TI Designs: TIDA-01581
Automotive, Daytime Running Light, Dual-String LED Driver Reference Design With Current Balancing

Description

This reference design is a dual-string, light-emitting-diode (LED) driver which implements an operational amplifier (op amp)-based circuit to balance the current in two LED strings. The op amp circuit senses current in a reference string and uses feedback from a mirrored string to bias a MOSFET that regulates the current between the strings. The design uses the TPS92692-Q1 multi-topology LED driver in a boost configuration to drive the LEDs. The TPS92692-Q1 features spread-spectrum frequency modulation for electromagnetic interference (EMI) performance, analog current adjustment, and internal pulse-width modulation (PWM) dimming. This design includes an adjustable linear thermal foldback using the LMT87-Q1 analog temperature sensor, as well as current limiting, in the event that the mirrored string fails to open the circuit. The design also features two brightness modes: One mode is a full brightness mode ('DRL') and the other is a PWM dimming mode ('Position') which reduces brightness.

Resources

TIDA-01581	Design Folder
TPS92692-Q1	Product Folder
TLV2316-Q1	Product Folder
LMT87-Q1	Product Folder
LM2901-Q1	Product Folder

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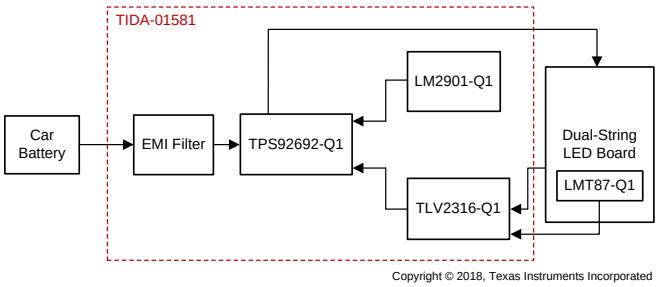
Features

- Dual-String Current Balancing Using a Single LED Driver
- Tested for CISPR25 Class-5 Conducted and Radiated Emissions
- PWM Dimming for Two Brightness Modes
- Current Limiting
- Operation Through Cold Crank
- Operation Without Microcontroller Unit (MCU)

Applications

- Automotive Daytime Running Lights
- Automotive Front Lighting
- Automotive Tail and Brake Lights



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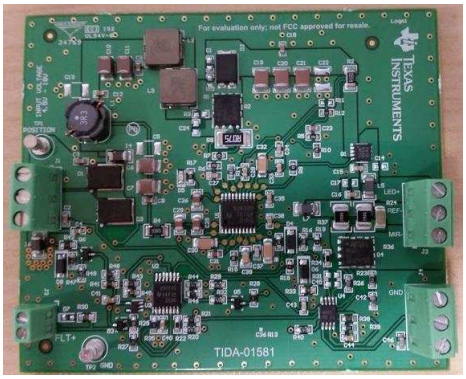

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1 System Description

This reference design details a solution for driving two parallel LED strings in applications for automotive daytime-running lights or position lamps using only a single LED driver, while keeping the current in the two LED strings equal. Implementation of this dual-string current mirror design can reduce the voltage required to drive the LEDs by half as compared to driving the same number of LEDs in series. The system also includes EMI filtering, thermal foldback, and current limiting. EMI filtering reduces conducted and radiated emissions. Thermal foldback can reduce the LED current as temperature increases, which protects the LEDs from thermal failure. Current limiting protects the reference string if the mirrored string fails to open. This feature is important because it prevents the intended current from doubling and flowing through the reference string in this condition.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS
Input voltage	6 V to 18 V, 14 V (typ)
Input current	980 mA at 14 V
Output current (per string)	200 mA
Output power (both strings)	12 W
Output voltage	30 V (typ)
Number of series LEDs	10
LED forward voltage	3 V (typ)
Current balance accuracy	±2%
Boost converter switching frequency	390 kHz
Spread-spectrum frequency modulation dither frequency	600 Hz
PWM dimming frequency	240 Hz
Form factor	77 mm × 66 mm, two-layer

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2 System Overview

2.1 Block Diagram

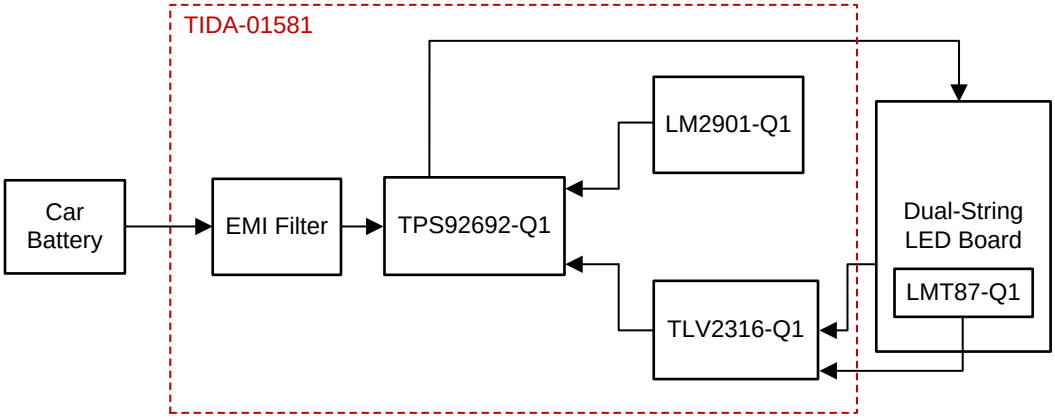

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Figure 1. TIDA-01581 Block Diagram

2.2 Highlighted Products

2.2.1 TPS92692-Q1

The TPS92692-Q1 is a high-accuracy, multi-topology peak current mode controller designed for driving LEDs. The driver incorporates a rail-to-rail current amplifier to directly measure LED current. The driver can accept a wide input voltage from 4.5 V to 65 V and step-up or step-down the voltage based on the desired LED current. The user can enable spread-spectrum frequency modulation, which adds dither to the switching frequency, improving EMI performance. Additional features include analog dimming, integrated PWM generation, fault protection, current monitoring, and thermal protection. This device also has an accessible internal 5-V reference voltage which is used to power the other devices, and can source up to 30 mA.

Control the LED current with analog or PWM dimming. A linear analog dimming response can be achieved by varying the voltage of the high-impedance IADJ pin between 140 mV to 2.25 V. In this design, analog dimming is coupled with the LMT87-Q1 and an amplifier to achieve linear thermal foldback. Alternately, the average LED current can be controlled with the internal PWM generator. Accomplish this task by varying the voltage on the DIM/PWM pin between 1 V and 3 V, which sets the duty cycle of the PWM waveform.

Figure 2 shows the TPS92692-Q1 functional block diagram.

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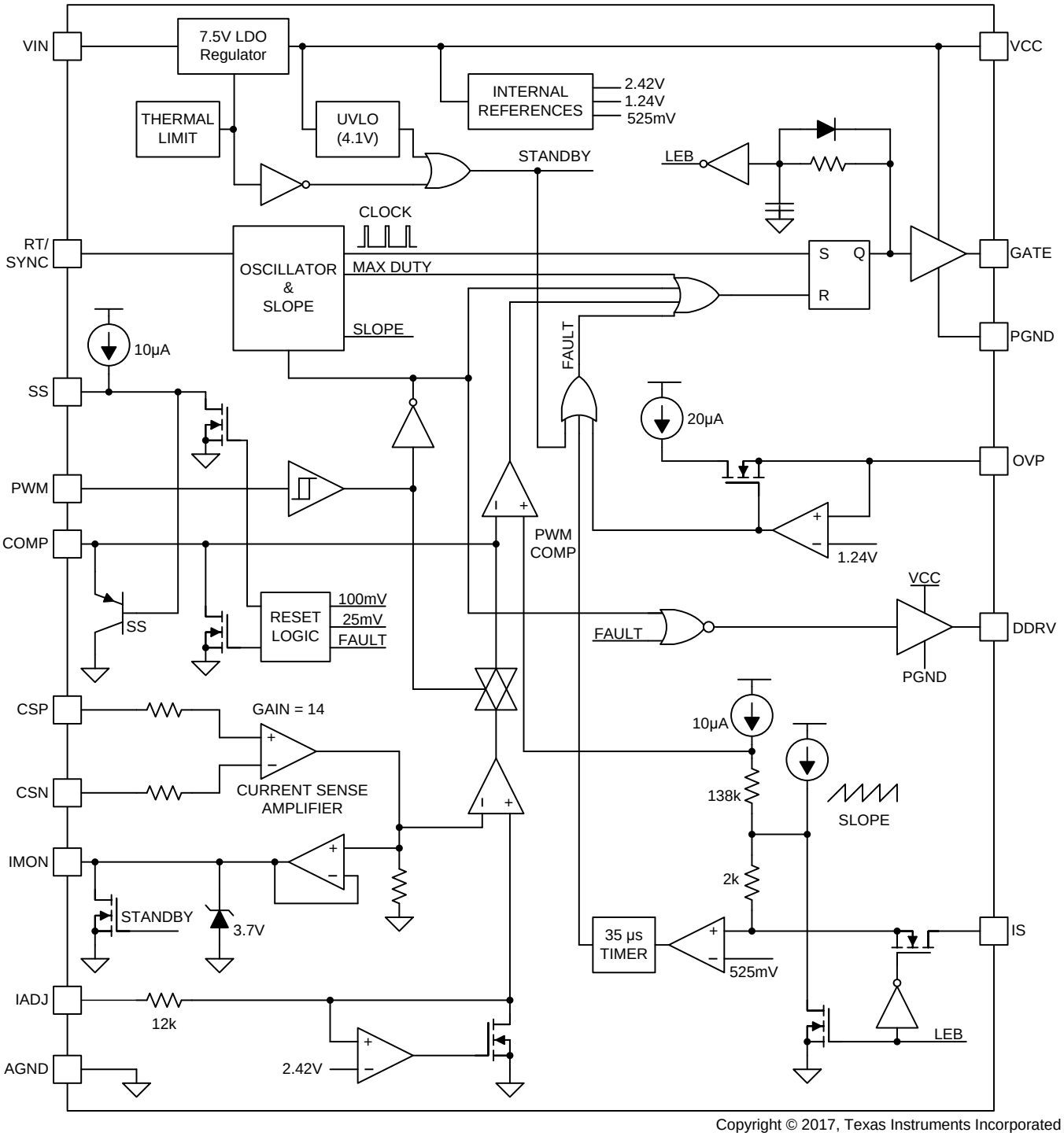

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Figure 2. TPS92692-Q1 Block Diagram

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2.2.2 LMT87-Q1

The LMT87-Q1 is a low-power, precision CMOS temperature sensor with a linear voltage output. The device emulates a negative temperature coefficient (NTC) thermistor by having an output voltage that is inversely proportional to temperature. Unlike a thermistor, the device has an exceptional linear response, which allows for linear thermal foldback in this design. The LMT87-Q1 resides on the printed-circuit board (PCB) containing the LED strings to sense the heat being generated by the LEDs, and reduce the current if necessary.

Figure 3 shows the LMT87-Q1 functional block diagram.

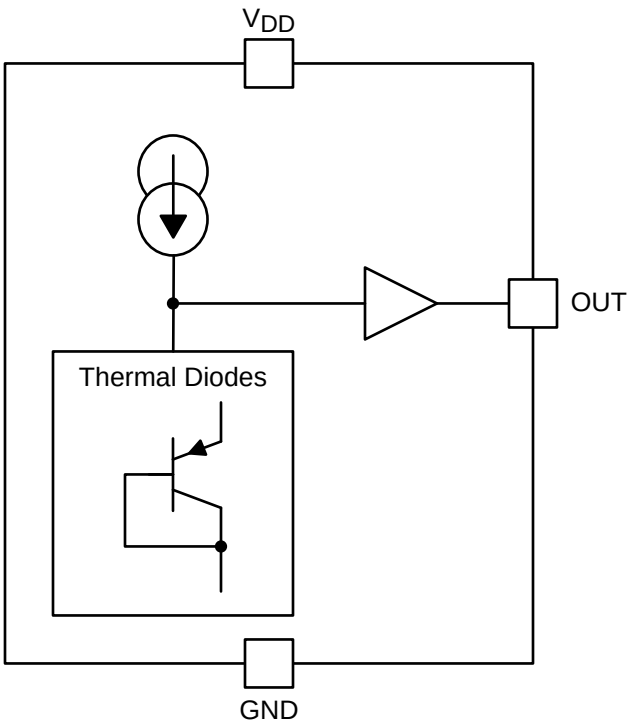

Figure 3. LMT87-Q1 Block Diagram

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2.2.3 TLV2316-Q1

TLV2316-Q1 is a dual-channel, low-power, general-purpose op amp for cost-sensitive systems. The device features rail-to-rail input and output swings, low quiescent current, and a wide bandwidth of 10 MHz. In this design, the TLV2316-Q1 is coupled with a MOSFET to accurately balance the current between the two strings of LEDs. In addition, one channel is used for signal conditioning the temperature sensor and allows the designer to adjust the thermal foldback start point.

Figure 4 shows the TLV2316-Q1 functional block diagram.

