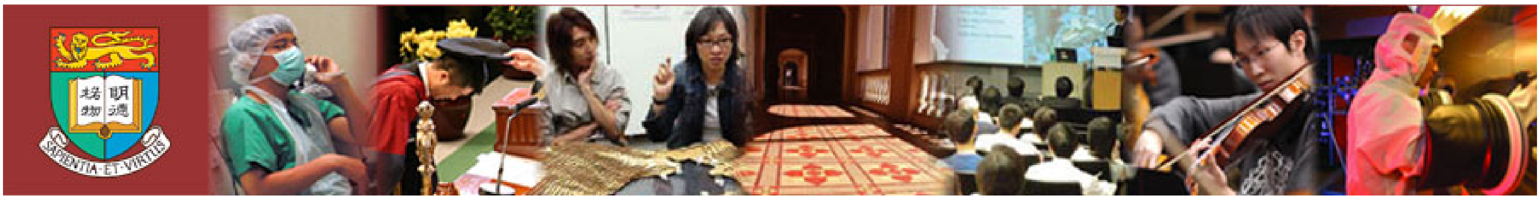

Title	Novel self-configurable current-mirror techniques for reducing current imbalance in parallel Light-Emitting Diode (LED) strings
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Novel Self-Configurable Current-Mirror Techniques for Reducing Current Imbalance in Parallel Light-Emitting Diode (LED) Strings

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***Abstract*—Traditional current-mirror methods require one fixed current reference for controlling other current source or sources. In this paper, a new self-configurable current-mirror method that can dynamically determine the best current branch as the current reference in order to ensure good balance of all parallel current sources is proposed. The operating principle involves a dynamic and self-configurable transistor-based current-balancing circuit that can be operated in saturation or linear mode. In either operating mode, good current balance or sharing among all parallel-connected current sources can be guaranteed. The novel current-balancing circuit does not require a separate power supply for powering their control circuits. The proposal is a modular one that can be expanded to any number of parallel current sources. Its principle has been successfully applied to current balancing of parallel LED strings.**

***Index Terms*—Current balance, current mirrors, LED.**

I. Introduction

CURRENT imbalance problems in parallel LED strings have attracted much attention in recent years as LED technology is perceived as an emerging technology for replacing incandescent and fluorescent lamps. Use of series-connected LED packages requires a high voltage power supply and so parallel arrangements of LED strings are common practice particularly in medium- and high-power LED systems. However, it has been pointed out [1] that, due to the variations of LED packages, even a small mismatch of 0.42 V among parallel LED strings could lead to significant current imbalance and reduction of system reliability and lifetime. To cope with the current imbalance problem in parallel-connected LED strings, researchers have proposed various methods. For parallel LED strings driven by a common dc current source, the simplest but highly inefficient method is to have a current-balance resistor in each LED string. Other relatively efficient methods for reduction of current imbalance include 1) the use of current-mirror (CM) techniques [2]–[5] (with an example shown in Fig. 1); 2) linear- or switched-mode current regulator [6]–[10] (with an example shown in Fig. 2) and 3) the use of coupled magnetic circuits [11], [12] (with an example shown in Fig. 3). It should be noted that existing CM circuits require one controlled current source as a fixed current reference and a power supply to create this current reference. For the current regulator approach, a power supply is required for the linear- or switched-mode circuits and the closed-loop control electronics [15]–[17]. The use of current-balancing transformers in linking adjacent

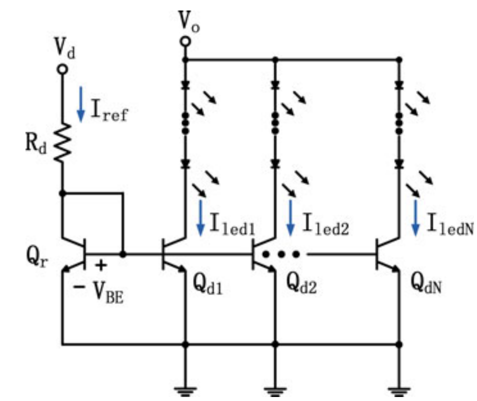

Fig. 1. CM circuit for balancing currents in parallel LED strings [2].

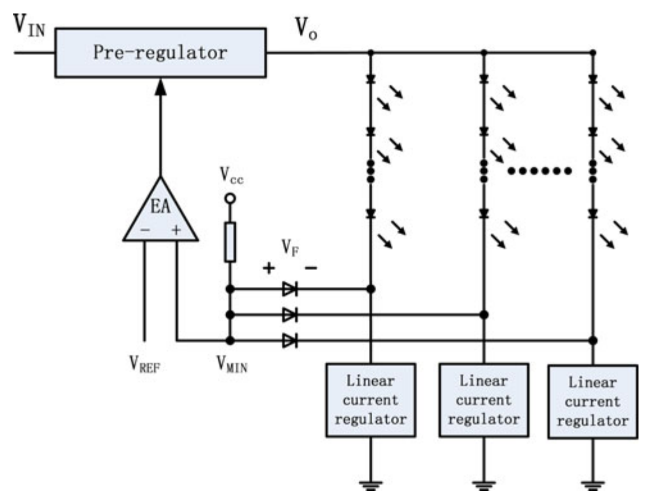

Fig. 2. Previous proposal of current balancing of LED strings using linear current regulators powered by a separate power supply V_{cc} [6].

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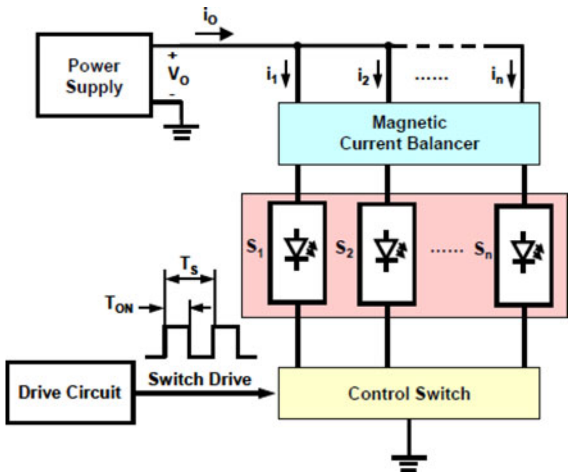

Fig. 3. Current-balancing technique based on coupled magnetic circuits [12].

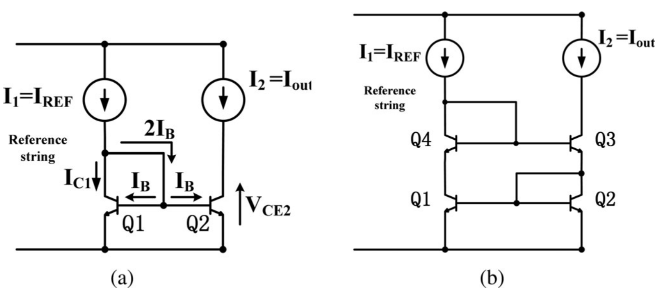

Fig. 4. (a) Basic current-mirror circuit. (b) Wilson current-mirror circuit.

