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Adaptive Current-Mirror LED Driver employing Super-diode Configuration

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***Abstract*— An improved current-mirror LED driver is presented in this paper. Incorporating a super-diode configuration, this circuit selects a reference current automatically to prevent transistor saturation even in a wide forward voltage spread in the LED string voltage. Using a statistical cost function evaluation based on a Monte-Carlo analysis through MATLAB/PSIM co-simulation, the performance of the proposed circuit is analyzed and compared with that of the conventional circuit using a self-configurable Darlington-pair.**

Keywords*— *LED driver; current-mirror; super-diode

I. INTRODUCTION

For its environmentally-friendly and long-lasting features, the light emitting diode (LED) is popular in both lighting and display applications. To extend the light capacity, LEDs are normally connected in series, which is called an "LED string". To prevent an excessive driving voltage or a light-source blackout failure in the event of a single point fault, the LED strings are placed in parallel to make a light source.

The main function of LED drivers is to provide nearly equal currents in each string to ensure uniform brightness and to prevent short LED life, because the LED forward voltage shows a production spread that causes inherent current imbalances when operating in parallel. Many researchers have investigated current balancing methods, including linear and switching power converter driver circuits [1]-[2].

Especially for small-powered applications such as the LED backlighting of monitors where the forward current is not high and the number of LED packages is not large, the current-mirror driver is usually adopted because of the circuit simplicity and low cost [3]. When every transistor in the circuit is well-matched and operating in forward active mode, this circuit provides good current balancing performance, but in an actual mass production situation with large variations among the forward voltages in LED strings, the dc drive voltage should be designed with additional margin, called "headroom", in order to prevent transistor saturation, which increases the power dissipation in the driver circuit. Recently, to alleviate this problem, a novel self-configurable current-mirror has been suggested [5]. This circuit utilizes a Darlington-pair transistor and selects the reference branch automatically. However, this scheme results in additional increases in the collector voltage of the drive transistors and is not optimized for loss.

In this paper, an improved current-mirror driver is proposed. With super-diode operation, it enhances current balancing capability with no additional headroom voltage to minimize the drive loss. To estimate the performance of the proposed circuit and compare it with that of the conventional circuit, a cost function is defined and evaluated with a randomly-generated LED string voltage for a prototype dual channel LED driver.

II. PROBLEMS IN CONVENTIONAL WORKS

A. Statistical distribution in the forward voltage

In mass production, each LED package shows a slightly different forward voltage because it has been picked at random from among samples having the same nominal value. Because several LEDs are assembled in series into an LED string, the overall forward voltage of the LED string also shows a probabilistic distribution and if the number of series connections is large, the distribution approaches Gaussian according to the central limit theorem [10].

From this fact, the LED string voltage, V_D, can be regarded as a random variable that has a truncated normal distribution as shown in Fig. 1 with the upper limit, V_{UL}, and lower limit, V_{LL}, specified from the manufacturer's datasheet. In practice, we may not know the exact value of V_D, since the LEDs may have been picked at random. For each LED string, the string voltage will have a value between those two extreme values. If we define V_{MAX} and V_{MIN} as the maximum value and the minimum value among the measured voltages of multiple LED

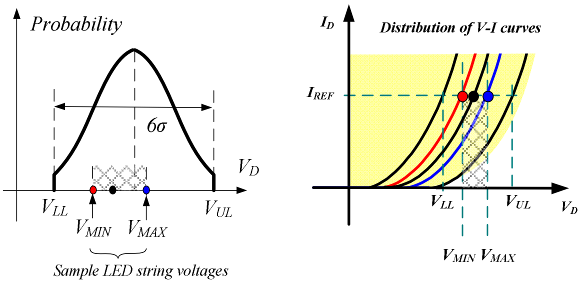

Figure 1. LED string voltage distribution

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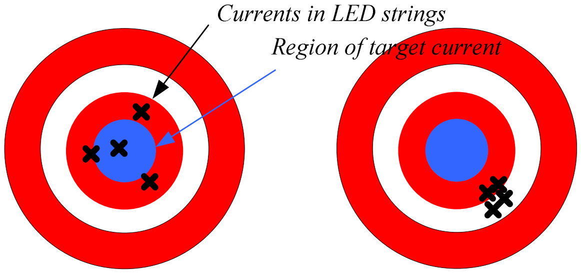


(a) accurate but not uniform (b) uniform but not accurate

Figure 2. Current-driving performance : accuracy vs. uniformity

strings in an implementation of an LED driver, the following holds:

$$V_{LL} \leq V_{MIN} \leq V_{MAX} \leq V_{UL} \tag{1}$$

B. *Current-driving performance and driver loss*

As for current-driving performance, accuracy as well as uniformity in the LED string currents should be considered. Accuracy is the degree of closeness to the target current specification, whereas uniformity is the degree to which the current in each branch is equalized. Fig. 2 illustrates the performance by analogy with aiming at a mark, and the target current is compared to the bull's eye.

