Designing Efficiency Enhanced Low-Dropout Linear High-Brightness LED Drivers for Automotive Applications

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Abstract

In this paper, an innovative efficiency-boosting technique is successfully applied to typical linear light emitting diode (LED) drivers. Furthermore, p-channel MOSFET (PMOS) pass element with elaborate metal layout pattern is used to reduce dropout loss and a 5V regulated voltage is obtained from the wide range input voltage to power some sub-circuits. This will further diminish power dissipation and thus enhance efficiency. The proposed driver has been fabricated on a 0.5μm Bipolar CMOS DMOS (BCD) process. Post-simulation results show that when driving three high brightness light emitting diodes (HB-LEDs) in series, it can achieve maximum efficiency of 91.12% at \( I_{LOAD} = 350 \text{ mA} \), which is improved by 7.3%, as compared with that of the typical one under the same condition. Besides, the proposed driver is able to operate with a wide input voltage range (6V~32V) and deliver output current up to 350 mA, with an accuracy of ±3%, regardless of process voltage temperature (PVT) variations. Besides, the dropout voltage is only 450mV when \( I_{LOAD} = 350 \text{ mA} \) and \( V_{IN} = 12 \text{ V} \).

Keywords
Current-sense voltage, Efficiency-boosting technique, HB LED, Linear LED drivers, Low dropout, Pass element.

1. Introduction

As the most promising light source, High Brightness Light Emitting Diode (HB-LED) has many advantages such as high luminous efficiency, reduced energy consumption, long operating life, durability, reduced heat production, smaller package size etc. It is being used more and more extensively in automobile safety and signal lights, aircraft passenger reading lights, airport taxiway edge lights, commercial advertising signs and holiday lights. This is a fallout of the fact that aggressive price erosion is occurring in the HB-LED market, which is expected to continue [1-2]. The increasing application of LED imposes a clear demand on the design of controllable LED drivers. Innovative driver circuits optimized with respect to functionality, efficiency, cost, size and reliability are an enabler for the successful introduction of LED based lighting application [2]. Trying to operate LEDs, which basically need to be driven by a current source [3], by drivers that have been designed for voltage or resistive loads usually results in nonoptimized solutions that are less efficient, expensive and often bulky.

Over the years, numerous LED driving topologies have been proposed, and selecting an appropriate one is a trade-off between accuracy, efficiency, cost, scalability, component size and specifications. It is well known that various LED driver techniques are based on switching power supplies. The most commonly used ones are standard non-isolated DC-DC topologies [4-7] such as buck, boost and buck-boost. These topologies could be used as LED driver by adding a shunt resistor Rs in series to the LEDs. A boost topology is appropriate for operating from a battery voltage or standardized low voltage bus, and the LED open-protection circuit should be considered.

Buck converter is popular as an LED driver because it can allow continuous flowing current operation without an output bulky capacitor, which may result in simple and low cost solution. In addition to the advantage of being able to increase or decrease the output voltage higher or lower than the input voltage, buck-boost converter can provide an LED short circuit protection feature, which is very crucial in many LED based lighting applications. Besides, LED strings may also be fed by galvanic isolated converter topologies [7-9], such as the forward, fly back, or push pull converters. However, these drivers are more complex and bulky, and require a larger effort on current sense feedback loop than those non-isolated topologies. Therefore, they are seldom used in portable applications. For LED driver representing upcoming intelligent driver generation, it has been considered that the use of the smoothing capacitor at the output node can be eliminated. LEDs would then be supplied by pulsating currents, because this reduces component count and simplifies design of the LED driver. Based on this concept, different topologies, including none-isolated DC-DC
converters and galvanic isolated converters are analyzed [7]. Nevertheless, pulsating current increases the peak and root mean square (RMS) value of the LED current and electromagnetic interference (EMI) problems may also be caused due to the high frequency components.

Thanks to the continuously decreased cost of digital processors, digital controlled LED drivers have also been presented recently [10-12], besides the pure analog controlled switching power supply mentioned above. Its advantages include adding communication capability without extra circuitry and being capable of control scheme re-design by means of software re-programming. Also, their controls are very accurate with immunity to any direct physical magnitude dependencies (e.g. temperature). The main drawback is that a limit cycle could appear and stability may not be guaranteed because of the discrete resolution of the Digital Pulse Width Modulation (PWM). Therefore, some requirements must be fulfilled in order to avoid limit cycle conditions [13].