LED strings may impose complication in production process. For example, some LED strings may have to pass through two transformers.

In this paper, a novel self-configurable CM method for reducing current imbalance in parallel LED strings powered by a single dc current source is proposed. This patent-pending method does not require a separate power supply for powering the CM circuit and involves no current-balancing transformers. Beginning with a brief introduction of CM circuits, this paper includes the operating principles and an analysis of a new CM circuit that can automatically and dynamically select the best LED string current as the reference for the CM circuit in order to achieve good current balance among parallel LED strings. The criteria for choosing the optimal current reference are explained. Practical implementations have been conducted and test results confirming the validity and effectiveness of the proposal are included.

II. Principles and Limitations of Existing Current-Mirror Techniques for DC Current Balancing of Parallel LED Strings

A. Principles of Current-Mirror Techniques

Current-mirror techniques are well-known methods for creating a current source or several current sources that follow a reference current. As shown in Fig. 4(a), a basic CM circuit can be constructed with bipolar junction transistors (BJTs) [13]. Essentially, the two BJTs are assumed to be matched or identical. Usually, the current in the branch where the collector terminal and the base terminal are tied together forms the reference current. In Fig. 4(a), the collector current I_{REF} in the BJT $Q1$ is used as the reference current. CM-based current-balancing techniques in [2]–[5] generally follow this principle with a predetermined current reference that is set for all parallel LED strings to follow. Other improved versions of CM such as the Wilson CM circuit [14] can also be used [see Fig. 4(b)].

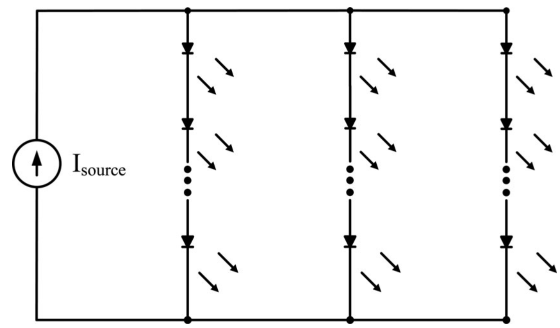

Fig. 5. Parallel-connected LED strings with imbalanced currents.

The equations of this circuit are listed as follows:

$$I_{\mathrm{REF}} = I_{C_1} + 2I_B \tag{1}$$

where I_{C1} is the collector current of BJT Q_1 and I_B is the base current of both $Q1$ and $Q2$. Since $I_{C1} = \beta I_B$, (1) can be expressed as

$$I_{\mathrm{REF}} = \beta I_B + 2I_B = (\beta + 2)\, I_B \tag{2}$$

where β is the current gain of the BJT.

For BJT $Q2$, the collector current is

$$I_{\mathrm{OUT}} = \beta I_B. \tag{3}$$

From (2) and (3)

$$I_{\mathrm{OUT}} = \frac{\beta}{\beta + 2} I_{\mathrm{REF}}. \tag{4}$$

Since β of a BJT can be in the order of typically 40 to 250, the controlled current source I_{OUT} in (4) is approximately equal to I_{REF}. Therefore, the controlled current source I_{OUT} is said to follow the reference current source I_{REF}.

B. Limitations of Current-Mirror Techniques

In existing CM techniques, one current branch must be fixed as the reference current source. For a given I_{REF}, the collector–emitter voltage V_{ce} across the BJT Q_2 will vary in order that I_{c2} will follow I_{REF}. It is important to note that I_{REF} must not be larger than the current capability of the parallel current sources. Otherwise, the parallel current sources cannot follow I_{REF} even when their currents are at their maximum values. This important condition imposes a problem in the use of traditional CM for parallel LED strings because it is generally not possible to predetermine the variations of the LED strings. The requirement for a known reference current source could be a major limitation in some applications such as the dynamic current balancing

TABLE I
PRACTICAL TEST RESULTS OF CURRENT-MIRROR CIRCUITS FOR CURRENT-BALANCING APPLICATION

	Reference Current	Current (mA)	V_{CE} (V)	**Mirror Current**	Current (mA)	V_{CE} (V)	**Current imbalance** (mA)	**Success**
Fig.6a	**String 1 (Smaller current)**	234		**String 2 (Larger current)**	284		50	**As benchmark**
Fig.6b	String 1	237	0.91	String 2	282	1.1	45	**No**
			Q1 linear			Q2 nonlinear		Transistor Q2 Thermal runaway
Fig.6c	String 2	286	0.95	String 1	232	0.5	54	**No**
			Q2 Linear			Q1 Saturated		Large current as I_{ref} Transistor saturated
Fig.6d	String 1	252	1.73	String 2	263	2.79	**11**	**Yes**
			Q1 Linear			Q2 Linear		Small current as I_{ref} Transistor linear
Fig.6e	String 2	282	1.8	String 1	236	1.07	46	**No**
			Q2 Linear			Q1 Saturated		Large current as I_{ref} Transistor saturated

of LED strings. Fig. 5 shows one example of such application in which LED devices are arranged in three strings. Even if each LED string has the same number of series-connected LED devices, the voltage drops across the LED strings are not identical because of slight variations of characteristics of LED devices. There is even a possibility that the current imbalance may change with temperature because LED devices are sensitive to temperature. Therefore, imbalance of currents among the LED strings is a common problem in LED applications. Such current imbalance would lead to nonuniform light generation among the LED strings. Since the lifetime of the LED devices is sensitive to the current, if the LED current exceeds its maximum current rating due to the current imbalance, the lifetime of the LED product would be reduced.

It should be noted that (1)–(4) are valid if Q_1 and Q_2 transistors both are working in linear area. Another major problem of using existing current-mirror methods for parallel LED strings that is not often mentioned in the literature is that, unless a separate well-controlled reference current source is used, it is not easy to select the best current source in one of the parallel LED strings as the reference. In the example of Fig. 5, the amount of current imbalance between the parallel LED strings is usually not known. An improper choice of the current string as the reference will cause the Q-transistor in another string to saturate and, thus, disabling the current-mirror function. Therefore, choosing the proper current reference for the current-mirror circuit in this unknown situation becomes a practical issue. This problem can be explained with the following description.