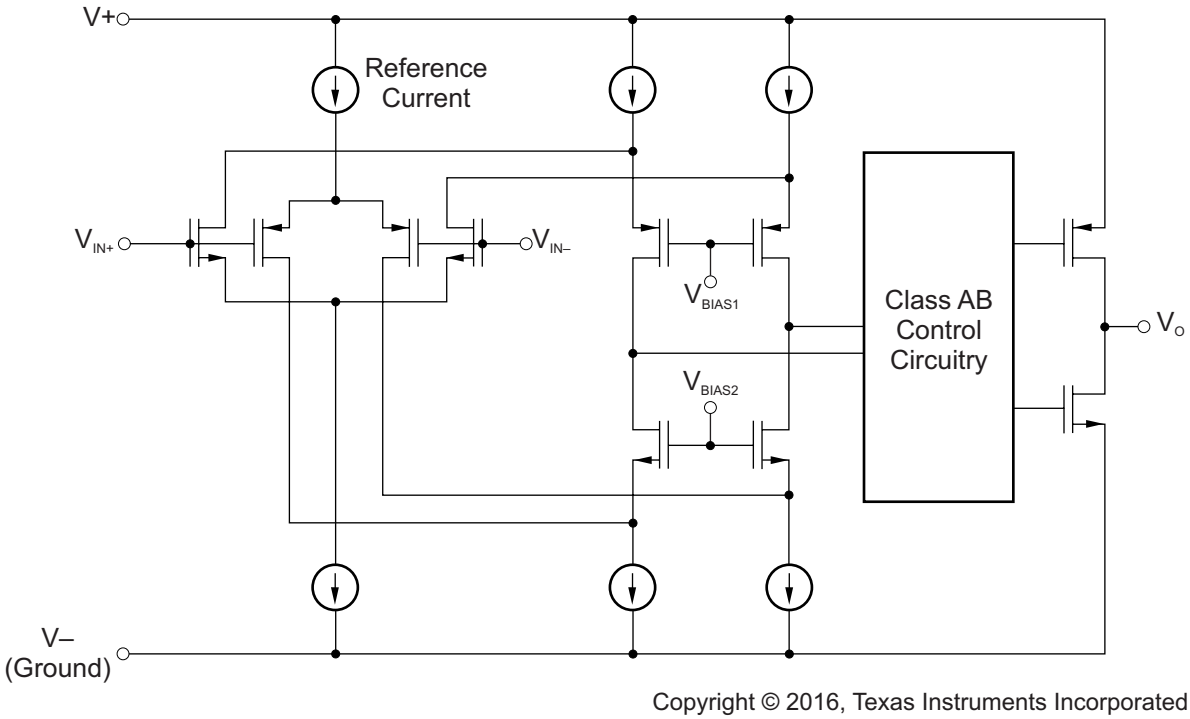

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Figure 4. TLV2316-Q1 Block Diagram

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2.2.4 LM2901-Q1

LM2901-Q1 is a quad-channel, high voltage comparator. In this reference design, one channel is used to current limit the reference string in the event of an open-circuit failure of the secondary string. The other channels can be used for fault detection or other functions.

Figure 5 shows the LM2901-Q1 functional block diagram.

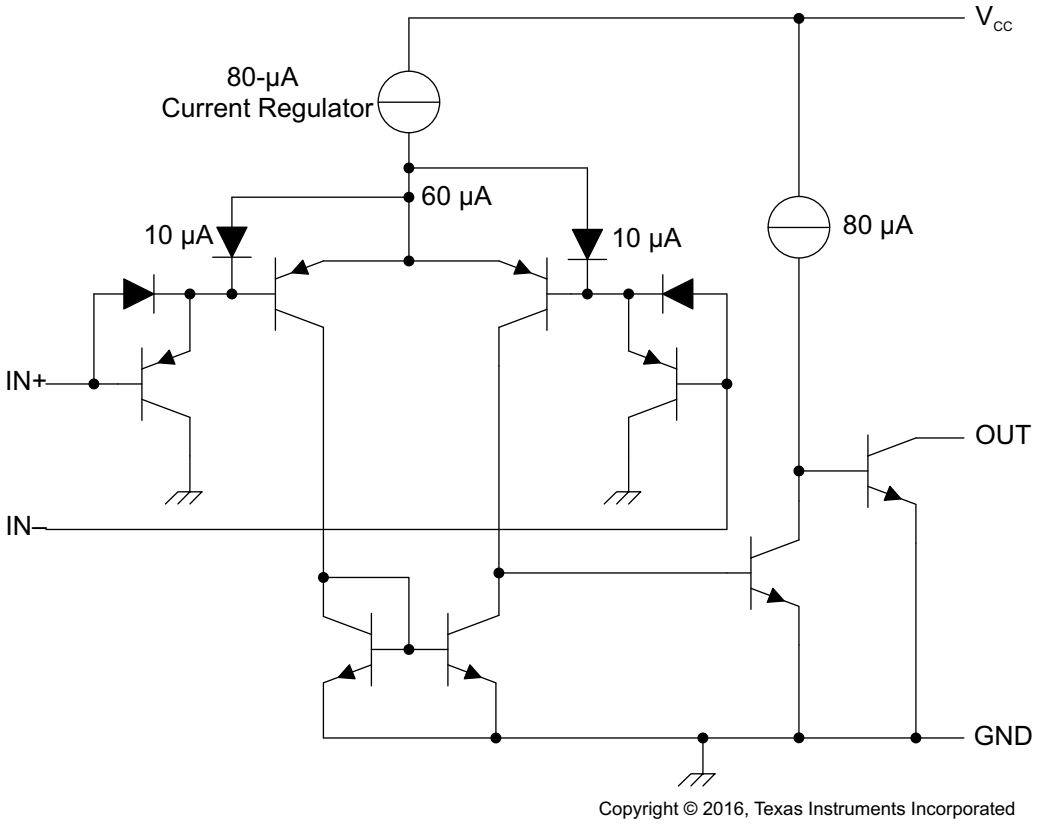

Figure 5. LM2901-Q1 Block Diagram

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2.3 System Design Theory

2.3.1 Current Balancing

A requirement of this design is to use a single LED driver to drive two parallel strings of LEDs. If the LED strings are connected in parallel without a balancing circuit, the current in each string fluctuates due to variation in the LED forward voltage. The LED forward voltage can change with both temperature and manufacturing process variation. Use of an op-amp-based mirror accomplishes the current balancing in this design, as Figure 6 shows. The low-side resistors measure the current in each string. The reference string is a string of LEDs with a low-side sense resistor that sets the current through the mirrored string. The mirrored string is in series with a low-side MOSFET that can control the amount of current flowing in the string. The op amp biases the MOSFET to force the voltage at the source to be equal to the voltage at the non-inverting terminal of the op amp. This biasing ensures that the current in each string is equal. A restriction on this circuit is that the forward voltage drop of the reference string must be greater than the mirrored string, which ensures that the MOSFET has sufficient headroom for correct biasing. The designer can accomplish this extra voltage drop in the reference string by implementing at least one more LED or a series resistor. This additional voltage drop is observable across the MOSFET in the mirrored string. Therefore, the MOSFET must dissipate the same amount of power dissipated by the additional LED or series resistor to ensure equal current in both strings. Although this requirement is restrictive, it allows for convenient fault detection that can detect a single LED that has been shorted or opened in either string.

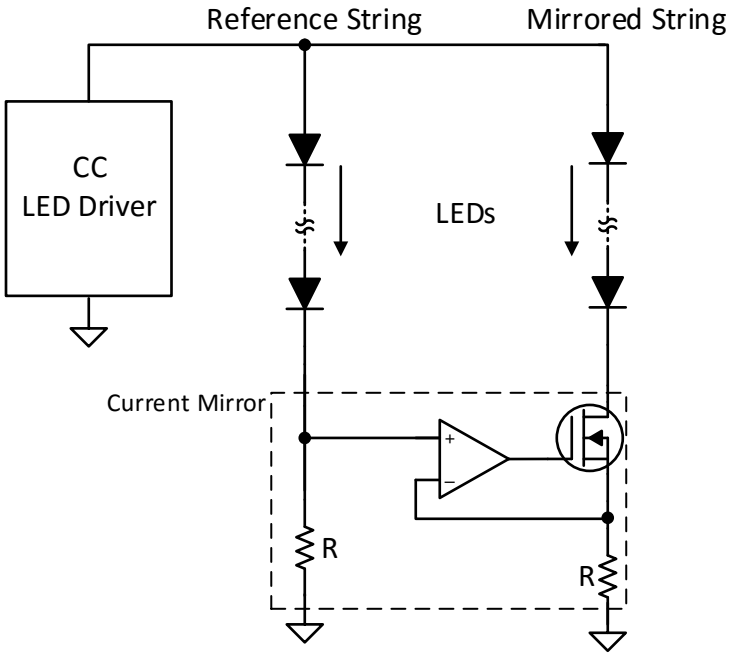

Figure 6. Block Diagram for Op-Amp-Based Current Mirror

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2.3.2 Stability Analysis

Analyze the stability of this op-amp-based circuit and then provide any necessary compensation to achieve a stable design. Unstable designs may have unbalanced currents and undesired transient behavior. An effective way to perform this analysis is by using the TINA-TI™ SPICE simulation tool for AC loop-gain analysis.

To perform an AC loop-gain analysis, the user must first break the feedback loop and inject a small signal AC source. However, simply breaking the feedback path does not provide the correct DC operating point and causes the op amp to saturate to one rail. Instead, this reference design implements a circuit as shown in Figure 7. The large capacitance of C1 allows AC to pass, while the large inductance of L1 blocks AC and allows DC to pass. This provides a correct DC bias point to the op-amp circuit while still allowing the designer to inject a small signal source. In this circuit, VF1 represents the loop gain and indicates stability. For more information on op-amp AC analysis in TINA-TI, see the section regarding Stability in the *TI Precision Labs - Op Amps* training resource.

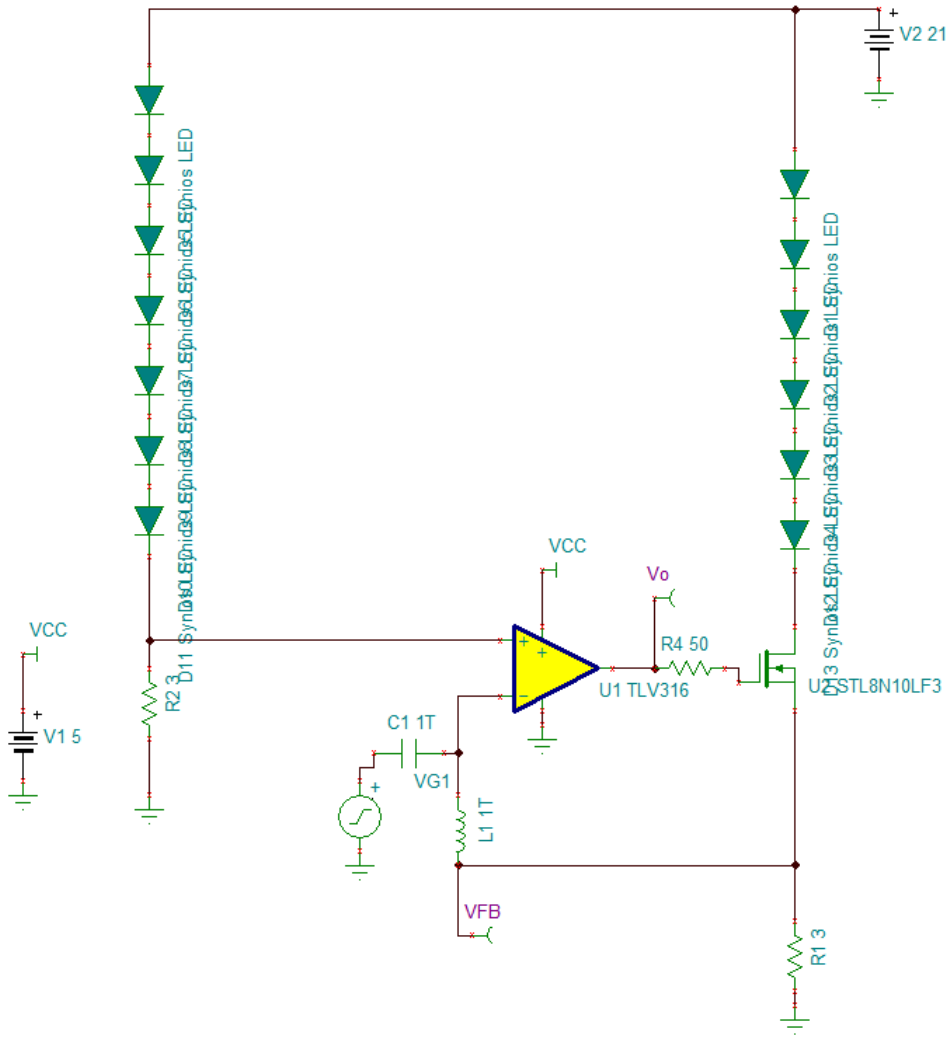

Figure 7. TINA-TI™ Circuit for AC Analysis

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Figure 8 shows the results of an AC sweep. The phase margin is approximately 8° and the rate of closure is greater than 20 dB, so the system is unstable. Additional compensation is necessary to achieve a stable design.

