# Current Distribution in Parallel LED Strings

Introduction

Many LED applications require more than one LED in a system. When multiple LEDs are used in a system, the LEDs can be arranged in series, parallel, or series- parallel configurations. Due to regulatory requirements (especially in Class II environments) there is always a limitation as to how many LEDs can be connected in series. One of the standard practices to overcome this issue is to have multiple parallel strings of series LEDs that are driven from a single constant current source. This Application Guide describes the issues and solutions that may be encountered when multiple strings are driven from a constant current source (CC source).
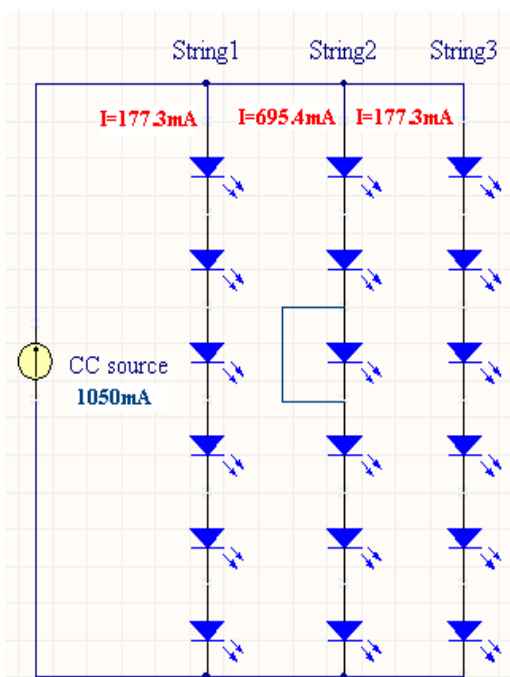
Series- Parallel configuration

In series-parallel configuration, there are multiple strings of series LEDs. It is always better to limit the number of LEDs in series to minimize total Vf (threshold voltage) mismatch between strings. It is recommended to have 4 to 6 LEDs in a series so the difference in voltage between strings is not significant.
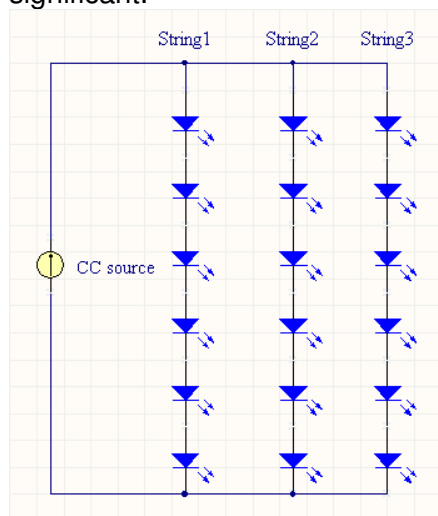
Figure 1. Series-Parallel configuration Difference of Vf in LEDs

In LEDs, Vf is the threshold voltage at which an LED starts to turn on. Due to manufacturing tolerances and material properties, Vf can vary between LEDs even if they are from the same wafer. Depending on the technology used, the range in difference can be a few millivolts to up to a volt. When multiple LEDs are connected in series, this Vf mismatch between LEDs adds up and becomes significant. In series-parallel configuration, if the string voltage is significantly different between stings, the current through each string will vary (become imbalanced) when a single constant current source is used. Figure 2 shows what the string currents would be if one of the strings has ~3V (caused by a shorted LED) less than the other two strings.

Figure 2. String Voltage vs string current

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Impacts of imbalanced string currents