Consider two parallel LED strings represented as current sources in Fig. 1. If I_1 is smaller than I_2, then I_1 can be used as the reference current in the basic current-mirror circuit for current balancing because the BJT $Q2$ can be operated in the "linear mode" so that the voltage across its collector and emitter terminal V_{CE2} will be controlled by the current-mirror action in the LED string-2 in order to reduce the voltage imbalance among the LED strings and, therefore, reduce I_2. However, if I_1 is greater than I_2, then even if $Q2$ is saturated (i.e., fully turned ON in the saturation mode) with minimum V_{CE2}, I_2 may not be increased sufficiently to match I_1 (if I_1 is much larger than I_2). This means that, for reducing the current imbalance among parallel LED strings, the best choice of the reference current source is the LED string with the lowest current.

In order to confirm this important point, several sets of experiments based on the BJT current-mirror circuit in Fig. 1 have been conducted as tabulated in Table I. Fig. 6(a) shows two LED strings with imbalanced current as tabulated in Table I.

In summary, for the experimental setup in Table I, reduction of current imbalance of parallel LED strings can be achieved under the following conditions:

1) the smallest current source is chosen as the reference current;
2) no thermal runaway of transistors should occur.

Condition (2) can usually be met with careful circuit design. However, condition (1) is a general issue for current balancing of parallel LED strings because it is difficult in mass production to predetermine which LED string has the smallest current among several parallel LED strings in the product, unless every LED string is tested before production.

III. SELF-CONFIGURABLE CURRENT-MIRROR TECHNIQUE

A. *Self-Configurable Current-Mirror Circuit*

The proposed principle has a dynamic and self-configurable current-balancing circuit structure that allows the best current source (i.e., the smallest current source in the case of current balancing of parallel LED strings) to be selected. The proposed CM-based current-balancing circuit (see Fig. 7) does not require 1) external power supply and 2) its associated control circuit. Several parallel current sources (such as the LED strings) are connected to a self-configurable current-mirror circuit. The

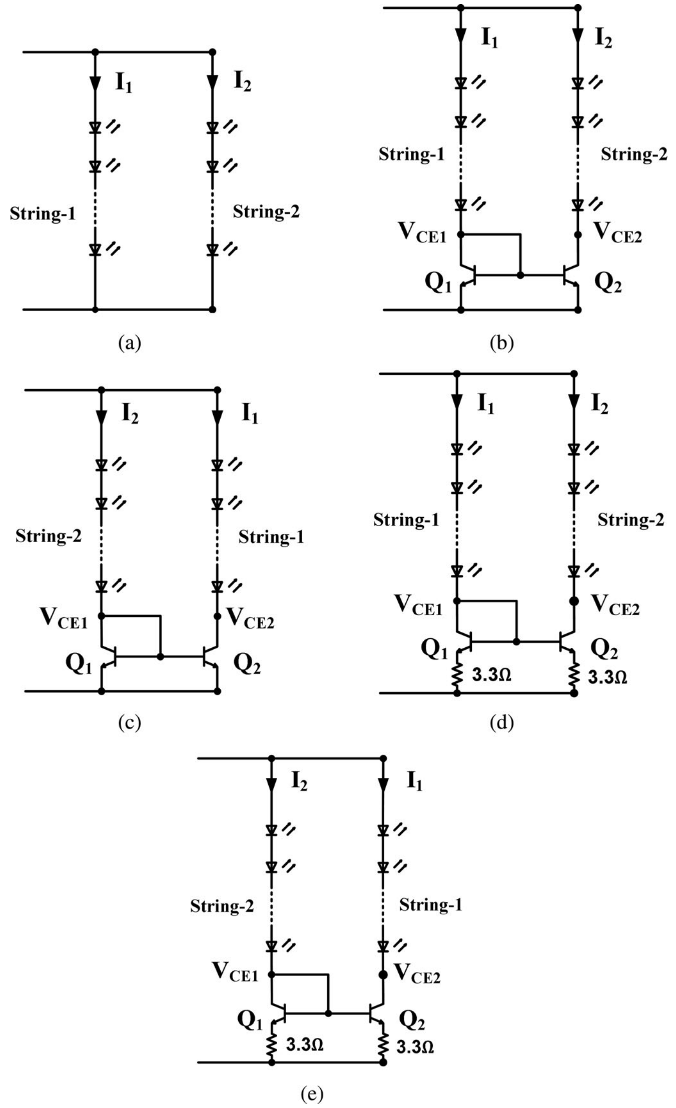

Fig. 6. (a) Two LED strings with imbalanced currents ($I_1 < I_2$)—as benchmark. (b) Using String-1 (small current) as current reference. (c) Using String-2 (large current) as current reference. (d) Using String-1 (small current) as current reference and resistors to avoid transistor saturation. (e) Using String-2 (large current) as current reference and resistors to avoid transistor saturation.

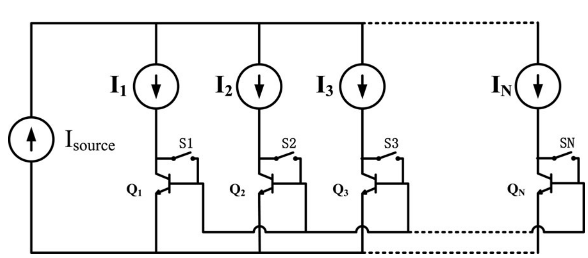

Fig. 7. Schematic of the novel self-configurable current-mirror principle using self-driven transistors (S_1 to S_N).

transistors Q_1 to Q_N (also called Q-transistors) represent the transistors used in a traditional CM circuit such as the one shown in Fig. 1. Extra resistors that may be required to avoid thermal runaway [see Fig. 6(d)] in these Q-transistors are not shown in Fig. 7 for the sake of simplicity, but they may be needed in practice as later shown in Fig. 11. Extra transistors S_1 to S_N (called S-transistors) are introduced as a new feature in this proposal to make the CM self-configurable, i.e., the choice of the reference current source can be changed or self-configured.

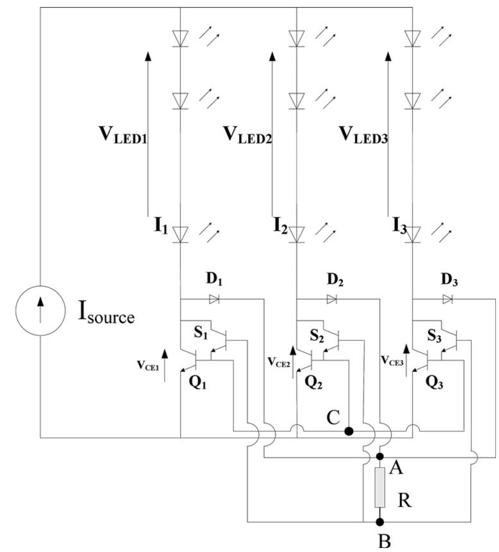

Fig. 8. Practical self-configurable current-mirror circuit for current-balancing applications [Note: external power supply and predetermined reference current source are not needed].