Another important performance factor is the loss dissipation of the drive circuit. For example, linear passive balancing scheme utilizes a series resistor in each string to equalize the LED currents [4]. The current in each string is calculated as

$$I_D = \frac{V_S - V_D}{R_S} \tag{2}$$

where V_S, V_D, and R_S are the supply voltage, the LED string voltage, and the balancing resistor, respectively. This circuit cannot achieve good uniformity in the LED currents because of the finite impedance of the resistor. For the finite resistance, the current is inevitably dependent on the string voltage. Moreover, component tolerances in the resistors may make the accuracy even worse. The loss dissipation in the resistor is represented as

$$P_L = I_D^2 R_S \, . \tag{3}$$

To make the current independent of V_D, R_S should be very large, which means uniformity should be sacrificed in order to suppress high loss dissipation in the balancing resistors.

C. *Limitation of Conventional Current-Mirror driver*

The conventional current-mirror driver shown in Fig. 3 can be a good alternative. A front-end dc/dc converter provides at least two regulated output voltages: one is a main bus voltage, V_S, to provide the common drive power for all of the LED strings, and the other is an auxiliary voltage, V_{AUX}, for the reference current generation and/or IC circuitry. To increase the accuracy in the string currents, we need to regulate the auxiliary voltage tightly and choose a high-precision resistor, R_{REF}. Well-matched and high current-gain transistors provide good current uniformity of the circuit.

However, base currents flowing out of the reference branches to bias the transistors make the current replication imperfect even in the well-matched case and cause errors in the accuracy. This accuracy error increases with the number of parallel branches as follows:

$$I_D = \frac{\beta}{\beta + N + 1} I_{REF} \tag{4}$$

where N is the number of LED strings and I_{REF} is the target current. Furthermore, to cope with the wide variations in the forward voltage in mass-produced LED packages, the dc drive voltage should be designed with additional margin, called "headroom", to prevent transistor saturation. Without the headroom voltage, the transistor would go into saturation mode and lose all of the current-mirror features in that branch, and would not achieve uniformity in LED currents. This situation is illustrated in Fig. 4. To prevent saturation even in the highest possible LED voltage, V_{UL}, the supply voltage V_S should be chosen as

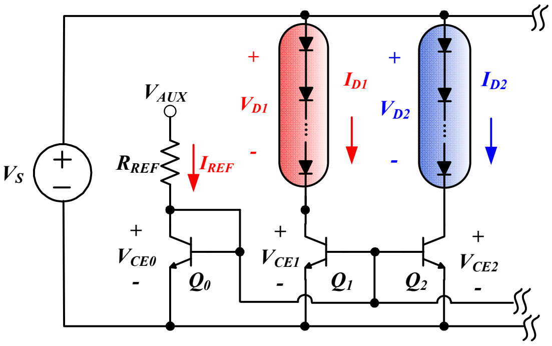


Figure 3. Conventional current-mirror LED driver

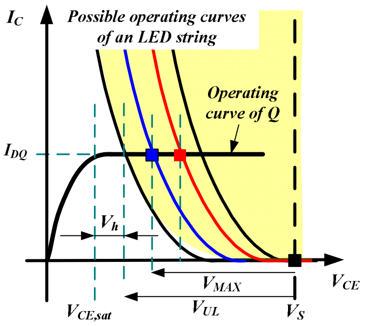


Figure 4. Headroom voltage to prevent transistor saturation

$$V_S = V_{CE,sat} + V_{UL} + V_h \tag{5}$$

where V_h is the headroom voltage to ensure linear operation and is usually set to a non-zero value, which causes additional loss dissipation in every branch. The loss in each branch transistor is represented as

$$P_L = (V_{CE,sat} + V_{UL} + V_h - V_D)I_D \tag{6}$$

where more headroom being placed results in higher power loss.