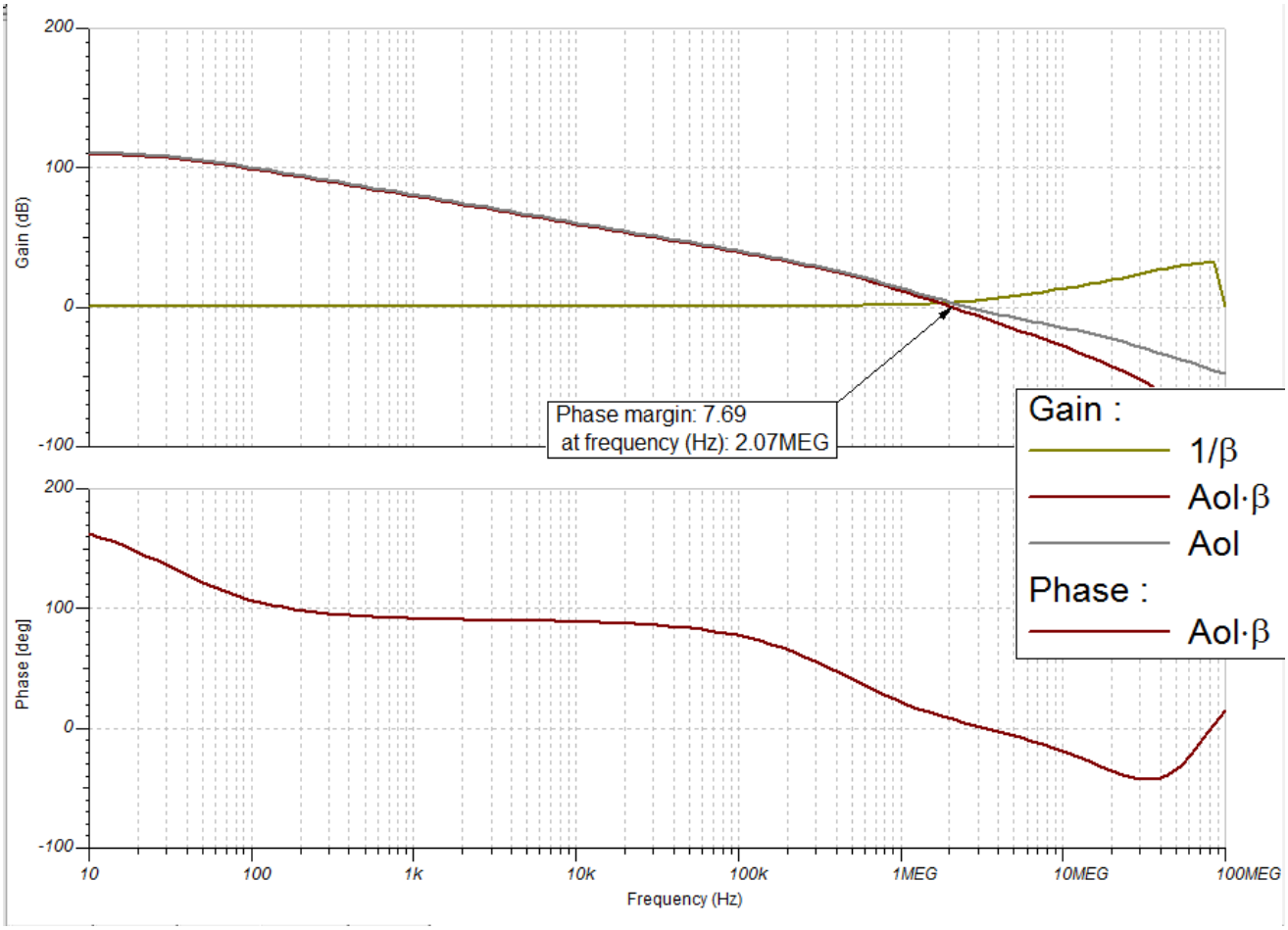

Figure 8. TINA-TI™ AC Sweep Showing Circuit Instability

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Figure 9 shows the circuit with compensation. R3, R5, and C2 form a noise-gain compensation network that pushes up the loop-gain phase at the crossover frequency. Figure 10 shows the AC sweep after the compensation components have been added. The phase margin is approximately 49°. Noise-gain compensation adds a zero-pole pair to the 1/beta curve and increases the gain at high frequency. This compensation results in a lower frequency intersection of the Aol and 1/beta curves with a stable 20-dB per decade rate of closure between them.

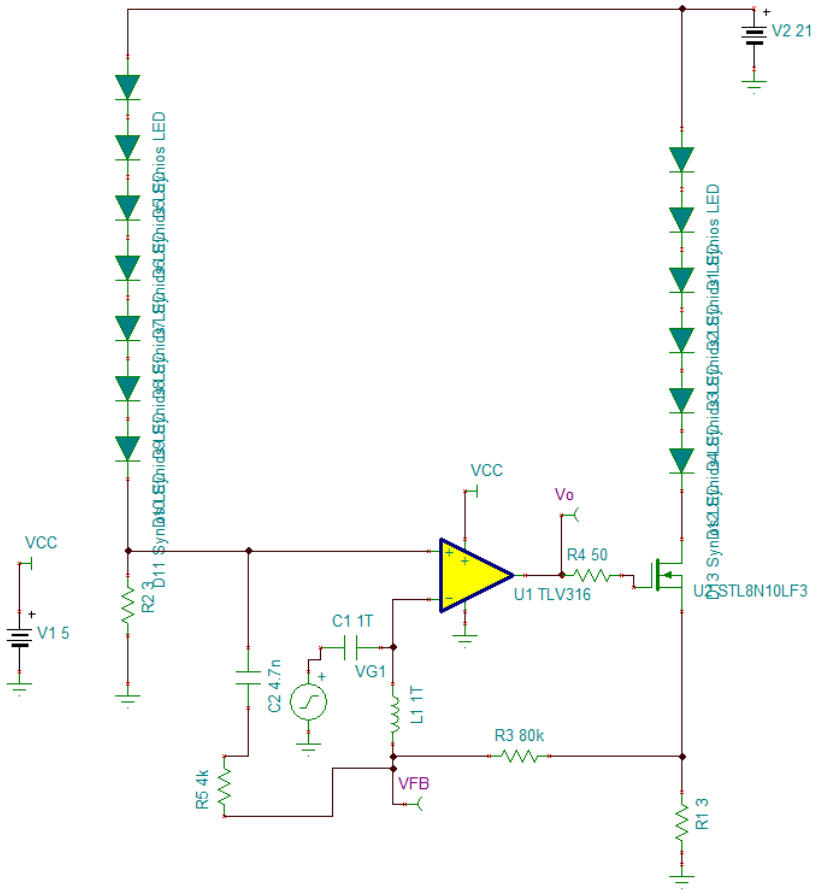

Figure 9. TINA-TI™ Compensated Current Mirror Circuit

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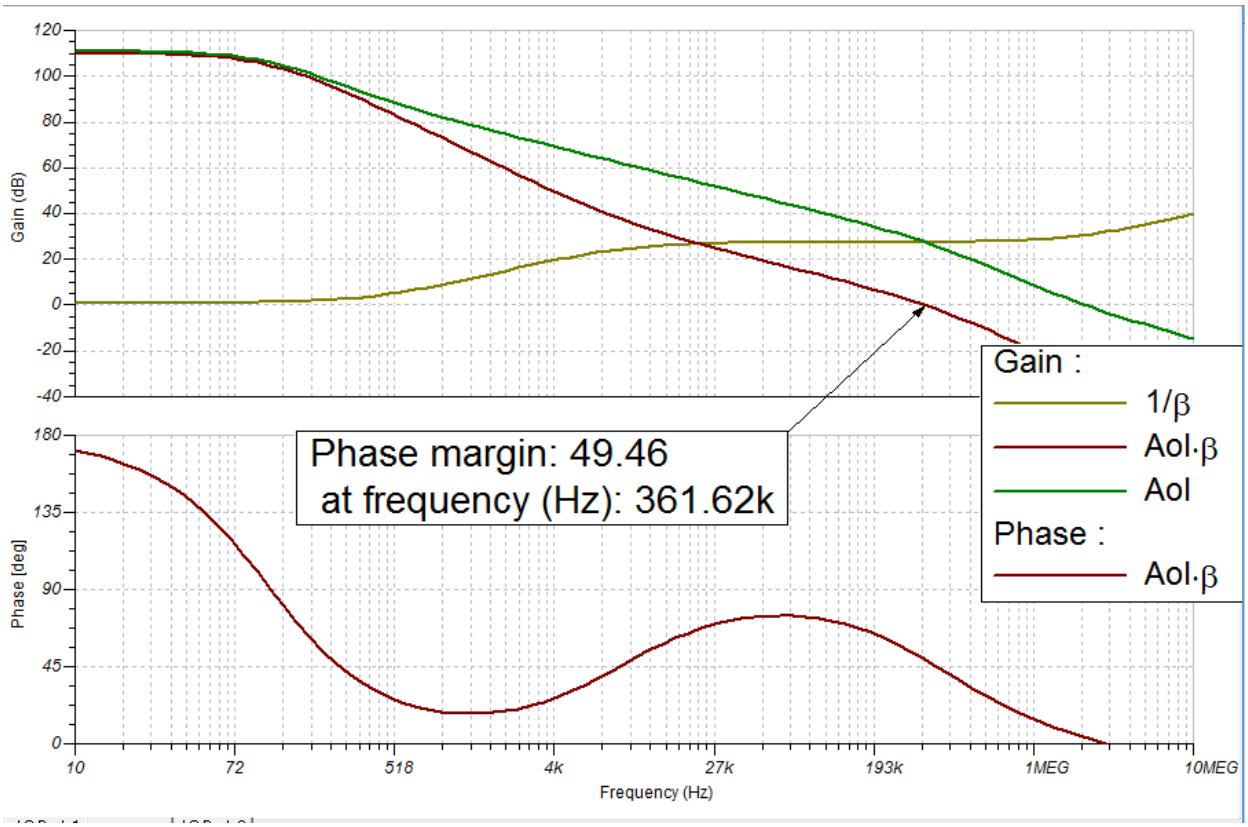

Figure 10. TINA-TI™ AC Sweep of Compensated Circuit

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2.3.3 Position and DRL Modes

This design features two operating modes for setting the brightness of the LEDs: Position and DRL. In DRL mode, the LEDs operate at full brightness and the current is limited by the internal current sense amplifier connected to the current sense resistor R_{CS}. Equation 1 sets the LED current. A value of 0.43 Ω has been chosen to set the total current to approximately 400 mA, or 200 mA per string.

$$I_{LED} = 170.7 \frac{mV}{R_{CS}} \quad (1)$$

In Position mode, the LEDs are dimmed using the TPS92692 internal PWM generator. A voltage between 1 V and 3 V sets the PWM duty cycle between 0% and 100%, respectively. In this design, the duty cycle is set to 8% after enabling the Position mode. Figure 11 shows the components used to set up the two modes. In Position mode, the resistor divider formed by R16 and R19 sets the voltage at the DIM/PWM pin. If connecting the DRL pin instead, the VBAT2 connection that sets the duty cycle to 100% overrides the voltage at this pin. R18 and R19 set the voltage.

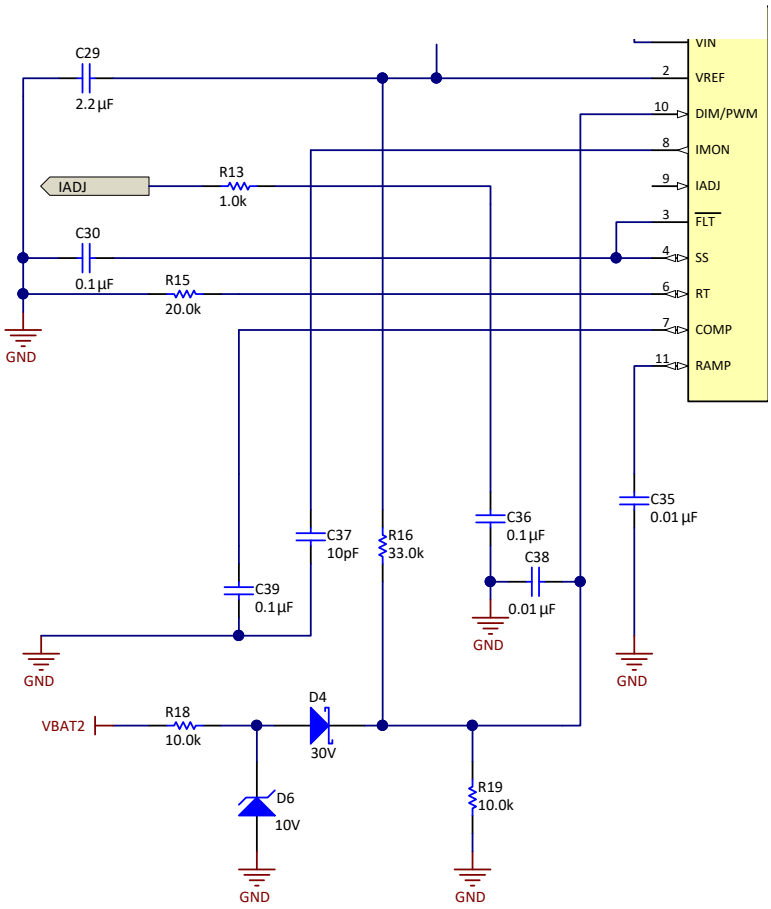

Figure 11. 'DRL' and 'Position' Schematic

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2.3.4 Reference String Current Limit

Because the current-balancing circuit relies on the reference string, if the mirrored string fails to open, then all of the current is free to flow through the reference string. The driver monitors the current it delivers and increases the voltage to push the full current through one string, which doubles the intended current through the LEDs. This high current can generate heat and pose a hazard if the LEDs are not rated for the current.