The S-transistor switch (i.e., S_1 to S_N) used for selecting the best reference current source can operate either in the saturation mode or in the linear mode [20]. When used in the saturation mode, this transistor is fully turned ON as a switch (by connecting the collector and base terminals) to self-configure the overall circuit to select the best current source as the reference current for the current-mirror circuit. When used in the linear mode, this transistor forms part of a cascaded transistor (sometimes called darlington transistor if BJTs are used) and the overall circuit still provides current-balancing function. The dual function of S_1 to S_N is a unique feature of this proposal. Therefore, this proposal can achieve current balancing for all of the parallel current sources regardless of whether the transistors (S_1 to S_N) are in the saturation mode or linear mode. This point will be illustrated by the following circuits.

In a practical situation such as having several LED strings connected in parallel, the current imbalance of the LED strings cannot be known without measurements. In this invention, transistors S_1 to S_N are employed to allow the most appropriate current source to be chosen as the "reference current source." In the case of current balancing of parallel LED strings, the LED string with the smallest current should be selected. A detection circuit is therefore necessary to detect the best current source so that the corresponding switch can be activated. This principle is now illustrated in an example with three LED strings (see Fig. 8).

For the LED strings, the strings with larger currents in the original current-unbalanced situation tend to have a lower voltage drop across the LED string when the CM circuit is introduced to balance the currents. This point is explained further in the Appendix. Therefore, if the total LED string voltages are assumed to be $V_{\mathrm{LED1}} < V_{\mathrm{LED2}} < V_{\mathrm{LED3}}$, then $I_1 > I_2$

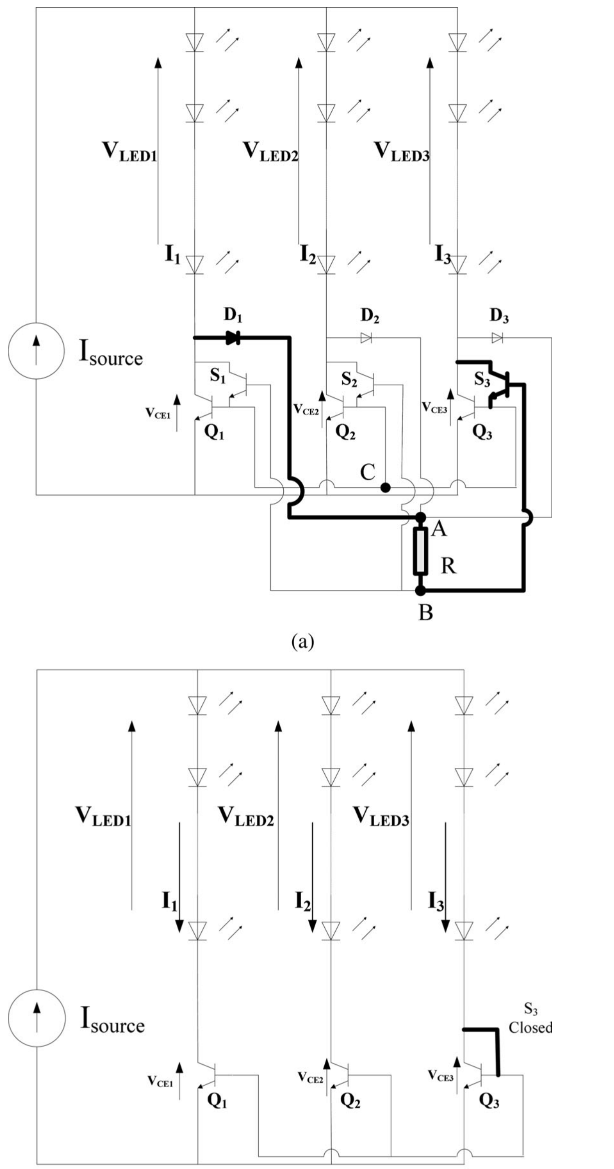

Fig. 9. (a) Self-configurable current-mirror circuit for current-balancing applications (Assuming that $I_1 > I_2 > I_3$, and $V_{\mathrm{CE}1} > V_{\mathrm{CE}2} > V_{\mathrm{CE}3}$) [Note: external power supply and predetermined reference current source are not needed]. (b) Effective circuit in Fig. 9(a) (with the smallest current source I_3 automatically selected as the reference current source for the current-mirror circuit) [Note: external power supply and predetermined reference current source are not needed].

$> I_3$, and $V_{\mathrm{CE}1} > V_{\mathrm{CE}2} > V_{\mathrm{CE}3}$. Now, consider a proposed self-configurable circuit shown in Fig. 8. The three switches S_1, S_2, and S_3 are transistors. They can be used 1) as switches (saturation mode) for selecting the corresponding current sources as the reference current source for the current-mirror action, or 2) as transistors in linear mode. When used in linear mode, the transistor-pair (S_1–Q_1, S_2–Q_2, and S_3–Q_3) also form a Darlington transistor. For each parallel branch, a diode (D_1 to D_3) is connected to point A, the bases of all S-transistors (S_1–S_3) are connected to point B and the bases of all Q-transistors (Q_1–Q_3) are connected to point C.

Mode 1: Self-configurable current-mirror circuit (one of the transistors S_1 to S_N is fully driven into the saturation region).

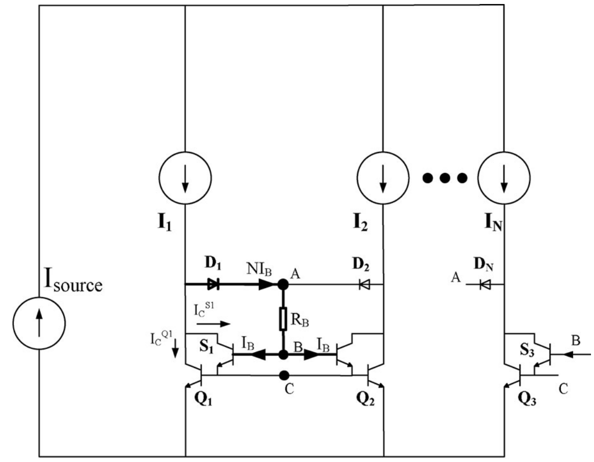

Fig. 10. General current-balancing circuit with N parallel current sources [Note: external power supply and predetermined reference current source are not needed].