If all of the strings in a series-parallel configuration don't have the same current going through them, there will be a number of issues that have to be dealt with during the design process. Imbalanced string current will result in lowering the overall system efficacy and this can be significant, depending on how wide the difference in string current is. It will also play a major role in LED lifetime and thermal management. Moreover, if the string current is considerably different between strings, the light output from each string would be different (Figure 3) and this difference will be visible to the naked eye. This is not desirable in a system with multiple LED strings. Displayed in Figure 3, the string with lower total Vf, due to a shorted LED, has lot more current going through it and a very small portion of the total current is split between the other two strings. Since Flux vs Current is not linear in LEDs (Figure 4), the system efficacy will be reduced when there is imbalanced string current. Also, note that the two strings with identical Vf have same current going through them. This can be witnessed by looking at the brightness of the LEDs in those two strings.
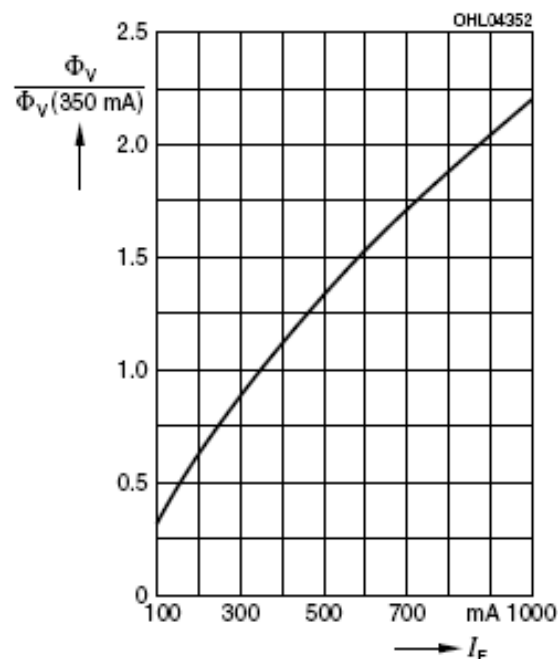
Relative Lichtstrom[2) 5) Seite 18]
Relative Luminous Flux[2) 5) page 18]
$\Phi_V / \Phi_V(350\ mA) = f(I_F);\ T_S = 25\ °C$

Figure 4. LED Current Vs Flux of OSLON LED

Figure 3. Representation of Figure 2 in real application

Impact on efficacy

With imbalanced string currents, and due to the fact that efficacy of an LED degrades with increasing current, the overall system efficacy of a system with multiple LED strings would be lower. Figure 5 shows the difference in efficacy with balanced and imbalanced string currents. In this example, OSLON LEDs from OSRAM Opto Semiconductors are used. The flux/light output from the OSLON LEDs at 350 mA is set to be 100 lm. The junction temperature of the LEDs are assumed to be room temperature to eliminate temperature dependency on flux and for ease of calculation. Circuit configuration for the example would be the same as in Figure 1. All the values used in the calculation are obtained from the datasheet that is available on

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the web site.

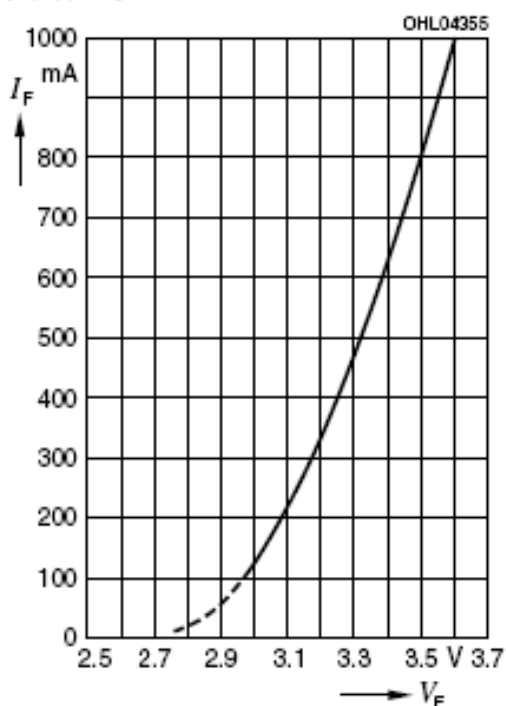Also required for the calculation is the I-V curve (Figure 5) for OSLON LEDs.