To account for this hazard, use a simple comparator circuit to monitor the current in the reference string. If the current rises above a threshold, the comparator turns on a field-effect transistor (FET) and pulls down the IADJ pin. This process repeats when the current falls back below the threshold, which causes a flickering. The purpose is not to maintain operation of the LEDs, but to prevent an overheating condition. The fault detection circuit will indicate if the mirrored string has failed. Figure 12 shows the current-limiting circuit. V_{ILM} is the voltage at which the current must be limited. Determine this voltage by using $V_{ILM} = I_{LM} \times R$ where I_{LM} is set at or below the maximum continuous LED current. In this case, the limit is set to 300 mA, which is the maximum current for these LEDs. If the LEDs used can handle double the intended current, implementing this circuit may not be necessary.

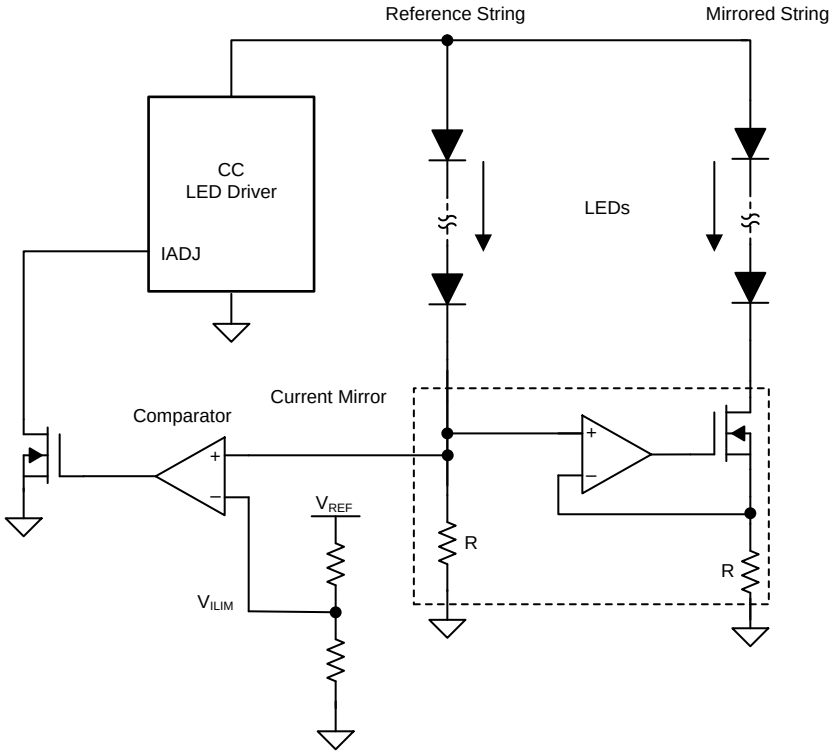

Figure 12. Reference String Current Limit

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2.3.5 Thermal Foldback

This design includes an adjustable thermal foldback that reduces the LED current as the LED board temperature increases. This foldback prevents the LEDs from overheating. Achieve this thermal foldback by using the LMT87-Q1 temperature sensor to adjust the voltage on the analog dimming pin (IADJ). Use a non-inverting amplifier to interface the temperature sensor with the LED driver. Figure 13 shows the amplifier schematic. J4 connects directly to the temperature sensor on the LED PCB.

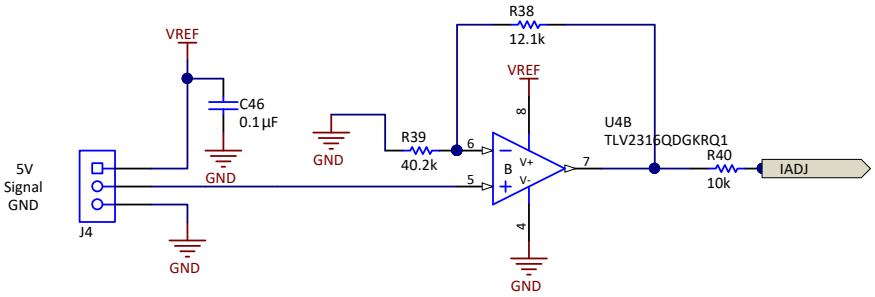

Figure 13. Thermal Foldback Amplifier Schematic

To set the led current between 0% and 100%, modulate the analog dimming pin (IADJ) between 140 mV to 2.25 V. The LMT87-Q1 varies the output voltage from 3.25 V to 0.5 V over a temperature range of –50°C to 150°C. Use the non-inverting amplifier to adjust the temperature at which the foldback begins, which is based on the gain value. Equation 2 shows the output voltage of the LMT87-Q1 as a function of temperature.

$$V_{TEMP}(mV) = 2230.8\ mV - \left(13.582\ \frac{mV}{°C}(T - 30°C)\right) - \left(0.00433\ \frac{mV}{°C^2}(T - 30°C)^2\right) \quad (2)$$

Figure 14 shows the voltage at the output of the LMT87-Q1 device as well as the output amplified by a gain of 1.3, which is the voltage at the IADJ pin. The black horizontal line shows where the thermal foldback begins for each voltage curve. Higher gains cause the thermal foldback to begin at a higher temperature.

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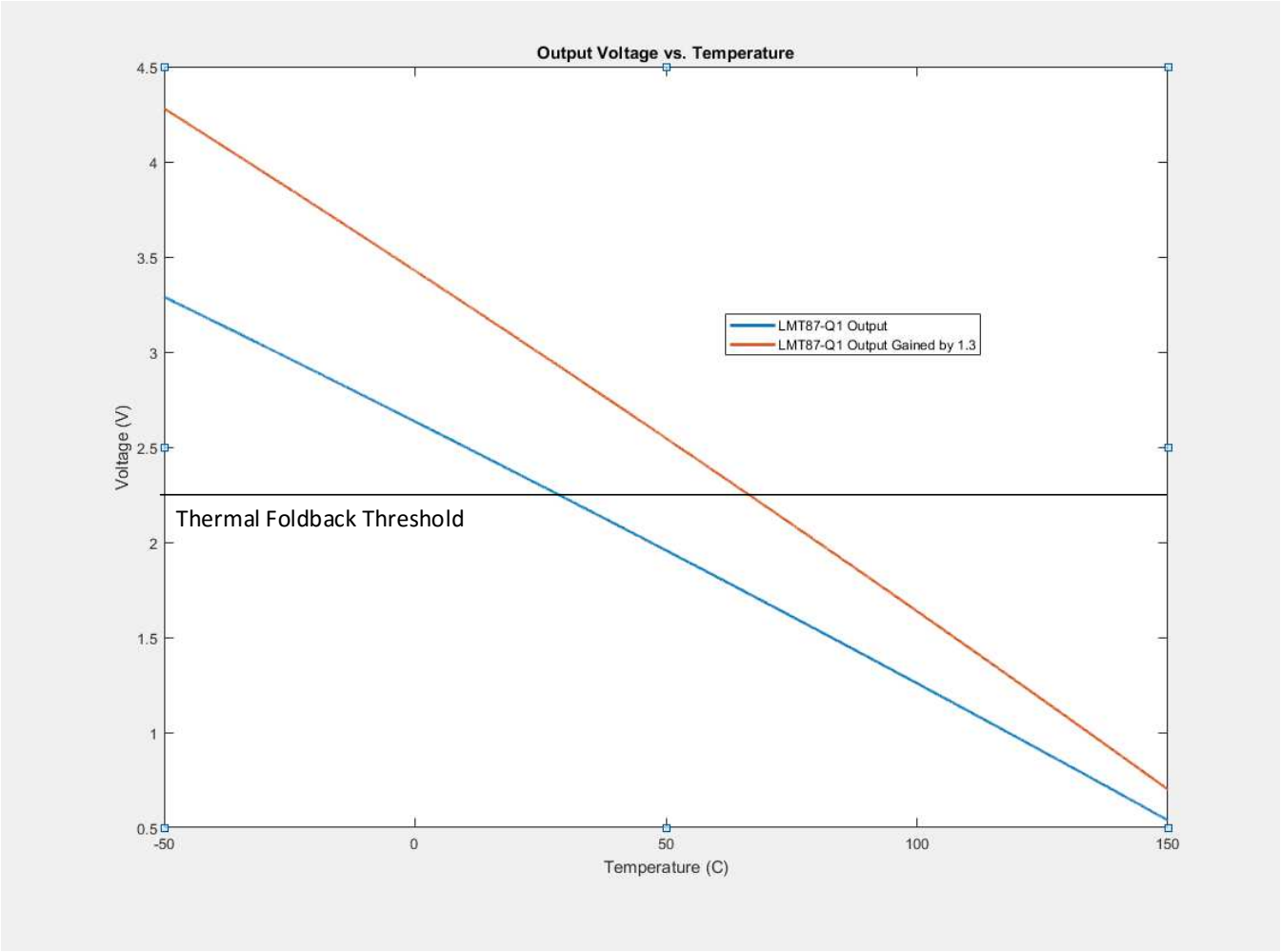

Figure 14. LMT87-Q1 Output Voltage and Amplified Output Voltage

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The result as given by Figure 15 is produced by multiplying the LMT87 output voltage by the chosen amplifier gain and calculating the LED current output . The gain in this design is set to 1.3.

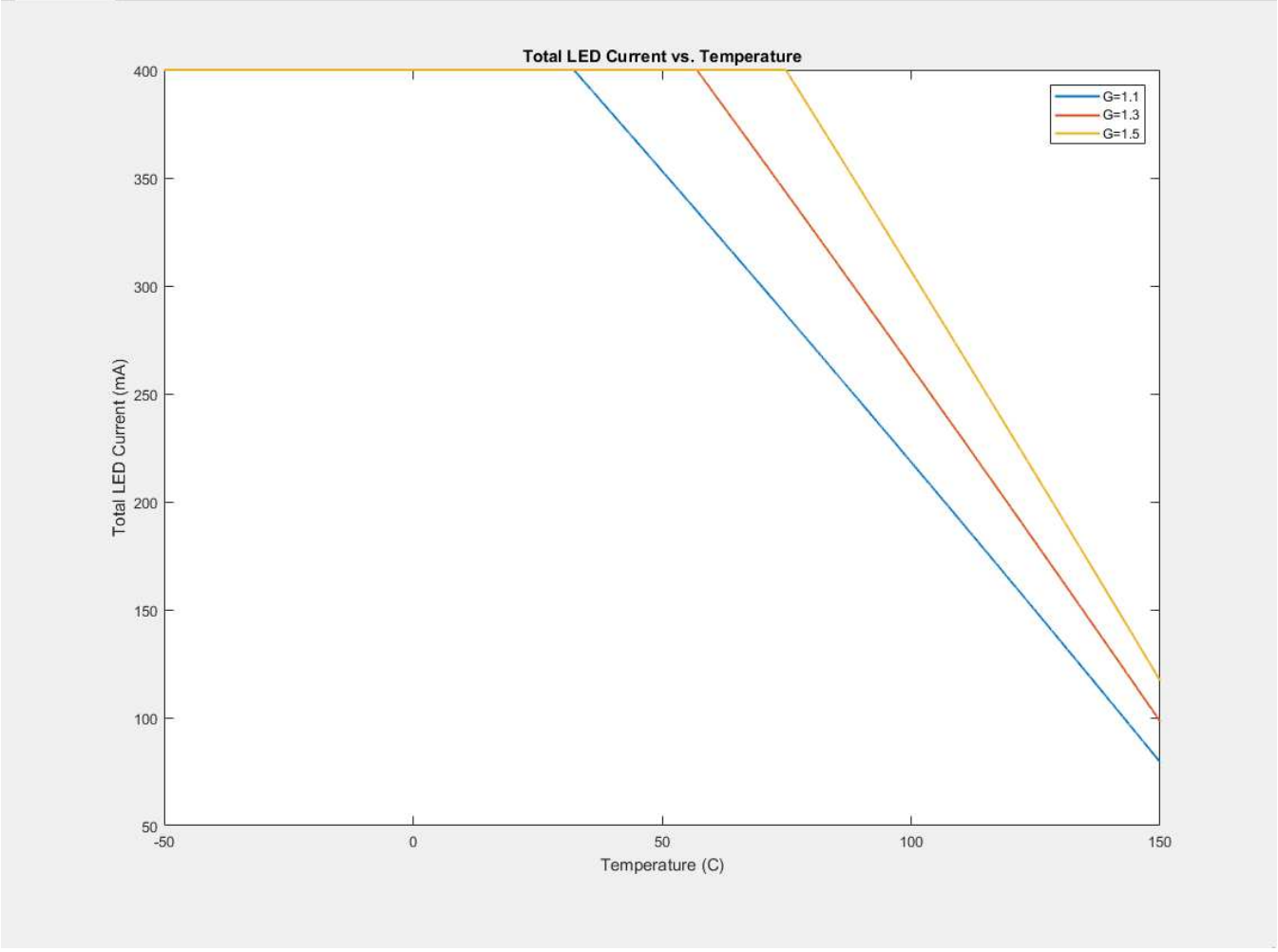

Figure 15. Thermal Foldback Response for Different Amplifier Gains

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3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

The required hardware consists of the LED driver board and an LED daughterboard which contains the LEDs and temperature sensor. The LEDs used on the LED board for testing are Osram Synios P2720. The LED+ connection on the driver board must be connected to the positive of both LED strings. The negative of the strings must be connected REF– and MIR– connections on the driver board. The temperature sensor must be properly connected to the 5V, GND, and Signal connections of the driver board.Figure 16 shows the proper way to connect the LED board and LED driver board.