Using the assumption that $I_1 > I_2 > I_3$, and $V_{\mathrm{CE}1} > V_{\mathrm{CE}2} > V_{\mathrm{CE}3}$, the self-configurable principle can be illustrated with the aid of Fig. 9(a). With $V_{\mathrm{CE}1}$ being highest, the critical conducting path is highlighted with bolded line in Fig. 9(a). Diode 1 is turned ON and the current will flow through a current-limiting resistor R to drive the base of the transistor with the smallest current and V_{CE} (i.e., S_3 in this case). If the current imbalance is significant enough so that the current caused by $V_{\mathrm{CE}1}$ is large enough to drive S_1 into saturation (i.e., S_3 is fully turned ON as a closed switch), the equivalent circuit can be redrawn as shown in Fig. 9(b). It can be seen from Fig. 9(b) that this equivalent circuit is like a current-mirror circuit with the smallest current source chosen as the reference current. Therefore, it can be seen that the proposed circuit (see Fig. 9) can automatically choose the smallest current source as the reference current. The current-mirror action of this circuit will cause $V_{\mathrm{CE}1}$ and $\mathrm{V}_{\mathrm{CE}2}$ to change in order to reduce I_1 and I_2 to follow the reference current I_3. The proposed circuit allows a dynamic change of reference current according to the smallest current source. This operating mode is still based on the current-mirror concept, except that there is a novelty of self-configurable feature that allows the best current source to be dynamically chosen as the reference current source for the current-mirror action.

Mode 2: Current-balancing circuit (with S_1 to S_N in the linear region).

If the current imbalance among the parallel current sources is not too significant (i.e., current imbalance has been reduced), the V_{CE} of the largest current source will still cause the corresponding diode to conduct. But the current caused by largest V_{CE} in the largest current source may not be large enough to drive the base of the S-transistor in the smallest current source into the saturation region. This means that this diode current will flow into the bases of all the S-transistors which now work in the linear region. The equivalent circuit for a system with N parallel current sources can be drawn as shown in Fig. 10.

The following assumptions are made in the analysis.

1) The current imbalance among current sources is not large enough that none of the S-transistor is fully driven into saturation, implying that all S-transistors are operated in the linear range.
2) All transistors are matched with the same current gain β.
3) Current source-1 is largest so that its corresponding highest V_{CE} will cause the diode D1 to turn ON.

$$I_1 = I_C^{S_1} + I_C^{Q_1} + NI_B \tag{5}$$

where $I_C^{S_1}$ is the collector current of S_1, $I_C^{Q_1}$ is the collector current of Q_1, N is the number of current sources, and I_B is the base current of $S_1, S_2, \ldots, S_N$.

$$I_C^{S_1} = \beta I_B \tag{6}$$

$$I_C^{Q_1} = \beta(I_B^{Q_1}) = \beta(I_E^{S_1}) \text{ and } I_E^{S_1} = I_C^{S_1} + I_B = (\beta+1)I_B.$$

Hence

$$I_C^{Q_1} = \beta\,(\beta+1)\,I_B. \tag{7}$$

From (5)–(7)

$$I_1 = \left(\beta^2 + 2\beta + N\right) I_B. \tag{8}$$

Now, we can determine the current in other branches with currents less than I_1. For branch-N, because the diode D_N is not turned ON

$$I_N = I_C^{S_N} + I_C^{Q_N} \tag{9}$$

$$I_C^{S_N} = \beta I_B \tag{10}$$

$$I_C^{Q_N} = \beta\,(\beta+1)\,I_B. \tag{11}$$

From (9)–(11)

$$I_N = \left(\beta^2 + 2\beta\right) I_B. \tag{12}$$

Using (8) and (12), the current I_N can be expressed as

$$I_N = \left(\frac{\beta^2 + 2\beta}{\beta^2 + 2\beta + N}\right) I_1. \tag{13}$$

For a typical current gain β of 40

$$\left(\frac{\beta^2 + 2\beta}{\beta^2 + 2\beta + N}\right) = \frac{1680}{1680 + N} \approx 1 \quad \text{for } N < 10.$$

Therefore, (13) confirms that good current balance can be achieved theoretically even when all the S-transistors are operated in the linear mode.

In summary, the proposed circuit enables the parallel current sources to reduce the current imbalance in both modes 1 and 2. A typical practical implementation of this approach including the stability improvement and avoidance of saturation of the Q-transistors is shown in Fig. 11, where resistors R_E are resistors of small values (of typically less than a few Ohms in order to reduce conduction loss) and are used to avoid thermal runaway of the transistors. If the Q-transistor current through the collector and the emitter increases dramatically (due to thermal runaway), the increase in voltage across the emitter resistor R_E will act in opposition to the base bias and, thus, reduce the transistor current. Therefore, the use of R_E resistors in the Q-transistors can reduce the chance of thermal runaway.

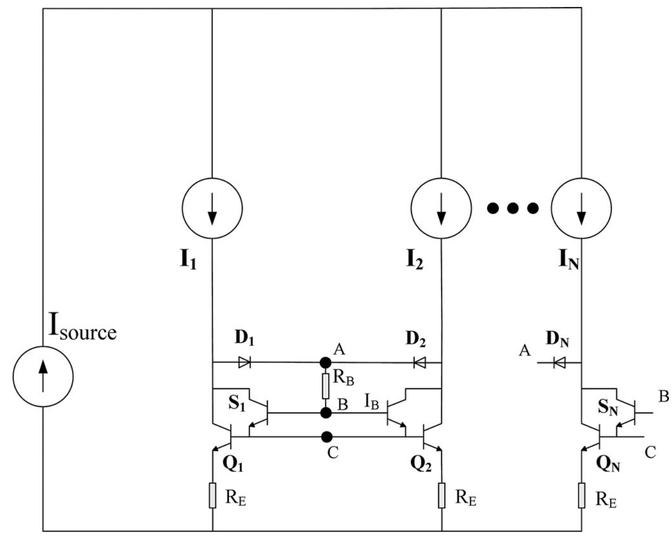

Fig. 11. General self-configurable current-balancing circuit including resistors R_E for improving the stability of the transistors [Note: external power supply and control circuit are not needed].

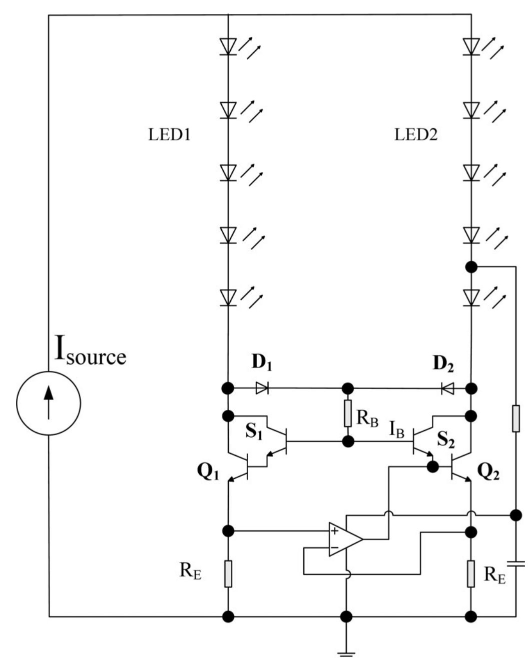

Fig. 12. Feedback-assisted self-configurable current-mirror circuit.