Figure 5. Current Vs Voltage of OSLON LED

With balanced LED strings, the total lumen would be:

$$18*100 = \textbf{1800lm}$$

(there are 18 LEDs in total and 100lm from each LED)

Total power in this case would be:

$$3.3*0.35*18 = \textbf{20.16W}$$

(typical Vf for Oslon is 3.2V)

The efficacy of the circuit without considering electrical, thermal, and optical losses would be:

$$1800lm/20.16W = \textbf{89.3lm/W}$$

With imbalanced current (per current distribution in Figure 2), the total lumen would be:

$$(1.75*100*6)+(0.54*100*12)= \textbf{1698lm}$$

(as per Figure 4, flux at 695mA is ~1.75 times the flux at 350mA and flux at 177mA is ~0.54 times the flux at 350mA)

The total power in this case would be:
$(0.177*12*3.05) + (0.695*6*3.45) = 20.86W$
(per Figure 5, Vf at 177mA is ~3.05V and Vf at 695mA is ~3.45V)

The efficacy in this case would be:

$$1698lm/ 20.86W = \textbf{81.38 lm/W}$$

One can easily see the difference of ~8lm/W between the two cases. The difference of 8lm/W is significant and should be taken into consideration during the design and development stages. It should be noted that the 8lm/W difference is due to the fact that the difference in string current, in this case, is significantly wider. If the difference in string current is narrower, then the loss of efficacy would be lower. The wider range string current is chosen in this example to easily explain the efficacy impact to the reader.

How to solve the issue?

There are multiple ways to address this issue. One of them is to use individual constant current sources for each string. This solution is costly and adds more components to the driver circuitry. As a result of adding passive and active components, more failure modes are introduced and reliability of the driver is also impacted to a certain degree. In some cases, the space requirement may be a factor as this solution requires considerably more space for the driver and control circuitry. Another

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way to address this issue is to use a current mirror to match the string currents. This solution would be much less expensive compared to individual current sources and uses very few components. At minimum, each string would require only one transistor, put in a current mirror form, to match current between the strings. As with any other solutions, this also has some dis-advantages. One of them is the reference current to the current mirror. The way it works in this case is that the reference current to the current mirror is set by one of the strings and current to the other strings are matched to the reference current. If the reference string has lower voltage compared to the other strings, then the current mirror will not work as expected. This can be solved by inserting a resistor in the reference string such that the reference string has slightly higher voltage compared to all other strings. The other issue is the dependency on the Vbe (base to emitter voltage of a transistor) of each transistor in the current mirror circuit. This issue can be addressed by selecting reasonably matched Vbe on the transistors. To reduce dependency on the Vbe, a small value resistor can be inserted at the emitter. However, it will add cost and may not be required for the specific application that is being considered. The circuit in Figure 2 is simulated with current mirror in place and shows the current distribution in each string.

With the addition of the current mirror in place the string currents are now matched within 3-5% between strings. However, note that the reference string doesn't have the lowest total Vf. As mentioned before, you may run into issues when the reference string has lower total Vf compared to other strings, Figure 7 illustrates this situation.
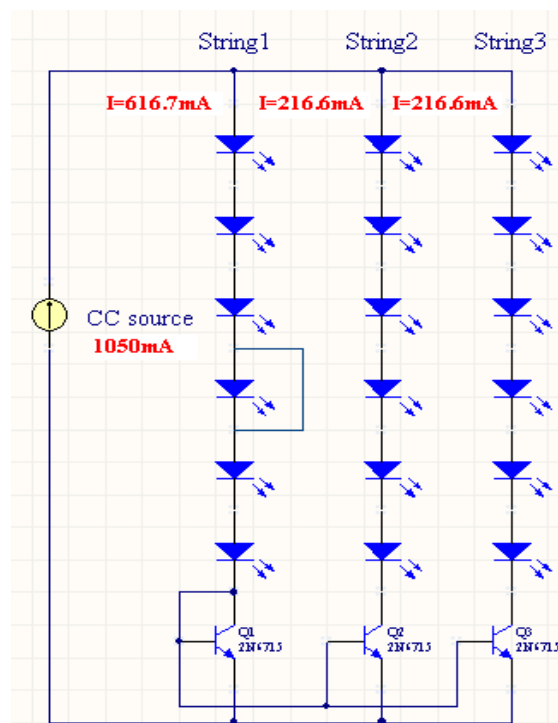
**Figure 6.   Current distribution with current mirror in place.**
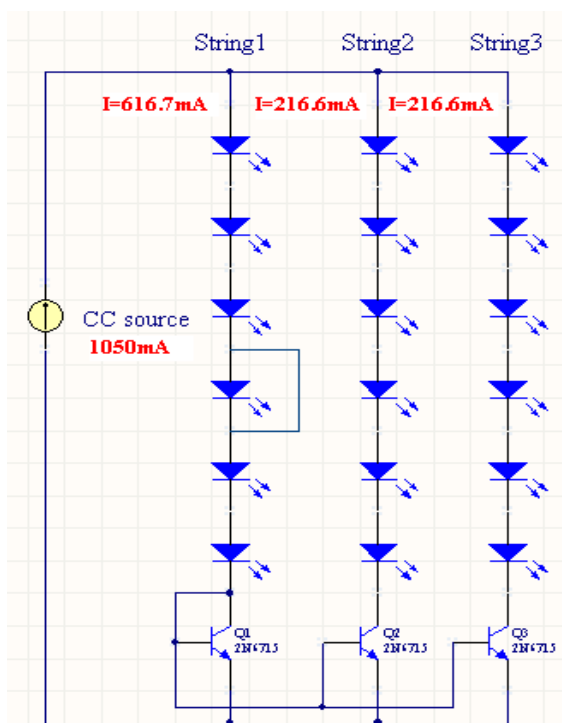
Figure 7. Current distribution with current mirror (reference current string has lower voltage) in place.