D. *Current-mirror employing Darlington-pair structure*

Recently, to alleviate the saturation problem, a novel self-configurable current-mirror was suggested in [5]. This circuit utilizes a Darlington-pair transistor and selects the reference branch automatically. Reference [5] adopted an unregulated current source; however, applying this method to a more elegant application such as an LED backlight will require a closed loop current control scheme.

When either of the auxiliary transistors, Q_{11} and Q_{22}, is saturated, the corresponding branch is selected as a reference branch. In some cases, neither of them is fully saturated and the transistors are in forward active mode to achieve Darlington operation. Therefore, the collector voltage of the main transistor always meets the condition of

$$V_{CE} \geq V_{CE,sat} + V_{BE} \tag{7}$$

where V_{BE} is the turn on voltage of the auxiliary transistors and $V_{CE,sat}$ is the collector voltage at the edge of saturation. Thus the current feedback loop regulates the supply voltage to be as high as

$$V_S = V_{CE} + V_{MAX}\,. \tag{8}$$

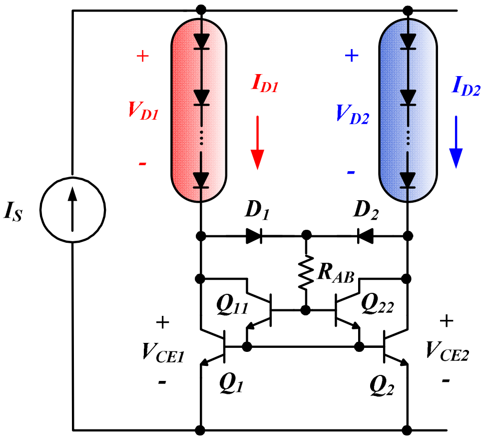


Figure 5. Current-mirror with Darlington-pair (current source version)

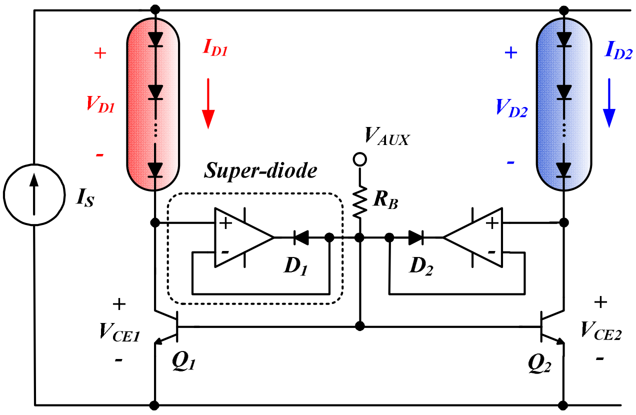


Figure 6. Proposed circuit (current source version)

where V_{MAX} is the highest voltage of paralleled LED strings in a circuit implementation. The power dissipation in each branch is determined by

$$P_L = (V_{CE,sat} + V_{BE} + V_{MAX} - V_D)I_{REF}\,. \tag{9}$$

If the current source, I_S, is tightly regulated to the N times the target LED current, this circuit provides better accuracy than that of the original current-mirror circuit in Fig. 3. However, unlike the original version, this circuit may degrade the uniformity. In other words, if Q_{11} is assumed to be saturated, the LED current is given by

$$I_{D2} = \frac{\beta}{\beta + N} I_{D1} \tag{10}$$

and the difference between the currents increases with the number of existing LED strings.

III. PROPOSED CIRCUIT

Figure 6 shows the proposed circuit. There are two LED strings only for explanation purposes, but it can be expanded to any number of strings. In this circuit, a buffer amplifier containing a diode in the feedback loop is added to the conventional current-mirror driver. This structure is usually called a “super-diode” because the original voltage drop in the diode is decreased to the forward drop divided by the open loop gain of the op-amp itself and approaches nearly zero theoretically. Actually, only a very small offset voltage is present between the input terminal and the output terminal of the super-diode whenever the diode turns on. This feature can be useful for improving the current-mirror action. In a slightly different LED forward voltage, only one diode turns on and the current-mirror reference is set up.

According to the analysis in [5], the V-I characteristics of the LED show that the branch that has the lowest LED current in a constant voltage driving test will present the highest LED string voltage in a constant current driving circuit, and thus that branch should be selected as a current reference in a current-mirror circuit to prevent the saturation of the remaining transistors. This means that the branch having the lowest collector voltage should be chosen as a reference branch. In the proposed circuit, super-diodes are configured as a wired-OR gate to select the lowest collector voltage. When a super-diode turns on, a virtual short from the feedback mechanism of the op-amp makes the collector voltage nearly equal to the base voltage, thus preventing the saturation of the transistor. Moreover, there is no current leakage flow from the collector to the base, so this circuit makes a unity current replication ratio.