While switching mode drivers offer efficiencies that can reach more than 90% in many practical realizations, they tend to have either slow transient response or large silicon area. Furthermore, their output voltage ripple and output noise might not be acceptable for several applications. On the other hand, the linear LED drivers, especially the low dropout (LD) linear LED drivers, become increasingly popular in recent years. Compared with switching ones, the linear drivers are less expensive, smaller in area and easier to be used. Besides, the noise of output voltage is lower and the response to input voltage transient and output load transient is faster [14-15]. All these advantages make linear LED drivers well suited for battery-powered illuminating fields, which are sensitive to noise and EMI. As it happens, LD linear drivers have improved efficiency over conventional linear drivers, due to their smaller voltage headroom in the pass element, which is very important in fields as automotive industry where the supply of electronic devices (injection, electronic engine control) must be guaranteed even when the battery voltage drops to 6V during the starter motor [16]. The approach of employing LD linear regulators suffers from a still dissatisfactory operating efficiency because the power dissipated in the current-sense resistor contributes to the un-negligible power lost in the supply [17]. So far, there are very few papers published, relating to the efficiency improvement technology for linear LED drivers, especially linear LED drivers with reduced current-sense voltage.

In this paper, a novel LD linear LED driver that offers efficiency improvement is proposed. Thanks to the operational amplifier introduced, voltage drop as well as power consumption on the current-sense resistor is remarkably decreased. Besides, pretty layout for the pass element and efforts made to reduce the sub-circuits’ dissipation contribute further to high efficiency.

2. Design Considerations

2.1 Efficiency Limitation in Typical Linear LED Driver

The structure of a typical linear LED driver, as shown in Figure 1, is mainly composed of an error amplifier, a series pass element, and a current-sense resistor $R_{SENSE}$. The current-sense resistor is used to monitor output current $I_{LED}$ and provides a feedback voltage $V_{FB}$ to the error amplifier $EA$. The error amplifier compares the reference voltage $V_{REF}$ and the feedback signal $V_{FB}$ and feeds a control voltage into the pass element to regulate the output current, based on the difference between $V_{REF}$ and $V_{FB}$.

In Figure 1, efficiency of the LED driver can be expressed as

$$\eta = \frac{I_{LED} \times V_{LED}}{(V_{DROPOUT} + V_{LED} + V_{SENSE})(I_{LED} + I_{Q})}$$

$$= \frac{P_{LED}}{P_{DRIVER} + P_{LED} + P_{SENSE}}$$

(1)

where $V_{DROPOUT}$ is the voltage difference between the supply voltage $V_{IN}$ and the output voltage of the driver, i.e. dropout voltage of the pass element and $I_{LED}$ is the provided current for the loading HB LEDs, while $I_{Q}$ is the dissipated quiescent current of the driver. From equation (1), it is clear that efficiency of the typical linear LED driver is limited by the current-sense voltage $V_{SENSE}$, the dropout voltage of the pass element $V_{DROPOUT}$ and the whole quiescent current of the driver $I_{Q}$. In particular, the smaller the value of $V_{SENSE}$, $V_{DROPOUT}$ or $I_{Q}$ is, the higher the efficiency of the driver will be.

![Figure 1: Structure of a typical linear LED driver.](image-url)
2.2 Proposed Efficiency Boosting Techniques

Proposed efficiency boosting techniques shown in Figure 2 is the structure of the proposed efficiency boosting linear LED driver. Based on the analysis of the efficiency limitations for the typical linear driver above, three efforts have been made in the proposed design, to boost efficiency of the driver. Firstly, referring to Figure 1, the current-sense voltage \( V_{\text{SENSE}} \) is equal to the feedback voltage \( V_{\text{FB}} \) entering the error amplifier; thus, power consumption dissipated by the current-sense resistor is

\[
P_{\text{SENSE}} = V_{\text{SENSE}} \times I_{\text{LED}} = V_{\text{FB}} \times I_{\text{LED}} = V_{\text{REF}} \times I_{\text{LED}}
\]  