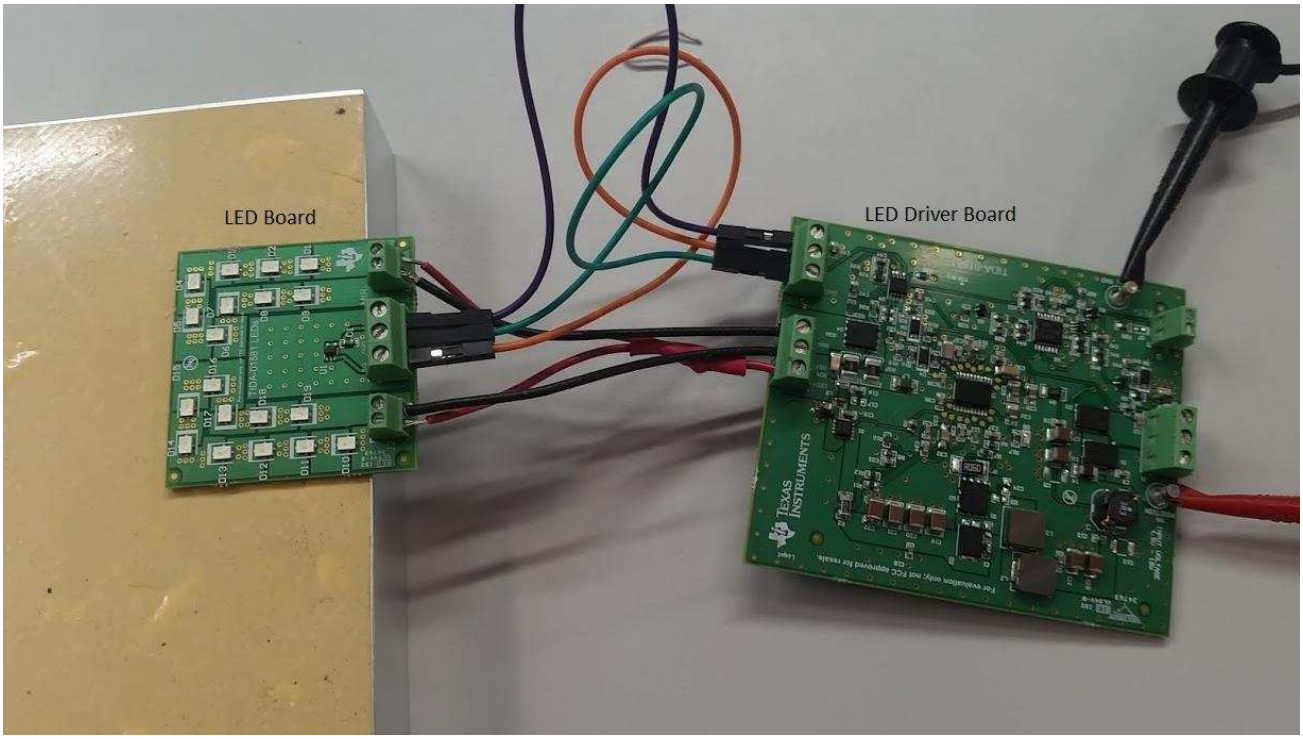

Figure 16. Driver Board and LED Board Connection

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3.2 Testing and Results

3.2.1 Current Balance Accuracy

After connecting the LED driver board to the LED board, as specified in *Hardware*, a 14-V DC was applied to the DRL connection. Current probes were used to measure the current in each string during start-up.Figure 17 shows the current in each string during start-up. This result shows that the current-balancing circuit accurately controls the current through both strings. The current in each string settles smoothly to 200 mA.

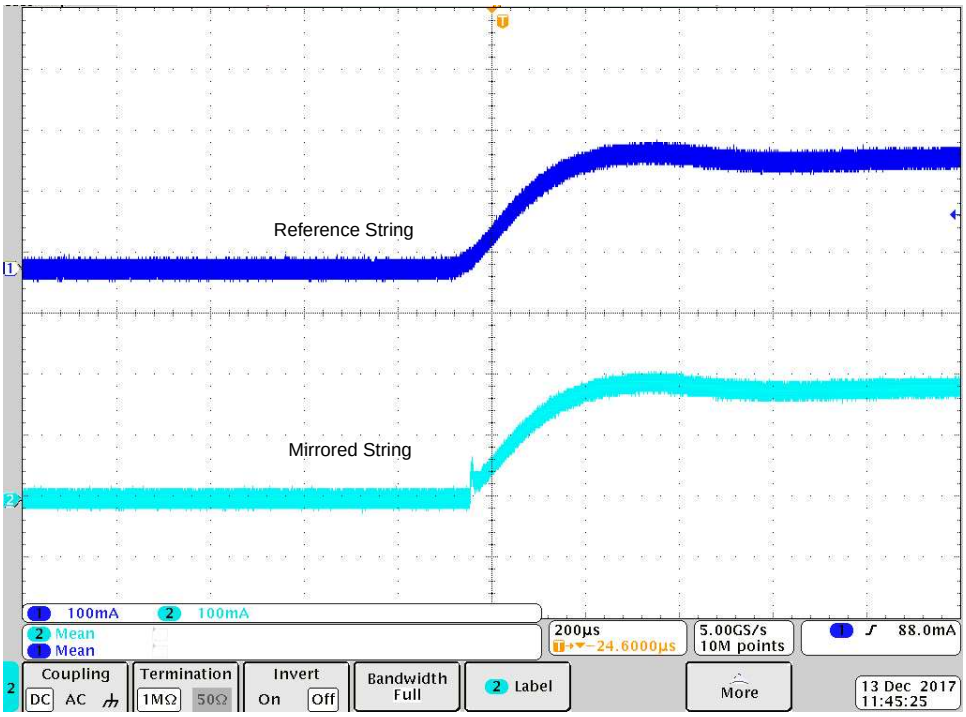

Figure 17. Turnon Current in Each String in 'DRL' Mode

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The steady-state current in DRL mode was also measured in both strings to indicate the accuracy balance, which Figure 18 shows. This result also shows a difference of 2 mA between the strings.

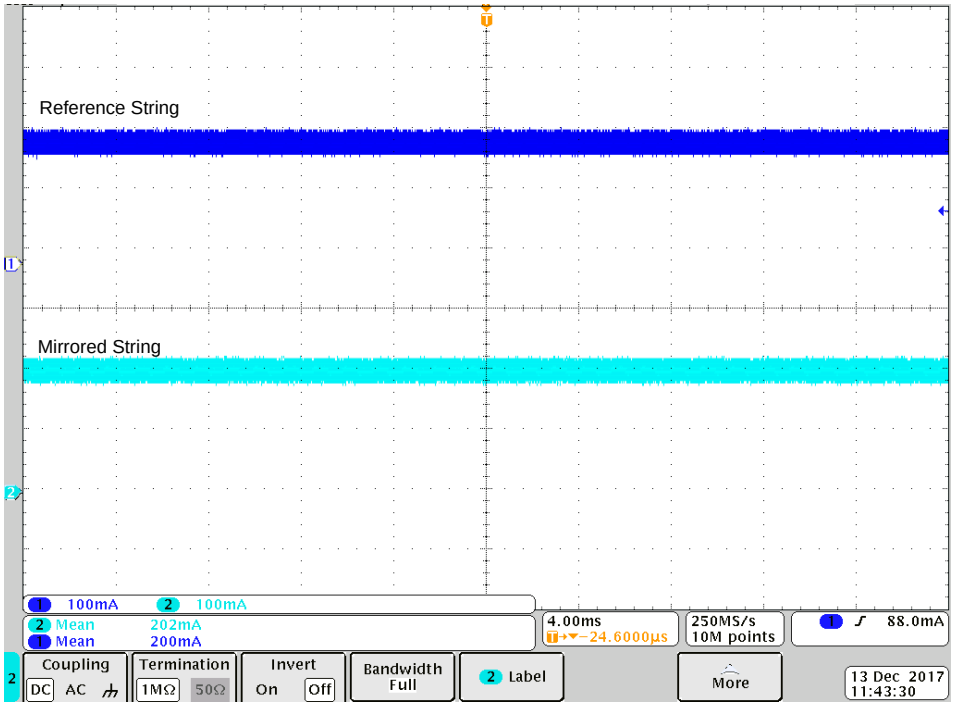

Figure 18. Steady-State Current Oscilloscope Capture in 'DRL' Mode

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The average current in each string was also measured with two ammeters in DRL mode. This result is more accurate than the oscilloscope capture. Figure 19 shows a photo of the results. The current difference between the strings is less than 1%.

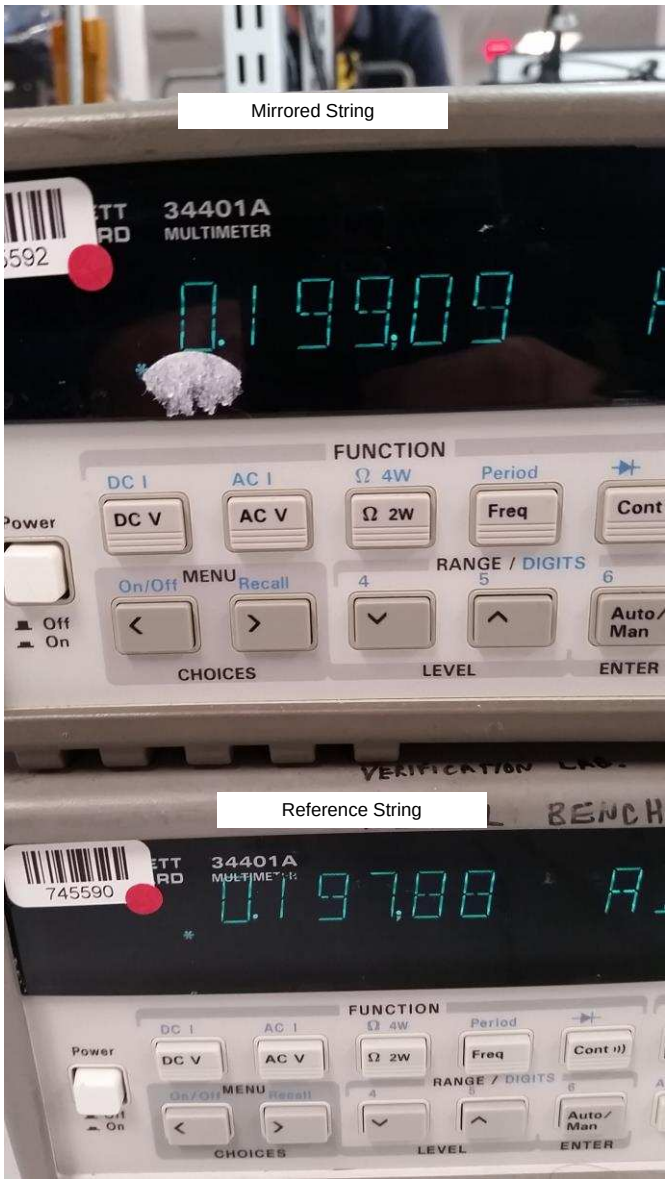

Figure 19. Ammeter Measurement of Average String Current in 'DRL' Mode

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The ammeter measurement was repeated for the Position mode to compare the average currents between the two strings during PWM. Figure 20 shows an image of this result. The current difference between the two strings is less than 1%.