To analyze the performance of the proposed circuit, assume that LED string #1 is has the lowest current branch, such that V_{CE1} is lower than V_{CE2}. This means that the string voltage is the maximum voltage, V_{MAX}, of the two branches. This situation turns D_1 on, and the op-amp feedback makes the collector of Q_1 have the same potential as the base, and the supply voltage is maintained as

$$V_S = V_{CE} + V_{MAX} = V_{BE} + V_{MAX}\,. \tag{11}$$

This condition prevents Q_1 from moving into saturation mode because V_{CE1} is always higher than the voltage at the edge of saturation, $V_{CE,sat}$, which is about 0.3V. Furthermore, from the initial assumption, V_{CE2} is higher than V_{CE1} and Q_2 operates in forward active mode. As a result, if transistors Q_1 and Q_2 are well-matched, the following holds:

$$\beta_1 = \beta_2 = \beta\,,\; I_{B1} = I_{B2} = I_B \tag{12}$$

and the LED string currents are equal to each other.

$$I_{D1} = I_{D2} = \beta I_B\,. \tag{13}$$

Finally, the power dissipation in each branch is represented as

$$P_L = (V_{BE} + V_{MAX} - V_D)I_{REF}\,. \tag{14}$$

From the above analysis, with the help of the super-diode's virtual short operation, the proposed circuit places no additional headroom voltage other than V_{BE} to the transistors, and the loss is minimized. Moreover, the collector current is perfectly mirrored to the remaining branch, so this scheme also shows good uniformity feature.

To ensure the accuracy, a tightly regulated current source, I_S, is needed. To implement the current source, a small current sensing resistor is inserted to monitor the total current in the overall branch. The sensed value is compared to the current reference corresponding to the number of parallel branches (in this case N = 2) multiplied by the target LED current, I_{REF}, as shown in

$$I_S = N \cdot I_{REF}\,, \tag{15}$$

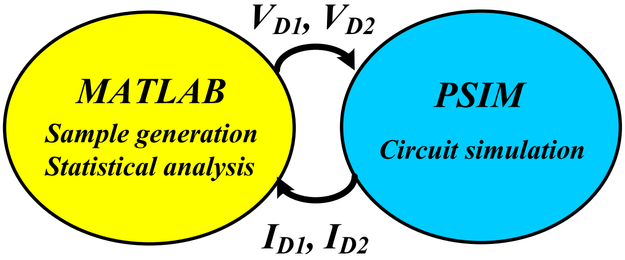


Figure 7. Monte-Carlo analysis using co-simulation

which completes the closed loop current control. For the above equation, N is the number of LED strings and thus it is 2 in this example. The total current control loop and the individual uniform current balancing function of the current-mirror ensures that each current is accurately equal to the target LED current.

IV. PERFORMANCE ANALYSIS

In this section, three different schemes are compared. To estimate the performance of the proposed circuit and compare it with that of the conventional circuit, statistical cost functions are defined and evaluated with a normally distributed LED forward voltage sample for a prototype dual channel LED driver.

A. Statistical performance test method

The statistical performance test procedure is shown in Fig. 7. The PSIM schematics are constructed and operated with MATLAB to perform a Monte-Carlo simulation. MATLAB generates the pseudo-random sample set of the LED string voltages for each channel and delivers them to the PSIM to perform the circuit simulation. The resulting data is collected and returned to MATLAB to analyze the performance. In the Monte-Carlo simulation, we repeatedly change the LED string voltages with a truncated Gaussian distribution to determine the performance in mass production. For each statistical occurrence, a circuit analysis is performed and evaluated by means of three statistical cost functions : E, S, and L. When the number of samples is N, the cost functions E and S describe the current accuracy and the uniformity of the LED currents, and L represents the driver circuit losses. These functions are calculated by the average error from the target current, the standard deviation of the LED currents, and the average power loss in each channel, and are defined by

$$E = \left(\frac{1}{N}\sum_{i=1}^{N} I_{D1,i} - I_{REF}\,, \frac{1}{N}\sum_{i=1}^{N} I_{D2,i} - I_{REF} \right) \tag{16}$$

$$S = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(I_{D1,i} - I_{D2,i}\right)^2} \tag{17}$$