The current mirror doesn't do any good in this case, this is due to the fact that the reference string has lower voltage compared to the other two strings. To address this issue, a resistor can be inserted in the reference strings so that the reference string has slightly higher voltage compared to the other strings. There will be an efficacy loss due to the resistor depending on the value of the resistor, which is dictated by how wide the expected voltage difference between strings is and how well the string current needs to be matched. Figure 8 shows simulation results with the addition of a resistor in the reference string.

Figure 8. Current distribution with current mirror
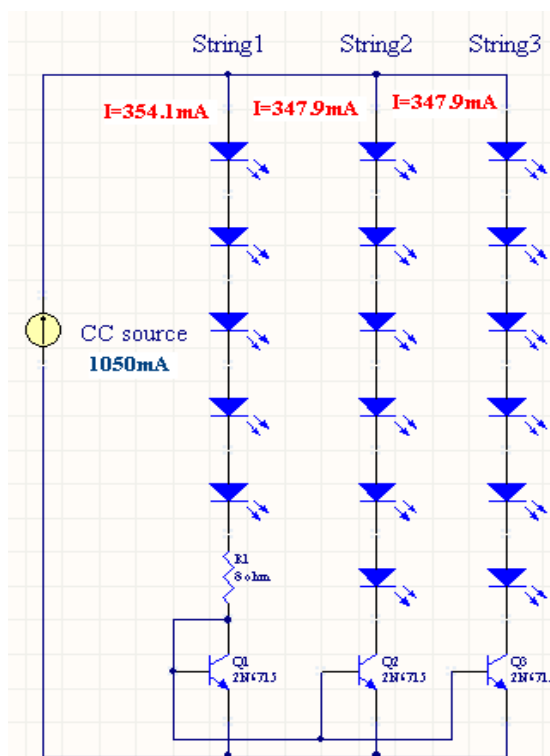
(with added resistor in the reference string) in place.

The addition of a resistor resolved the issue and the string currents are matched within 2% (Figure 9).

Figure 9. Representation of Figure 8

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Even without any technical understanding, one can easily see how the current mirror improved the string currents, and therefore the light output from each string, by comparing Figure 3 and Figure 9. Below is a side-by-side view of the pictures for comparison purpose.

Figure 10. Side-by-Side view (with and without current mirror circuit)

Things to remember when designing a current mirror
1. The transistors should be chosen such that Vbe of all the transistors are reasonably matched.
2. Adding a very small resistor at the emitter pins of the transistors will also help to reduce Vbe mismatch.
3. The selection of resistor should serve the purpose and minimize efficacy losses.
4. It is recommended to have all transistors operating at the same temperature to ensure or minimize variations due to thermal characteristics of transistors.
5. It is also possible to have one more transistor and shut off the reference string, if the current through the reference string exceeds a set value.

Conclusion
A well designed current mirror in a series-parallel LED configuration can match the string currents to within 3% to 5%. Since the passives used in a current mirror are very minimal and inexpensive, the added cost is almost negligible. Furthermore, if designed properly, efficacy losses due to the added components are insignificant.

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