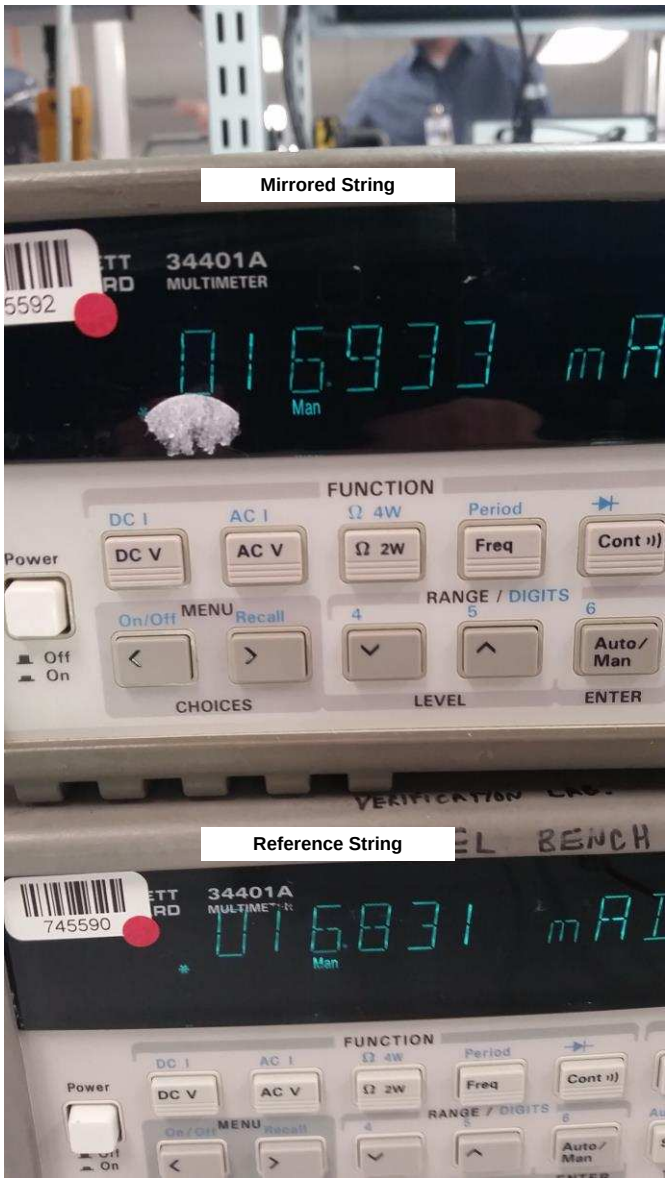

Figure 20. Ammeter Measurement of Average String Current in 'Position' Mode

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Figure 21 shows the PWM transient. Channel 1 is the reference current and channel 2 is the mirrored current. This result shows that the circuit accurately balances the current during PWM dimming. This result confirms an equal brightness of the strings when using the Position mode.

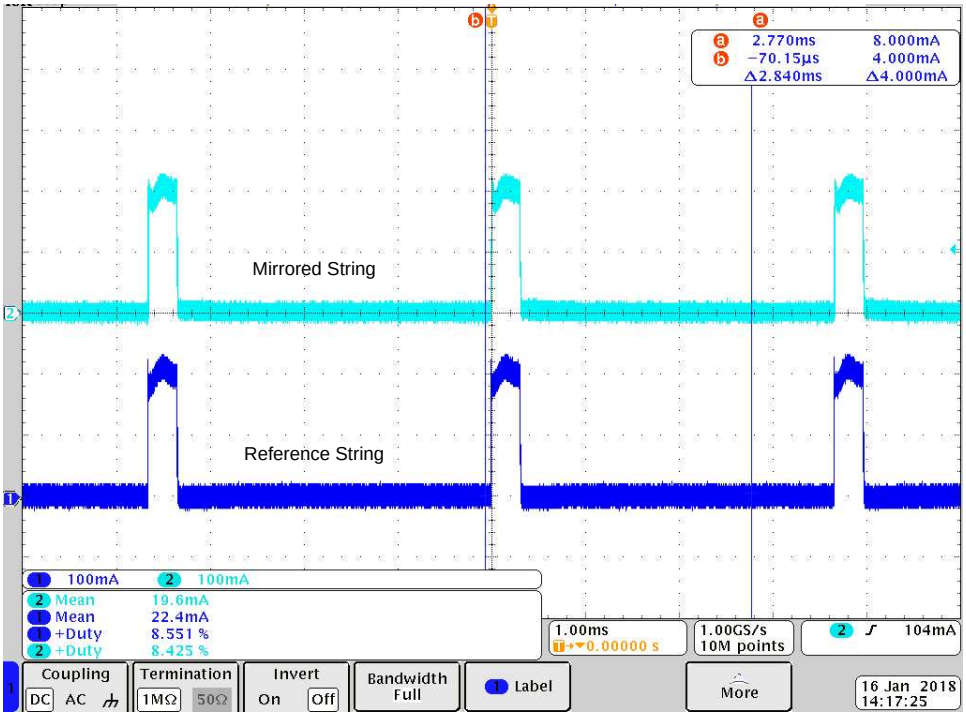

Figure 21. Reference and Mirrored-Current PWM Transient

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3.2.2 Reference String Current Limit

The reference string current limit was tested by disconnecting the mirrored string of LEDs while the power is connected to the DRL input. Figure 22 shows the current limit waveform. Channel 2 is the current flowing through the reference string of LEDs and channel 3 is the voltage of IADJ. When the current reaches 300 mA, the current limit circuit pulls IADJ to ground. This cycle repeats every 36 ms based on the LED driver fault timer because the device is in hiccup mode. The LEDs flicker in this condition.

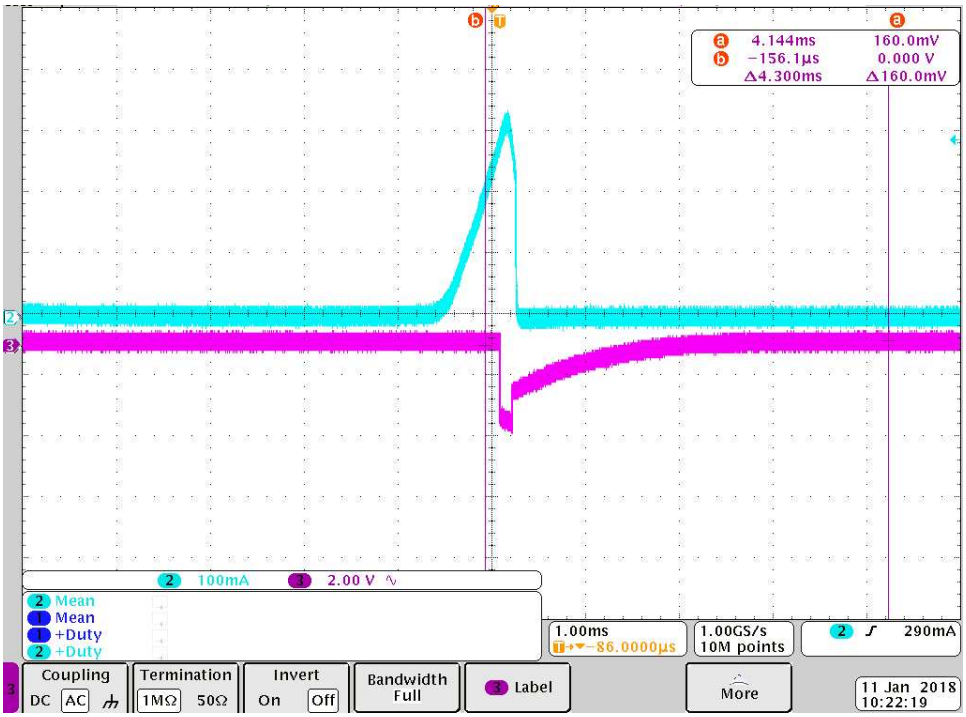

Figure 22. Waveform of Reference String Current Limit

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3.2.3 Thermal Foldback Response

The LED board was heated from 20°C to 125°C and the current was measured. Figure 23 shows both the calculated response and measured response. The measured response accurately corresponds with the calculated response described in Section 2.3.5.

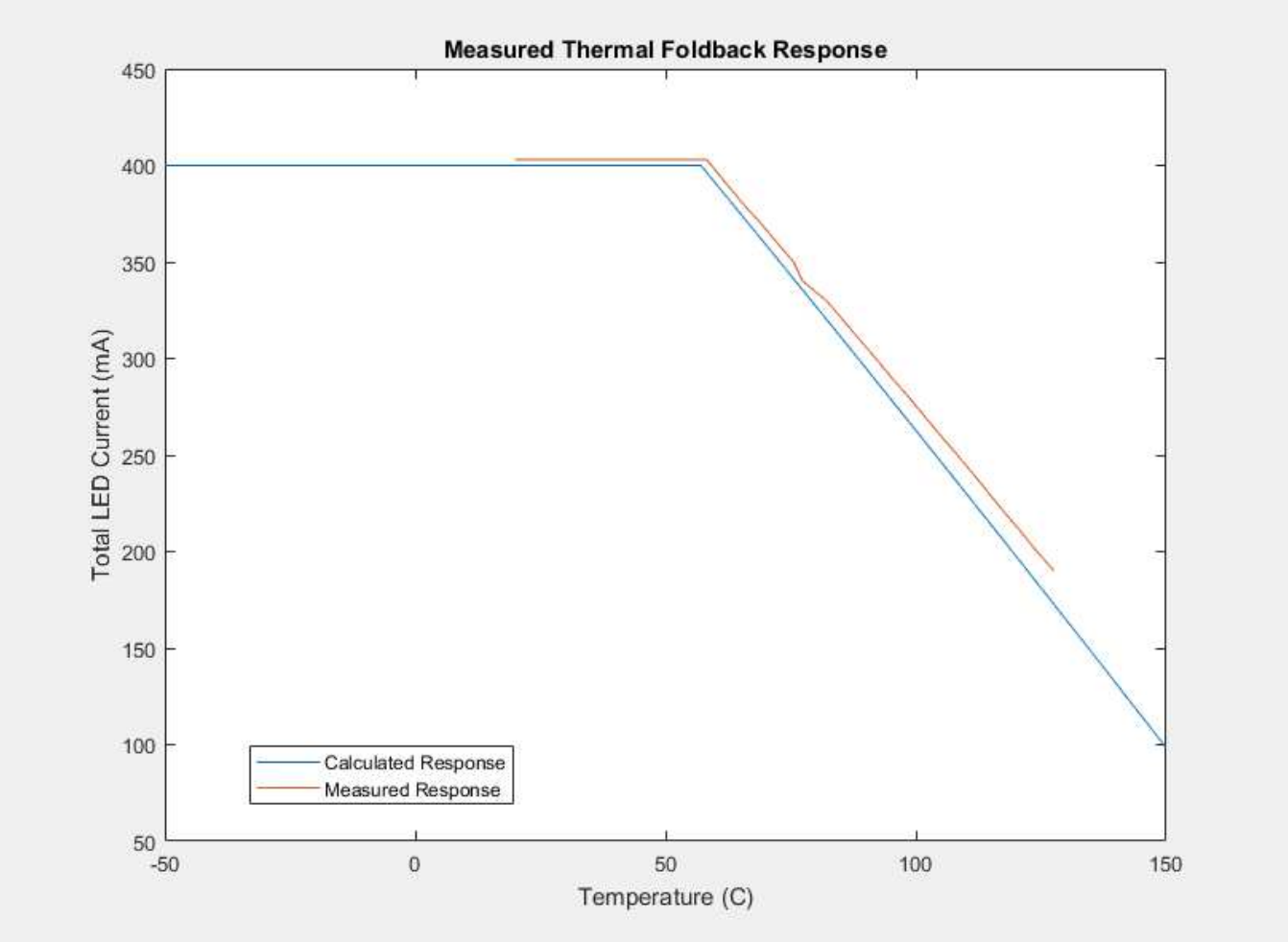

Figure 23. Calculated and Measured Thermal Foldback Response

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3.2.4 Thermal Image

Figure 24 shows a thermal image of the reference design in DRL mode operation at room temperature with the board driving the LEDs at 12 W. The recorded maximum temperature is 50°C. The reverse polarity protection diode, the switched-mode power-supply (SMPS) switching MOSFET, and the current balancing MOSFET have the highest temperature regions.

Figure 24. Thermal Image of TIDA-01581

3.2.5 EMI Testing Unshielded Inductors

The reference design was tested against CISPR25 Class-5 limits for both conducted and radiated emissions. The board was tested in DRL mode in which it drove 19 LEDs at a current of 200 mA and power of 12 W.

Before EMI testing, the switch node was examined for ringing. In Figure 25, the switch node is the node connected to the output of the inductor (L3), the anode of the rectification diode (D2), and the switching MOSEFT Q2. Switch node ringing has a significant negative impact on EMI results and must be addressed before running EMI tests. Figure 26 shows the switch node waveform measured directly from the inductor output to ground using the tip and barrel method. Note the significant ringing on the rising edge of the waveform.

A snubber circuit across the rectifying diode was used to eliminate this ringing before EMI testing. Figure 25 (R1,C1) shows this snubber circuit. The actual values used were R1 = 15 Ω and C1 = 470 pF. The snubber effectively dissipates high-frequency AC signals such as the ringing waveform. For additional details on using an RC snubber to minimize ringing in a boost converter design, see *Minimizing Ringing at the Switch Node of a Boost Converter*. A gate resistor was also added to the switching FET to slow the rise time, which results in a small decrease in efficiency but improves EMI performance.