B. Operational Amplifier (Op-Amp) Feedback-Assisted Self-Configurable Current-Mirror Circuit

It should be noted that the aforementioned analyses are all based on the assumption that all the Q-transistors are perfectly matched. This assumption is not realistic in practice. However, the proposed self-configurable current-mirror circuit can further be improved with an op-amp feedback-assisted circuit. It will be shown that the op-amp-assisted self-configurable CM circuit can offer very good performance even without using well-matched

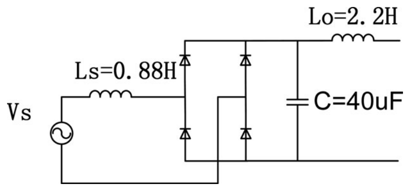

Fig. 13. Passive LED driver that generates a current source for three parallel LED strings.

TABLE II
COMPARISON OF THE STRING CURRENTS AND MAXIMUM CURRENT DIFFERENCE WITH AND WITHOUT THE SELF-CONFIGURABLE CIRCUIT

No CM circuit	Self-configurable CM circuit *without* op-amp feedback
I_1=252mA	I_1=250mA
I_2=231mA	I_2=251mA
I_3=298mA	I_3=277mA
Maximum ΔI = 67mA (ΔI = 25.7% of the average string current)	Maximum ΔI = 27mA (ΔI = 10.4% of the average string current)
(the total input power=76W)	Power consumption = 1.83W (2.4% of the total input power of 75.8W)

Q-transistors. Fig. 12 depicts a typical circuit implementation of the feedback-assisted circuit using an operational amplifier in an LED system with two parallel strings. The resistors used to avoid thermal runway of the Q-transistors can also be used as current sensors. The voltages across these resistors are used as current signals that are fed to the inputs of the operational amplifier. Since the inverting voltage follows the noninverting voltage, the two string currents should be matched. It is also important to note that the dc power supply for the op-amp feedback-assisted circuit is derived from the voltage drop across one LED device with the aid of a resistor and capacitor subcircuit. Therefore, no separate power supply is needed for this op-amp circuit.

IV. Experimental Confirmation

Two experimental LED systems have been set up to evaluate the performance of the self-configurable CM circuits. The current source is provided by a simple ac–dc power circuit as shown in Fig. 13. The diode rectifier turns the ac voltage into a dc voltage with the help of the output capacitor. The inductor turns the voltage source into a current source. In this passive LED driver, the output current is a dc current with some 100 Hz current ripple. This current ripple is not a concern for LED system if it is properly designed [18]. The photo-electro-thermal theory for LED systems [19] shows that the relationship between the luminous flux and the LED power is a parabolic curve. If the thermal design of the LED system is done in such a way that the operating point moves around the top region of the parabolic curve, the fluctuation of the luminous flux is minimal. Therefore, unlike previous switched-mode power supply technology that regulates the LED current, it has been proved that passive LED driver without power MOSFETs, auxiliary power supply, and control-integrated circuits can be used to drive LED systems [18].

A. Self-Configurable Current-Mirror Circuit Without Op-Amp Feedback Assistance

Before the proposed current-balancing circuit is used, the three LED string currents are first recorded. The current values

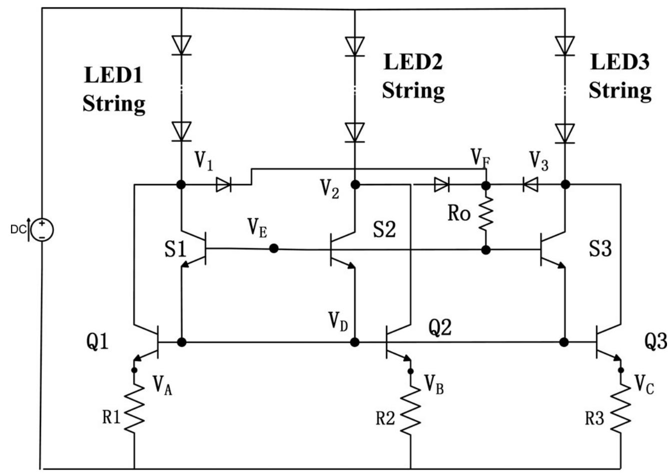

Fig. 14. Circuit arrangement of the experiment for current sharing ($R_0 = 2\,\mathrm{k}\Omega$, $R_1 = R_2 = R_3 = 2.7\ \Omega$).

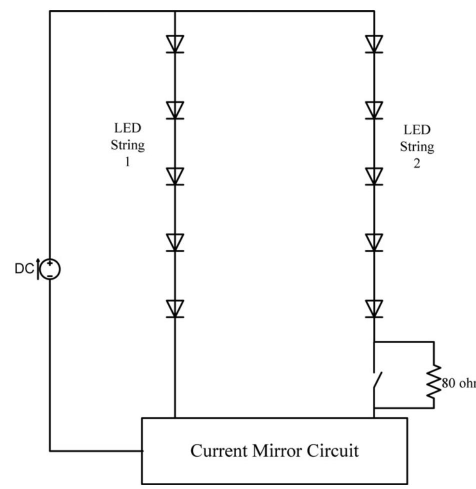

Fig. 15. Experimental setup of the self-configurable CM circuit with op-amp feedback assistance.

are shown in Table II. The maximum current difference is found to be 67 mA. Then, the proposed self-configurable CM circuit without feedback is added to three parallel LED strings as shown in Fig. 14. The string currents are much closer to each other and the maximum current difference is reduced to only 27 mA. Therefore, a reduction of 59.7% of the current imbalance has been achieved.

B. Self-Configurable Current-Mirror Circuit With Op-Amp Feedback Assistance

The operation of the feedback-assisted CM circuit is demonstrated in an LED system with two parallel strings. In one string, a switch in parallel with an 80-Ω resistor is included as shown in Fig. 15 so that the transient current-balancing performance can be observed. When switch is closed to bypass the additional resistor, the current source provides $I = 470$ mA. When switch is open so that R is in series with the second LED string, the circuit current source gives $I = 407$ mA appropriately.

