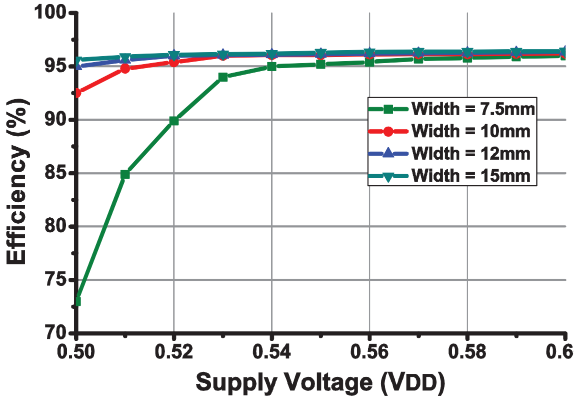


Fig. 6 Simulated power efficiency versus supply voltage and switch device width for 180nm NMOS (without gate bootstrapping)

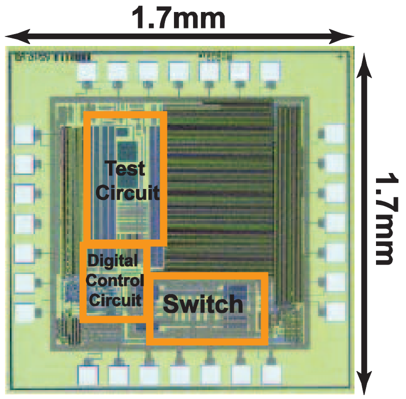


Fig.7 Die photo

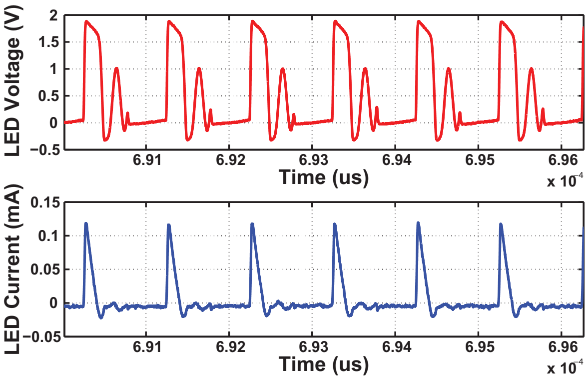


Fig. 8 Measured voltage and current waveforms of LED

Figures 9 and 10 show measured average LED current and power efficiency, respectively, versus pulse density and supply voltage, V_{DD}. The measurements confirm an output current range of 28uA to 1.3mA while maintaining > 89% efficiency over a supply voltage range of 0.5 to 0.6V. Note that lower pulse density reduces power efficiency due to the fixed power consumed by the digital PDM circuit, and lower supply voltage reduces power efficiency due to increased on-resistance of the NMOS switch. Fig. 11 provides further details on the source of power losses in the LED driver.

Fig. 12 shows a comparison table to other recently published work. This proposed LED driver offers high efficiency at very low supply voltage with a minimal number of components.

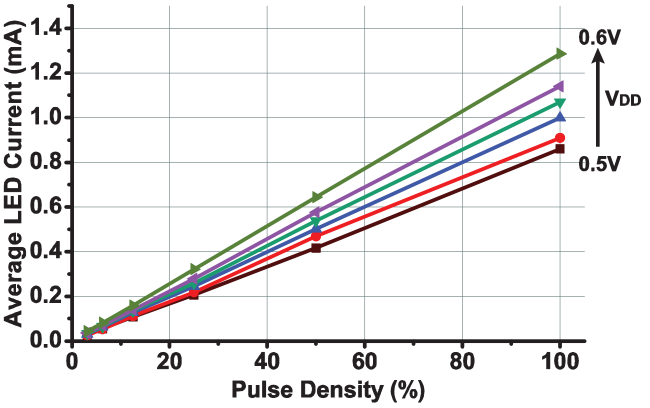


Fig. 9 Measured average LED current versus pulse density and V_{DD}

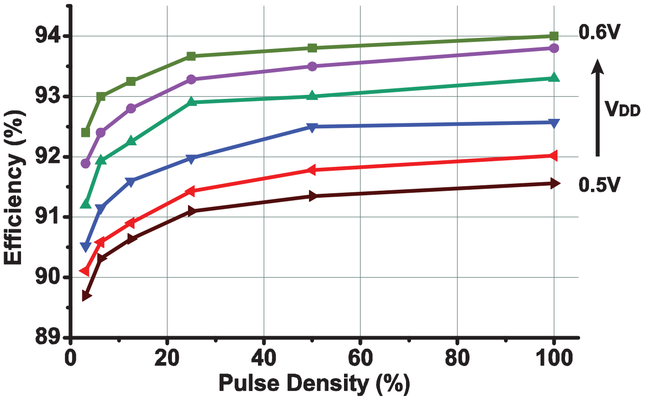


Fig. 10 Measured power efficiency versus pulse density and V_{DD}

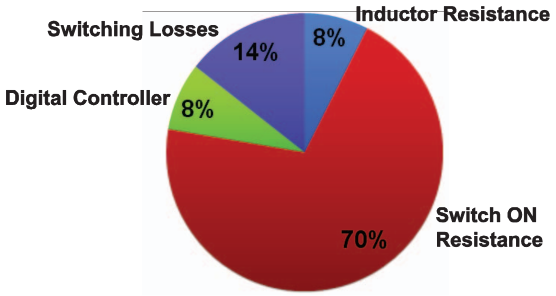
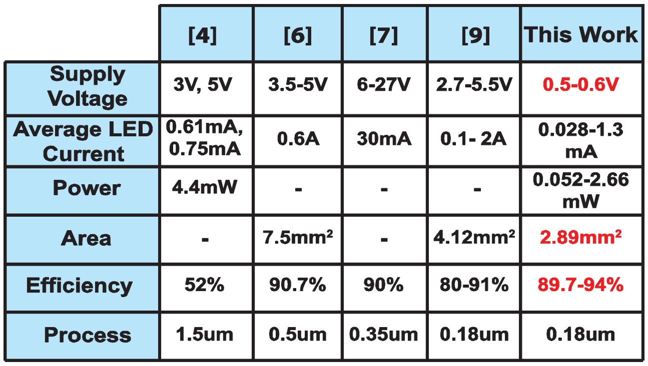


Fig. 11 Distribution of power losses in the LED driver

VI. CONCLUSION

A modified boost converter operating with 0.5V supply was proposed in this paper as an efficient LED driver for low average current applications such as a PPG heart rate monitor. By leveraging the rectifying behavior of the LED, a simple design is achieved in which the LED current is pulsed. Digital pulse density control is employed to adjust LED power, thus avoiding analog control circuits. For this proposed LED driver, the simplicity of the design allows fewer required components than conventional boost converter structures, and offers excellent power efficiency over a wide range of average LED current. Measured results verify >89% power efficiency across an LED current range of 28uA to 1.3mA and a supply voltage range of 0.5V to 0.6V.



	[4]	[6]	[7]	[9]	This Work
Supply Voltage	3V, 5V	3.5-5V	6-27V	2.7-5.5V	0.5-0.6V
Average LED Current	0.61mA, 0.75mA	0.6A	30mA	0.1- 2A	0.028-1.3 mA
Power	4.4mW	-	-	-	0.052-2.66 mW
Area	-	7.5mm²	-	4.12mm²	2.89mm²
Efficiency	52%	90.7%	90%	80-91%	89.7-94%
Process	1.5um	0.5um	0.35um	0.18um	0.18um

Fig.12 Comparison to recently published work.

VII. ACKNOWLEDGEMENT

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