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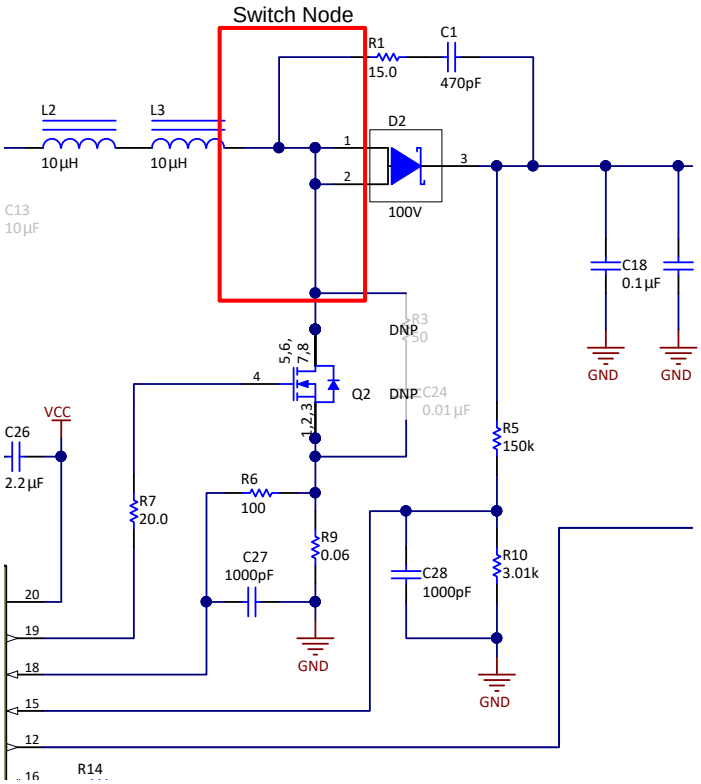

Figure 25. Snubber Circuit (R1,C1)

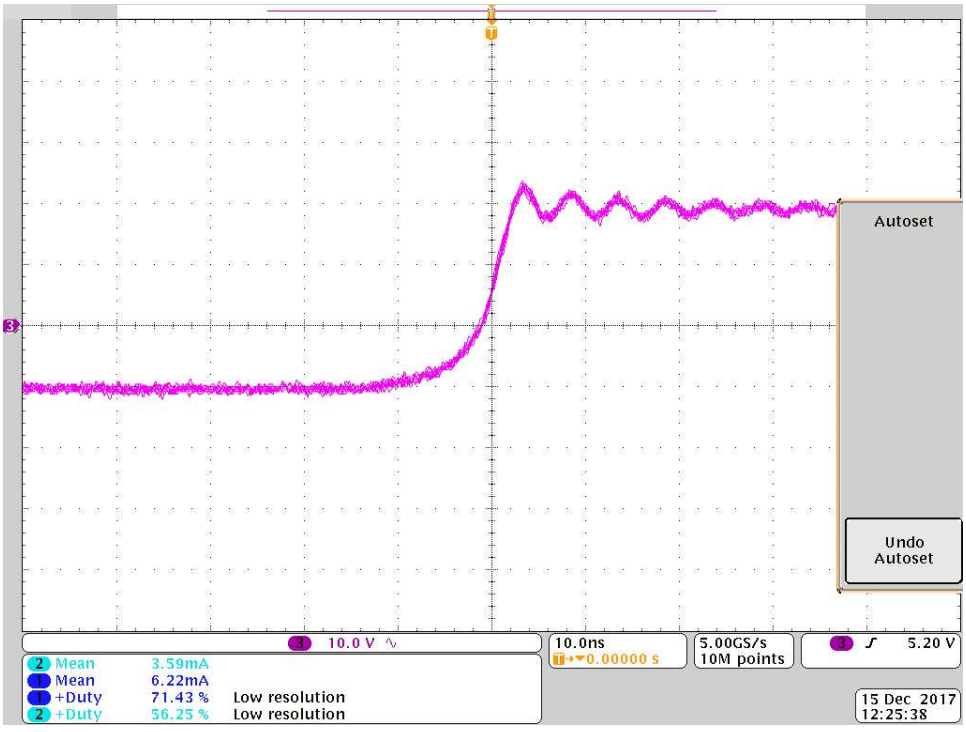

Figure 26. Switch Node Waveform

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EMI tests were performed on the board with both unshielded and shielded inductors. Figure 27 shows an image of the board with unshielded inductors (Vishay IHLP-2525BD-A1). In this design, two smaller inductors in series were used instead of one large inductor. In this case, two 10-uH were placed in series instead of a single 22 µH. The reason for doing this is because smaller components perform better in vibration and physical stress testing. The smaller inductors are less likely to have an issue, such as breaking off the board or breaking a solder joint during stress tests.

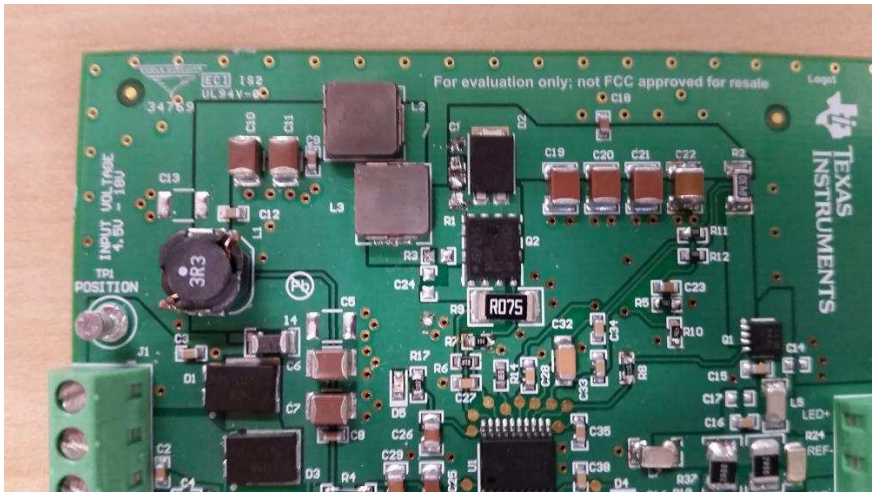

Figure 27. TIDA-01581 With Unshielded Inductors (Vishay IHLP-2525BD-A1)

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The EMI test was set up according to the CISPR25 standard with Class 5 limits. Figure 28 through Figure 33 show the results of the EMI testing.

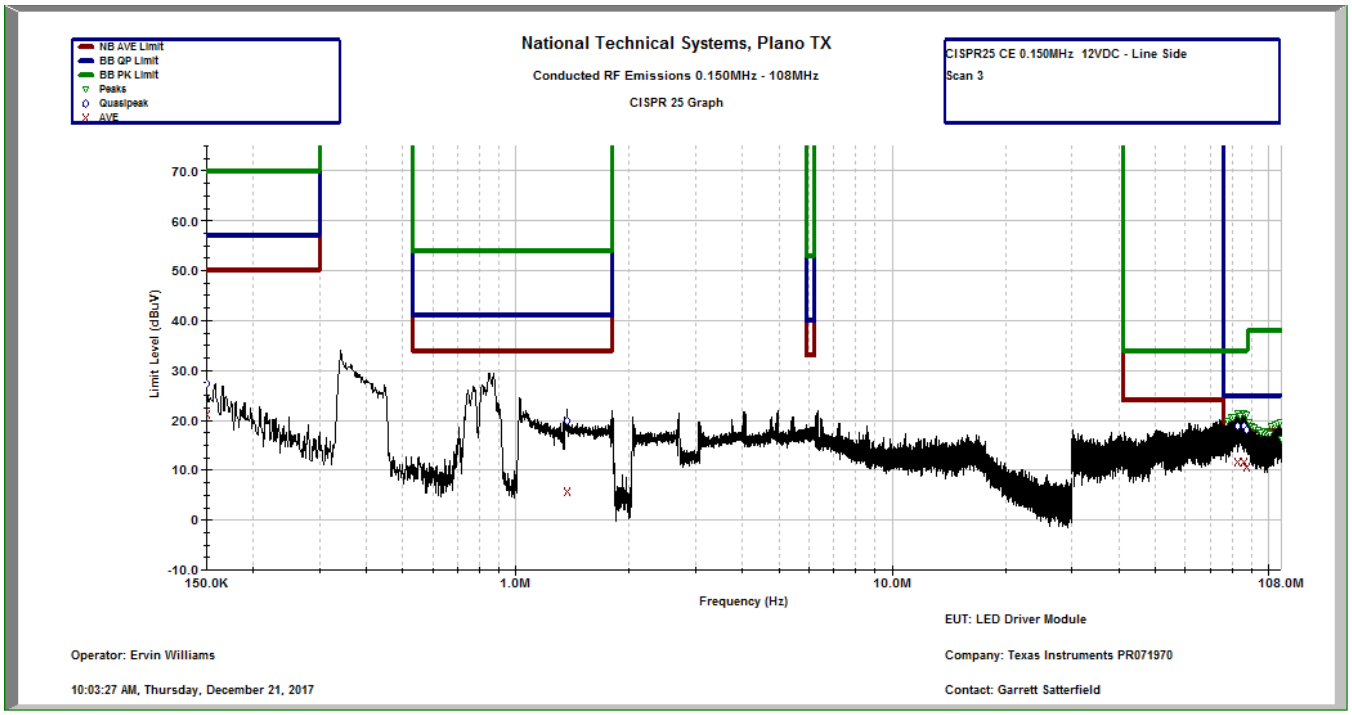

Figure 28. CISPR25 Class-5 Conducted Emissions (Line)