Fig. 16 shows the waveforms of the two string currents when the switch is closed. The 100-Hz ripple is due to the rectification of the 50-Hz mains as explained earlier. The current difference

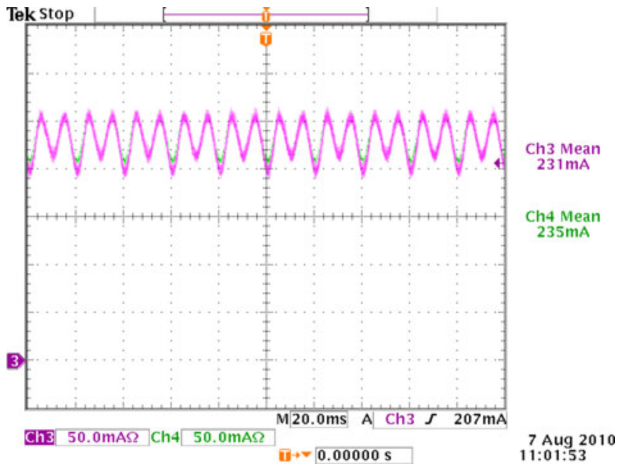

Fig. 16. Waveforms of the two LED string currents when switch is closed.

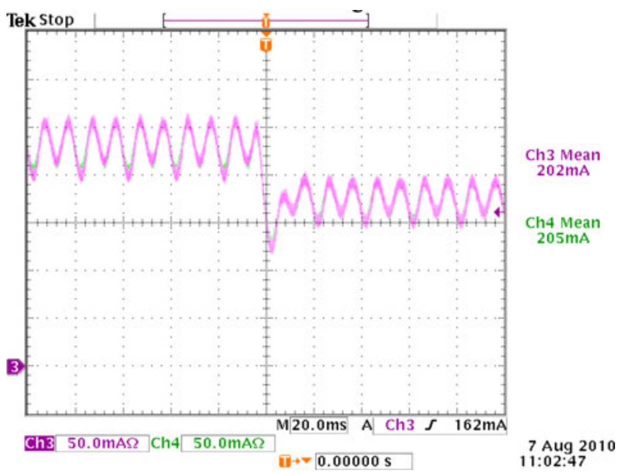

Fig. 17. Waveforms of the two LED string currents when switch is opened.

is only 4 mA for an average string current of 233 mA. Therefore, the feedback-assisted self-configurable CM circuit is more effective than that without feedback assistance. When the switch is opened, the two current waveforms are captured in Fig. 17. It can be seen that the two string currents follow each other closely even during the transient period. The switch is then closed again and the waveforms of the string currents are displayed in Fig. 18. The two string current waveforms virtually overlap each other.

A second series of tests have also been conducted on an LED system with three parallel strings as shown in Fig. 19. Instead of using the passive LED driver, a dc voltage source is used to power this LED system so that the steady-state current waveforms can be seen clearly. Each of the three strings consists of ten 3-W sharp LEDs (Model: GW5BWC15L02). BJT transistor, 2N2119, and op-amp, LM324, are used in the CM circuit. $R_B = 500\ \text{k}\Omega$ and $R_E = 2.7\ \Omega$. When the dc power supply is set at an output voltage of 97.3 V, the three string current waveforms before and after using the op-amp feedback-assisted CM circuit are recorded in Figs. 20 and 21, respectively. The details are also included in Table III for comparison. From Fig. 20, it can be seen that the three LED strings are not matched and the current difference is 102 mA for an average current of 267.3 mA

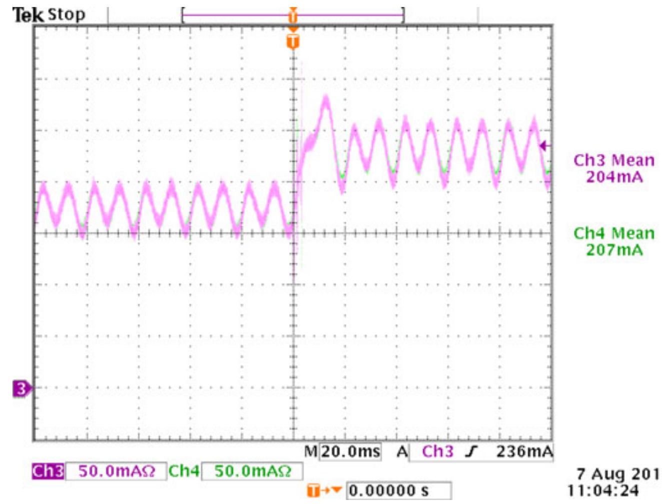

Fig. 18. Waveforms of the two LED string currents when switch is closed again.

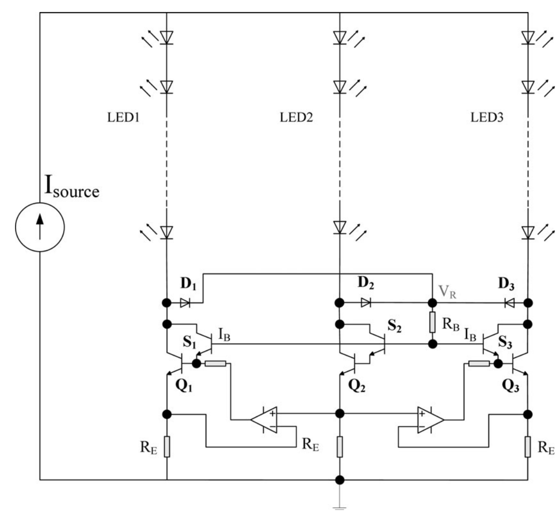

Fig. 19. Self-configurable current-mirror circuit with op-amp feedback for three parallel LED strings.

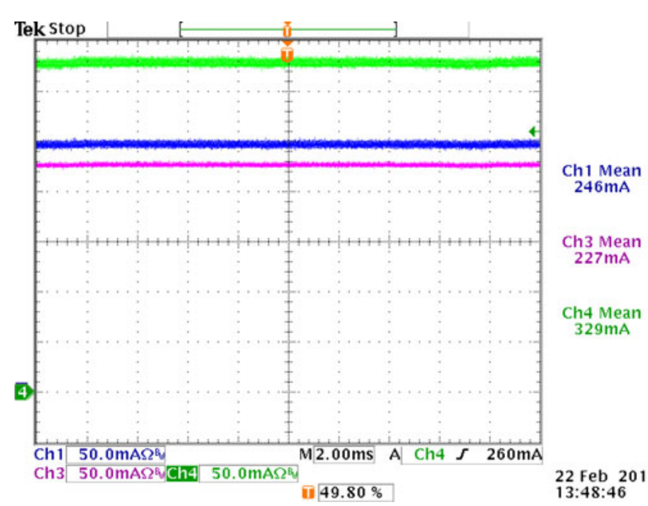

Fig. 20. Waveforms of the three string currents before using op-amp feedback-assisted CM circuit.