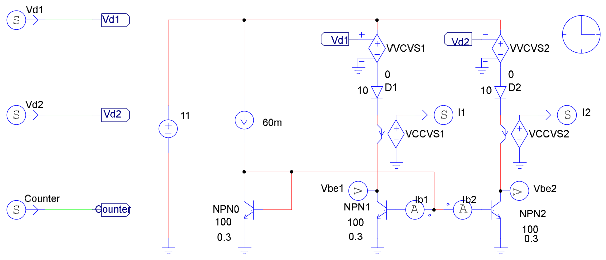


Figure 8. Circuit simulation schematics

$$L = \left(\frac{1}{N} \sum_{i=1}^{N} \left(V_{S,i} - V_{D,i}\right) I_{D1,i} \,, \frac{1}{N} \sum_{i=1}^{N} \left(V_{S,i} - V_{D2,i}\right) I_{D2,i} \right) \qquad (18)$$

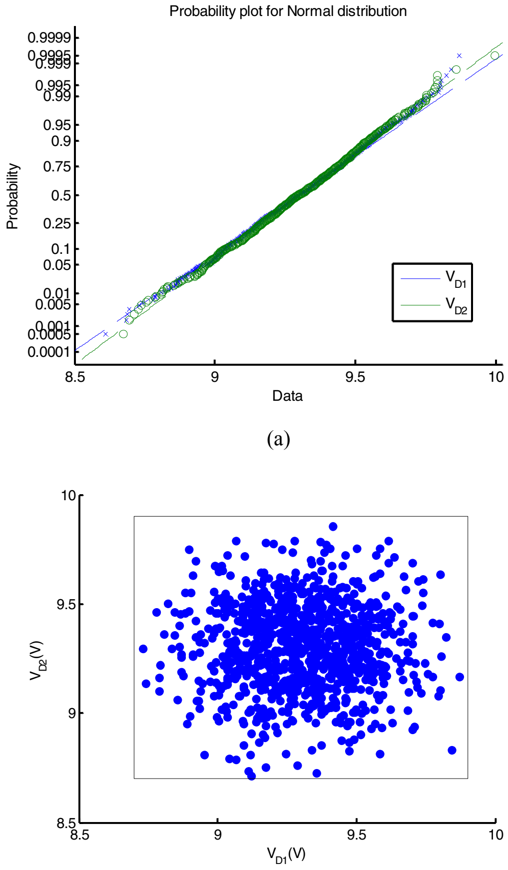
For each cost function, the smaller value indicates better performance. For example, a smaller absolute value of E indicates that most LED currents are closer to the target current, which means a higher level of accuracy. Similarly, a smaller S indicates a more uniform current distribution between parallel strings.

B. Test setup

The statistical simulation is performed for three different circuits: A is an original current-mirror driver driven by a constant voltage source, and B is a current-mirror with a Darlington-pair driven by a constant current source, all of which are the conventional circuits. C is the proposed circuit and its schematic is constructed as shown in Fig. 8.

Two-channel LED arrays are constructed with three LED chips in each string. The forward voltage data are obtained from the datasheet of commercial LED chips (D9WCZ11SC) made by Power Lightec Inc. They have production spreads in the forward voltage with a minimum of 2.9V, a maximum of 3.3V, and a nominal value of 3.1 V at the recommended target current of I_{REF}=60mA. In the design phase, we cannot use a whole population of mass produced samples and thus the LED string voltages for two channels, V_{D1} and V_{D2}, are assumed to be random variables having a two-dimensional normal distribution with truncations in the upper and lower limits as shown in Fig. 1, and their mean value at 9.3V. The standard deviations are assumed to be 0.2, which is one-sixth of the separation between the lower limit and the upper limit by conventions in [8]. To simulate the mass production situation, 1000 LED string voltage pairs are generated by the MATLAB pseudo-random number generator, the normality test plot of which is shown in Fig. 9(a) and proves that the generated set follows a normal distribution. After a truncation process involving deleting the samples located beyond the bounds of its limit values, 8.7V and 9.9V, we obtained 993 truncated Gaussian samples as shown in Fig. 9(b), which will be used throughout the performance analysis.

The LED chip internal resistance is assumed to be 10Ω. The headroom voltage, Vh, in (5) is set to 0.8V for circuit A, and R_{AB} is selected as 10kΩ for circuit B. For the current source driving in the circuits B and C, a buck converter is designed with a constant current regulation in which a small current sensing resistor is inserted into the return path to monitor the total current in the overall LED branch. The sensed value is compared to the current reference corresponding to twice the target LED current and thus it is set to 120mA, which completes the closed loop current control of the prototype circuits.