(2)

Nowadays, new HB LEDs are designed for nominal current of 350 mA or more [7]. The additional losses in the current-sense resistor can no longer be neglected and is very undesirable in electronic system, because it would limit the efficiency of the whole driver and, hence, decrease life-span of battery. This problem can be improved greatly by the proposed linear LED driver. As can be seen in Figure 2, an operational amplifier is introduced between the current-sense resistor and the error amplifier, based on the typical linear driver shown in Figure 1. Therefore, the current-sense voltage \( V_{\text{SENSE}} \) is firstly magnified by the operational amplifier before it enters the error amplifier, so as to minimize the power dissipation on the current-sense resistor and thus enhance efficiency of the driver. Assuming that the amplifying coefficient of the operational amplifier is \( K \) (in Figure 2, \( K = (R1 + R2) / R2 = 1 + R1 / R2 > 1 \)), then the current sense voltage would be

\[
V_{\text{SENSE}} = V_{\text{FB}} / K = V_{\text{REF}} / K
\]  

(3)

As a result, the power dissipation of the current-sense resistor will be reduced to

\[
P'_{\text{SENSE}} = V_{\text{SENSE}} \times I_{\text{LED}} = (V_{\text{REF}} / K) \times I_{\text{LED}} = P_{\text{SENSE}} / K
\]  

(4)

where, \( P_{\text{SENSE}} \) is the current-sense resistor’s power dissipation in a typical linear LED driver as shown in Figure 1, which is expressed by equation (2). Therefore, the power dissipation of the current-sense resistor in the proposed design is only \( 1 / K (K > 1) \), compared with that of the typical one. In other words, by introducing an operational amplifier into the feedback loop of the current regulation, the proposed linear driver is able to remarkably reduce the power dissipation of the current-sense resistor, and consequently advance the efficiency of the typical linear LED driver.

Secondly, careful considerations are given to decrease quiescent current and guarantee specific performance, at the same time, in the whole design flow of the proposed driver, especially in some critical sub-circuits, such as operational amplifier and error amplifier.

![Figure 2: Structure of the proposed efficiency boosting linear LED driver.](image)

Furthermore, from equation (1), the maximum achievable efficiency of a linear driver is also related to the minimum permissible dropout voltage of the pass element \( V_{\text{DROPOUT}} \). Several configurations of the pass element have been proposed, based on the system specification [17-18]. PMOS devices are typically the best overall choice, yielding a good compromise of dropout voltage, quiescent current flow, output current, and speed [19]. As a result, PMOS transistors, which exhibit the lowest dropout voltages because of their characteristically variable resistance, their VSD changes with gate drive and their aspect ratio, are chosen as pass element in the present design.

3. Implementation and Circuits Design

Figure 3 is a block diagram of the proposed driver, which consists of enable circuit, band-gap and regulator, bias generator, pass element, operational and error amplifier, as well as protecting circuit including thermal shutdown and current limiting. As shown in Figure 3, the proposed driver uses a feedback loop including the operational amplifier operational amplifier (OP-Amp), the error amplifier (EA) and the PMOS pass element MP to regulate the amount of current flowing into the loading HB LEDs. In addition, the proposed LED driver allows a wide-range “pulsed” dimming. The method for producing PWM dimming is by pulsing the enable input (EN) so as to generate a duty- cycle-regulated PWM current that can provide control over the brightness of LEDs. Additional features of the proposed driver include current limiting and thermal protection.