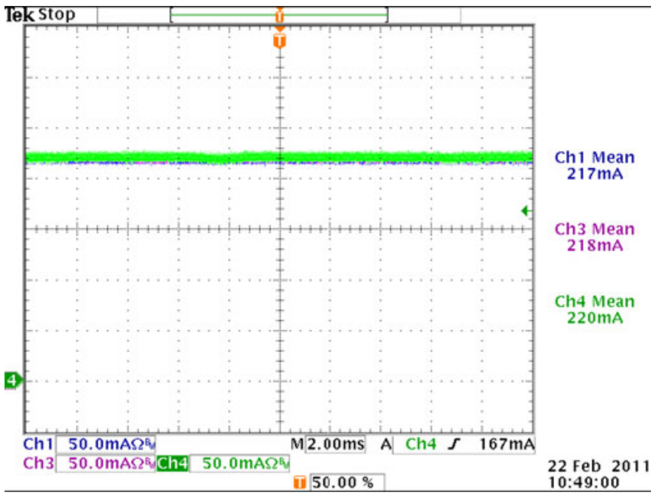

Fig. 21. Waveforms of the three string currents after using op-amp feedback-assisted CM circuit.

TABLE III
COMPARISON OF THE STRING CURRENTS AND MAXIMUM CURRENT DIFFERENCE WITH AND WITHOUT THE OP-AMP FEEDBACK-ASSISTED SELF-CONFIGURABLE CIRCUIT

No CM circuit	Self-configurable CM circuit with op-amp feedback
I_1=246mA	I_1=218mA
I_2=227mA	I_2=217mA
I_3=329mA	I_3=219mA
Maximum ΔI = 102mA (ΔI = 38.2% of the average string current)	Maximum ΔI = 2mA (ΔI = 0.9% of the average string current)
(the total input power=78.03W)	Power consumption = 1.18W (1.85% of the total input power of 63.63W)

TABLE IV
OPERATION OF THE CM

LED No.	Current/mA	Input voltage to CM/V
LED1	218.09	1.469
LED2	217.1	0.73(saturation, turned on)
LED3	219.29	3.2

(i.e., 38.2% current imbalance). With the use of the op-amp feedback-assisted CM circuit, the current difference is reduced to 2 mA for an average current of 218 mA (i.e., 0.9% current imbalance).

Table IV shows the voltage levels provided by the darlington transistor pairs formed by the S- and Q-transistors in each LED strings. The input voltage to the CM refers to the voltage difference between the collector terminal of the S-transistor (same as the collector terminal of the Q-transistor) and the ground. As Table III indicates that String-2 has the smallest current without using the CM circuit, it should be selected as the reference branch. The voltage provided by the CM circuit in String-2 is found to be lowest (0.73 V), confirming that it has been chosen as the reference because S_2 has been turned ON into the saturation mode to turn ON $Q2$. The voltage levels provided by String-1 and String-3 are higher so that their original currents can be reduced to match the reference current of String-2. It should be noted that the voltage generated in String-3 is highest because its original current is largest. A higher voltage is inserted in String-3 by the CM circuit to achieve such current reduction.

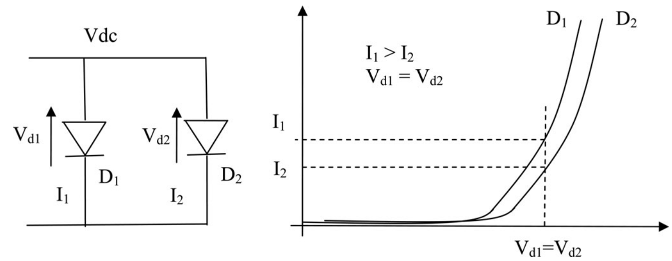

Fig. A1. Operating conditions of two parallel-connected diodes with imbalanced currents arising from differences in diode characteristics.

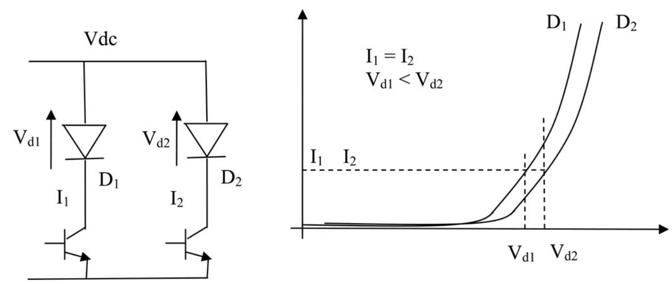

Fig. A2. Operating conditions of two parallel-connected diodes with balanced current based on the use of the current-mirror circuits.

V. CONCLUSION

A self-configurable current-mirror circuit for reducing current imbalance in parallel LED strings has been proposed. Unlike existing methods, it does not need a separate power supply for creating a predetermined current source. The proposed circuit involves the use of a self-configurable circuit based on the S-transistors to automatically and dynamically select the minimum current source as the current reference. The circuit provides effective current sharing capability when the S-transistors are in either linear or saturated mode. For further improvement in reducing current imbalance, existing op-amp feedback assistance can be incorporated into the proposed self-configurable current-mirror circuit. The theory of the proposal has been presented and verified by good practical performance. To achieve good current balance for parallel LED strings, the proposed circuit consumes less than 2.5% of the total system power in this study. Without using a separate power supply and an independent current source as the current-mirror-current reference, this new proposal offers a low-cost and effective solution to reduce current imbalance in multistring LED systems.

APPENDIX

Two parallel-connected LED strings can be considered as two equivalent diodes connected in parallel across the same dc voltage as shown in Fig. A1. The diode characteristics can be described by the diode equation (A1) that incorporates both the diode voltage drop and ac resistance characteristics

$$I = I_s(e^{V_D/(nV_T)} - 1). \quad \text{(A1)}$$

In a usual parallel connection of two diodes with $V_{d1} = V_{d2} = V_{\rm dc}$, it can be seen that the current imbalance is due to the mismatch in the characteristics of individual diodes. In this example, I_2 is smaller than I_1. In our proposal, LED String-2 should be chosen as the reference.

Now consider the situation when the currents are balanced by the proposed current-mirror circuit as shown in Fig. A2. Under this situation, I_1 is reduced to the level of I_2 by the current-mirror circuit. It can be seen from Fig. A2 that the operating point of diode D_1 will slide down the curve and the voltage drop across the diode V_{d1} becomes less that V_{d2}. This confirms the statement that the LED string with the smallest current (i.e., I_2) will have the largest voltage drop V_2 across the LED string in the LED system with the current-mirror circuit.

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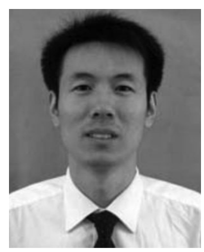

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