(a)

(b)

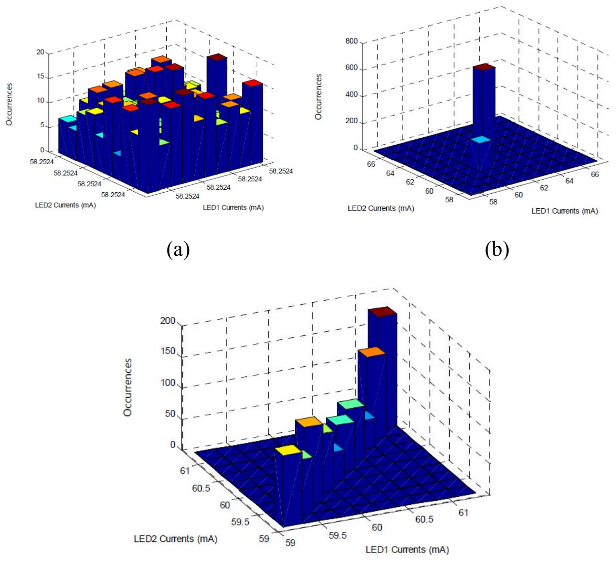
Figure 9. Distribution of the string voltages

C. Performance comparison by 2-D histograms

Figure 10 shows the current distributions in the test circuits. While circuit A shows slightly less current than the target value of 60 mA because of its imperfect reflection ratio as analyzed in (4), circuit C presents the better performance in terms of the current accuracy. For the current uniformity, both circuits A and C show superior characteristics, whereas, circuit B shows poor performance as predicted in (10). Figure 11 shows the distribution of loss generations in transistors Q_1 and Q_2. Circuit C shows the lowest loss dissipation among the test circuits.

D. Performance comparison by the statistical cost functions

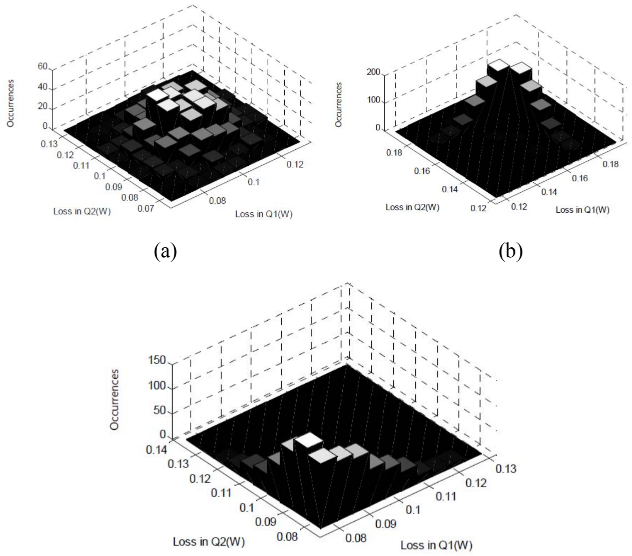
In order to investigate the performance of the circuits further, Table 1 shows the statistical cost function evaluations for the three circuits. The proposed design approach shows lowest values in E, which indicates superior performance in terms of the current precision. Circuit C has smaller value than circuit B and similar value to circuit A in terms of cost function S. In the cost function of L, circuit C has the lowest value among the three circuits. In summary, the proposed circuit shows the superior performance than that of the conventional circuits when the production spread is considered. We can estimate from (9) and (14) that the advantage will become greater with higher levels of LED current. A uniform distribution assumption in the forward voltage will also be advantageous to the proposed scheme.



(a) (b)

(c)

Figure 10. Statistical analysis results: current balancing



(a) (b)

(c)

Figure 11. Statistical analysis results: loss dissipation in transistors

TABLE I. TEST CIRCUIT COMPARISON RESULTS

Circuit	**Cost function evaluations**		
	E	***S***	***L***
A	(-0.0017, -0.0017)	3.5×10^{-10}	(0.0990, 0.0989)
B	(+0.0014, +0.0014)	5.4×10^{-5}	(0.1669, 0.1670)
C	(+0.0003, +0.0003)	3.4×10^{-10}	(0.0853, 0.0852)

V. CONCLUSION

In this paper, an adaptive balancing current-mirror driver is introduced. Especially for mass production, the statistical cost function analysis proves that the proposed circuit shows better current balance features with lower driver loss than the conventional circuits.

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