3.1 Operational Amplifier

As has been mentioned, a LED driver with a lower current-sense voltage \( V_{\text{SENSE}} \) is more efficient, regardless of the input voltage or LED current. Introducing an operational amplifier to achieve lower \( V_{\text{SENSE}} \) is a
novel design in the proposed driver, to boost efficiency. Figure 4 shows a schematic presentation of the operational amplifier, where $V_p$ and $V_n$ are non-inverting and inverting inputs respectively and $V_{fb}$ is its output voltage. The proposed operational amplifier is realized by a two-stage operational amplifier, which consists of a folded cascaded input stage (Q1–Q4) with a differential pair (Q1~2), followed by a second stage with a common-emitter amplifier (Q5). Transistor Q6 acts as an emitter follower output stage, to minimize the output impedance so that the voltage gain is relatively unaffected by load impedance of the latter circuits. The resistive feedback network of R1 and R2 measures the output $V_{fb}$ and provides a feedback to the inverting input. Besides, to avoid the possibility of oscillation, Miller compensation achieved by resistor R6 in series with capacitor C0 is exploited to ensure that the circuit does not oscillate when connected in a feedback loop [20]. Bias current of different branches in this amplifier is provided by a current mirror consisting of Q10~Q13, together with resistors R8~11, where $V_{b}$ is bias voltage from the bias generator (not shown here for brevity). By inserting resistors R8~11, these current mirrors are implemented with emitter degeneration, the purposes of which are two-fold [21]. Firstly, the matching performance of different mirrors can be greatly improved. Second, it would boost the output resistance of each output of the current mirror and, thus, improve the accuracy of the current mirror. It should be noted that the ratio of resistor R1 and R2, i.e. the amplifying coefficient of the operational amplifier, is set to be about 6 in this design, considering the trade-off of power dissipation on the sense resistors and the accuracy of it.

3.2 Band-gap and Regulator

The band-gap and regulator module is an important sub-circuit and should be carefully designed so that it directly guarantees the current accuracy of the driver. The band-gap core used in this design is based on the one proposed by Brukaw [22]. Figure 5 is the simplified schematic of the proposed band-gap and regulator, where the emitter area of transistor Q2 is made larger than that of transistor Q1, in the ratio of 8 : 1, while transistors Q3~5 form a current mirror to help keep emitter currents of Q1 and Q2 equal. Therefore, the bandgap voltage can be expressed as

$$V_{ref} = V_{be1} + V_{be2} = V_{be1} + 2 \frac{R2}{R1} \left( kT \ln N \right)$$

where $V_{be1}$ is the base-emitter junction voltage of transistor Q1, $k$ is Boltzmann’s constant and $N$ (N=8) is the ratio of the collector current density between transistor Q1 and Q2.

As shown in Figure 5, the function of the operational amplifier in a typical band-gap circuit is replaced by transistors Q3~7. The proposed band-gap and regulator operate essentially as follows. Transistors Q3~5 and resistor R5 form a current mirror with a Beta helper which detects the difference of collector currents between transistors Q1 and Q2. This current difference drives the base of transistor Q7 through a source follower formed by transistor Q6, together with resistor R6, to supply the...
regulated output voltage $V_5$. The regulated voltage $V_5$ is divided by $R_3$ and $R_4$ and applied to the base of $Q_1$ and $Q_2$, to minimize their collector current difference. Besides, it should also be noticed that NMOS transistors $N_1$ to $N_2$, with the gate voltage $V_B$ which is derived from another module (not shown here for brevity), are added in the proposed band-gap core for the special purpose of providing high-voltage protection for other devices.

The advantage of the proposed band-gap and regulator is that the stability of the band-gap reference $V_{REF}$, as well as the regulated voltage $V_5$, depends simultaneously on one common feedback loop, which could effectively reduce circuit complexity and chip size. Besides, by designing the circuit to stabilize the base voltage at the band-gap voltage $V_{REF}$, the output voltage $V_5$ is set to be 5V and will be applied to some other sub-circuits of the proposed driver as power supply, where the wide range input voltage $V_{IN}$ is unnecessary and unfeasible, so that power dissipation of those sub-circuits is reduced.

### 3.3 Pass Element

In linear LED driver, the pass element’s function is to boost the output-current capabilities of the error amplifier to the higher levels required by the load, which involves transferring large currents from the source $V_{IN}$ to the loading LEDs [23]. The size of the pass element is determined by the maximum load current and the minimum dropout requirements, usually resulting in a large pass device with large chip area and complicated layout. The low ground current and low dropout voltage of PMOS devices make it the best choice of pass element for linear drivers [19]. Besides, resistance of the metallization is a significant fraction of the pass element’s total on-resistance $R_{ON}$, and proper metal layout is critical to attain the lowest possible on-resistance $R_{ON}$ of the pass element, because the smaller the on-resistance of the pass element, the lower its dropout voltage would be. Therefore, PMOS transistor implemented with the multi-finger angled MTT (top metal) pattern as shown in Figure 6, which is the best MTT pattern aiming at the lowest $R_{ON}$ in the selected 0.5 µm BCD process, is chosen as the pass element in the proposed design.

### 4. Simulation Results and IC Implementation

In order to verify the proposed efficiency boosting technique, experiments have been performed to check the maximum achievable efficiency of the linear LED driver without/with the proposed operational amplifier Op-AMP. For the linear LED driver without the introduced amplifier Op-Amp, 3.57 Ω current-sense resistor is chosen to obtain 350 mA loading current while the current-sense resistor is 0.585 Ω at the same condition for the linear LED driver with the OP-Amp. In experiments, input voltage is scanned to observe the minimum required input voltage and the maximum achievable efficiency. Figures 7(a) and (b) illustrate the simulation results for the two drivers with three HB-LEDs in series. In Figure 7, it is illustrated that the minimum required input voltage to attain 350 mA load current is 12.78 V and 11.76 V respectively for the drivers without/with the proposed OP-Amp. Besides, the maximum achievable efficiency is 83.84% for the scheme, without the proposed OP-Amp, while it rises to 91.12% for the proposed scheme with the OP-Amp. Therefore, experiments are in good agreement with the theoretical analysis that introducing an operational amplifier to minimize
current-sense voltage can effectively improve efficiency and also reduce the required minimum input voltage.

The proposed efficiency-boosted linear LED driver has been fabricated in a Jazz 0.5 µm BCD technology. Figure 8 shows the layout of the proposed driver. Its effective die area is 1.4 mm × 1.8 mm, including pads and ESD structures. Table 1 summarizes the post simulation results for the main characteristics of the proposed driver over temperature (−40°C ~ 125°C). In Table 1, it is indicated that the proposed driver operates a wide range input voltage (6V~32V) and is able to provide 35mA~350mA output current with an accuracy of ±3% (considering PVT variations) to one or more strings of HB LEDs. Its quiescent current is 1 mA, with a dropout voltage of only 0.45 V at 350 mA-load and VIN = 12 V condition. Besides, it also shows fine transient performance. For example, it takes only 99 µs when the output current IOUT rises from 0 to 90% of the preset value (350 mA). All these features of the proposed driver make it suitable for automotive applications, as well as other battery-power illumination systems.

Figure 8: Layout of the proposed driver.

| Table 1: Specifications of the proposed driver over temperature (−40°C ~ 125°C) |
|-----------------------------|-----------------------------|-----------------------------|
| Parameters                  | Conditions                  | Results                     |
| Input voltage range (VIN)   | 35mA < IOUT < 350mA         | 6.0V~32V                    |
| Quiescent current (IQ)      | IOUT = 350mA, VIN = 12V     | 1mA                        |
| Output current accuracy     | 35mA < IOUT < 350mA         | ±3%                        |
| Dropout voltage (VDROP)     | IOUT = 350mA, VIN = 12V     | 0.45 V                      |
| Turn on time (tON)          | IOUT rises to 90% of the preset value 350mA | 99µs                       |
| Current-sense voltage (VSENSE) | IOUT = 350mA | 204mV                     |
| Line regulation             | IOUT = 35mA, VIN from 6V to 32V | 144µV/V @ to 32V |
|                           |                             | VOUT = 4.5V                  |
|                           | IOUT = 350mA, VIN from 6V to 32V | 196µV/V @ to 32V |
|                           |                             | VOUT = 4.5V                  |
| Thermal shut                | 35mA < IOUT < 350mA         | 155°C                      |
| Thermal shut Hysteresis     | 35mA < IOUT < 350mA         | 23°C                       |
| Current limiting            | VOUT = 0V, VIN = 12V        | 500mA                      |

5. Conclusions

A new linear LED driver has been developed and fabricated based on the analysis of efficiency deficiency on the typical drivers. In the proposed design, efforts are effectively made to diminish current-sense dissipation, regardless of input voltage or LED current, the dropout voltage of the pass element as well as the dissipation of sub-circuits, so that efficiency of the whole driver can be significantly boosted. Experimental results of the whole driver have confirmed this efficiency improvement as well as extra features including PWM dimming, thermal-shutdown and current-limiting of the proposed linear LED driver.

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References


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