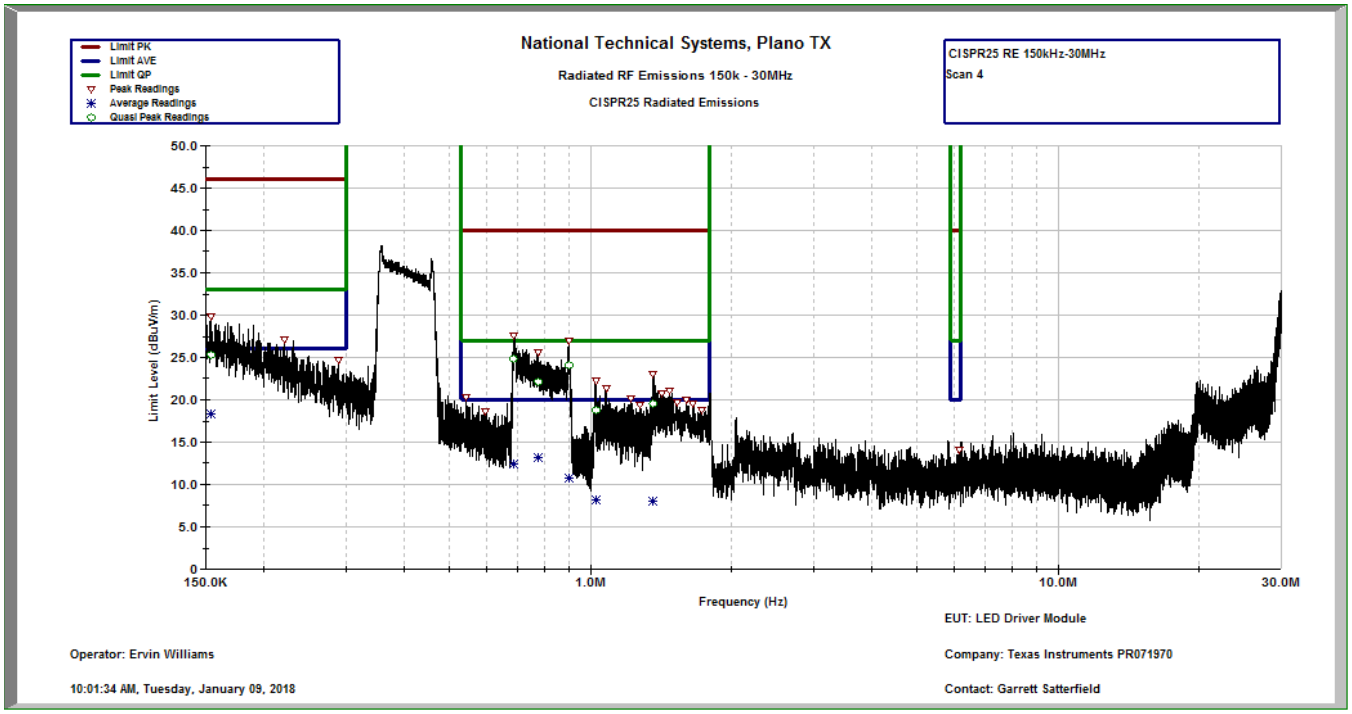

Figure 29. CISPR25 Class-5 Radiated Emissions: 150 KHz to 30 MHz

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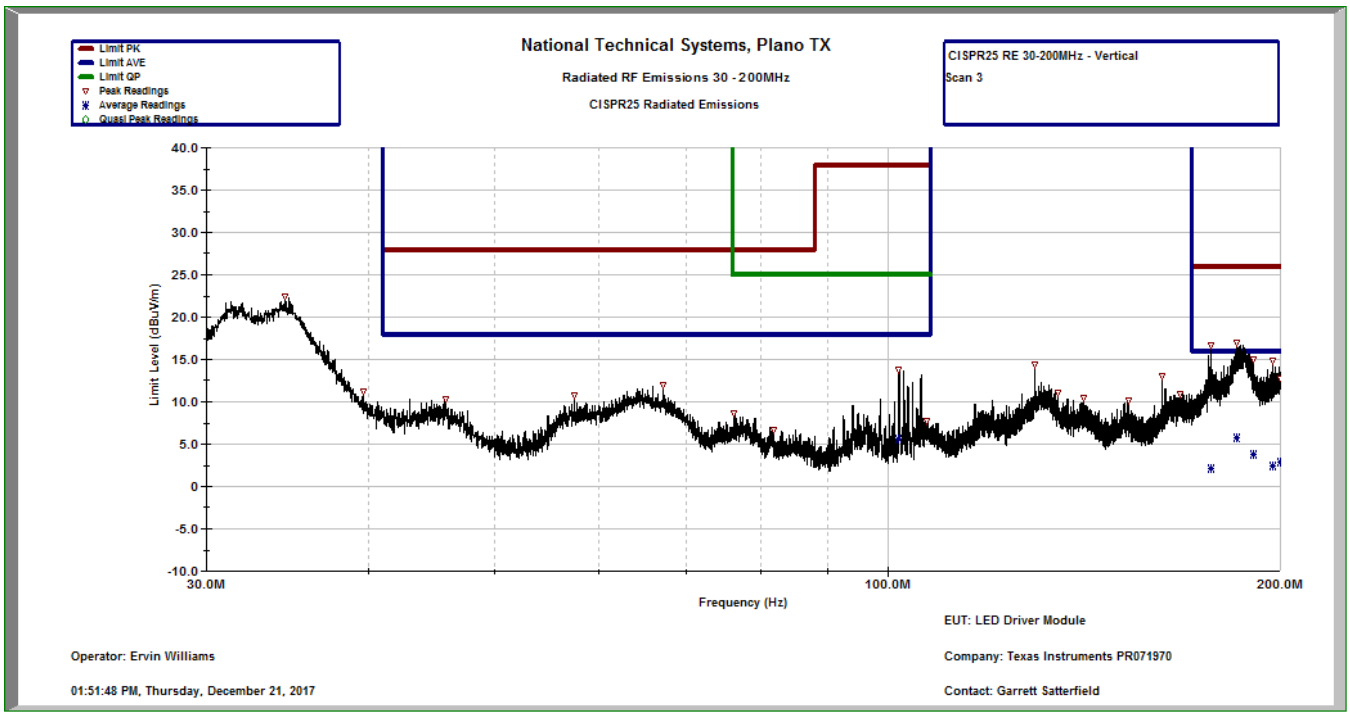

Figure 30. CISPR25 Class-5 Radiated Emissions: 30 MHz to 200 MHz (Vertical)

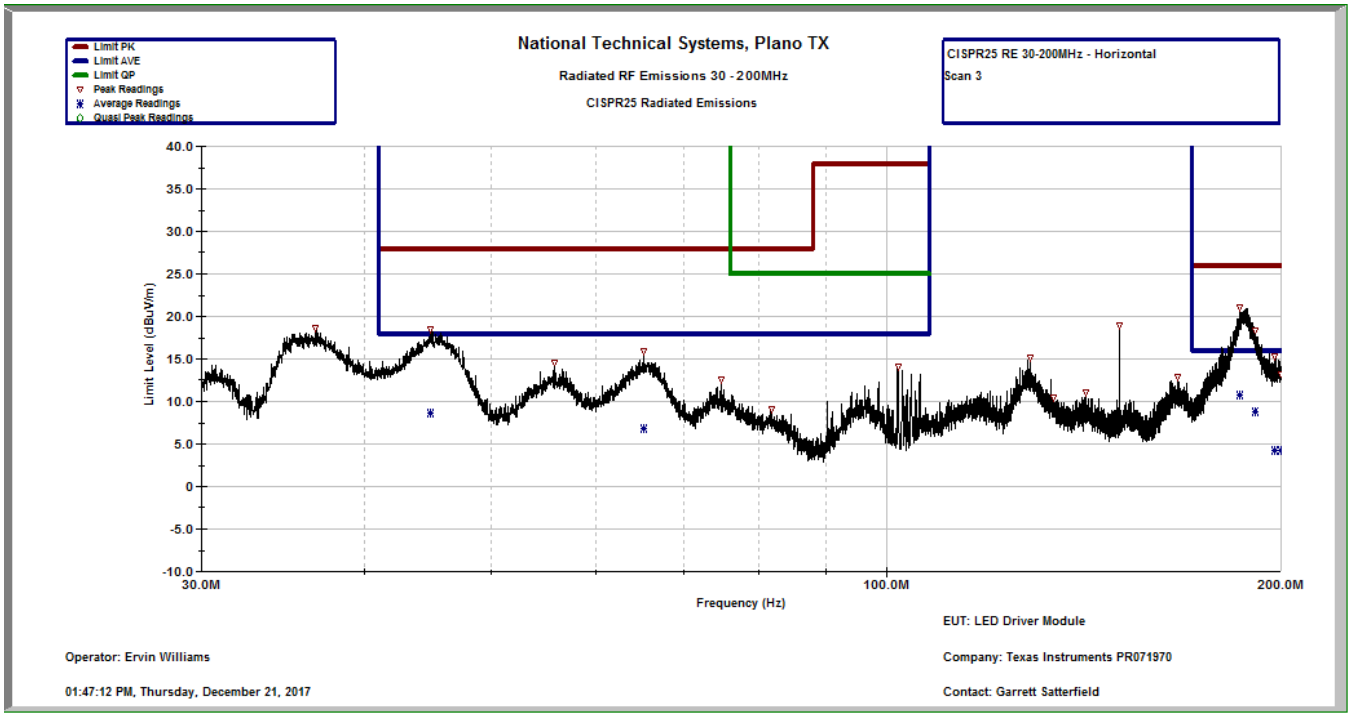

Figure 31. CISPR25 Class-5 Radiated Emissions: 30 MHz to 200 MHz (Horizontal)

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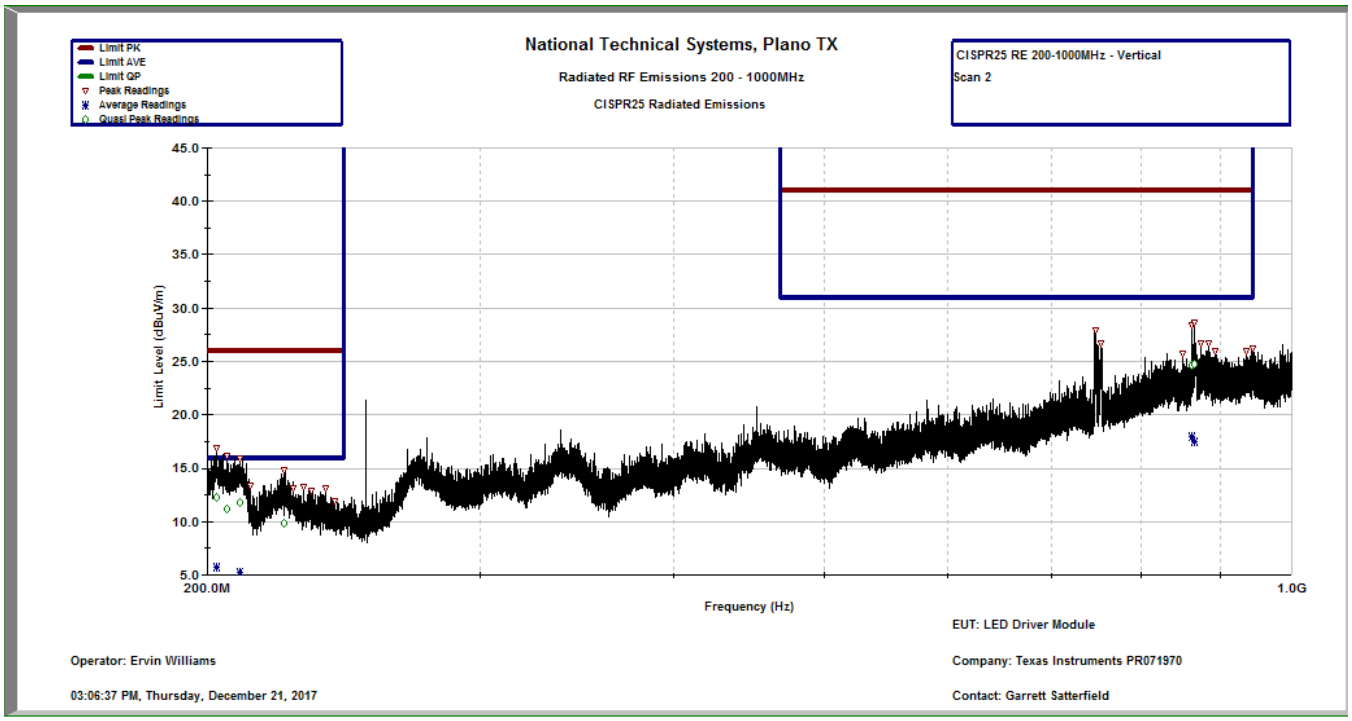

Figure 32. CISPR25 Class-5 Radiated Emissions: 200 MHz to 1 GHz (Vertical)

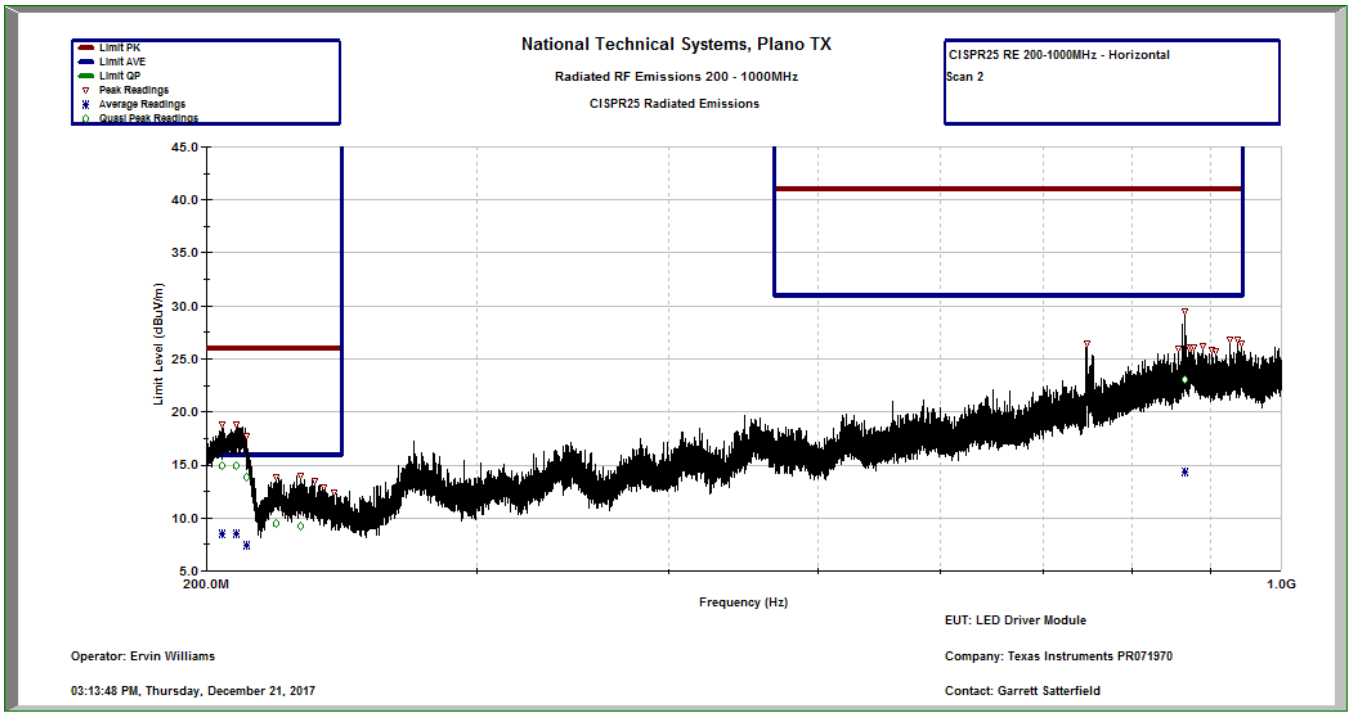

Figure 33. CISPR25 Class-5 Radiated Emissions: 200 MHz to 1 GHz (Horizontal)

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3.2.6 EMI Testing Shielded Inductors

Additional tests were completed using shielded inductors instead of the standard inductors. Figure 34 shows how the shielded inductors were mounted to the board. The inductors used were Cyntec VCMT053-T-100MN5 (shielded). These inductors included two extra PCB connections that attach to ground and connect to the metal shield that covers the inductor.

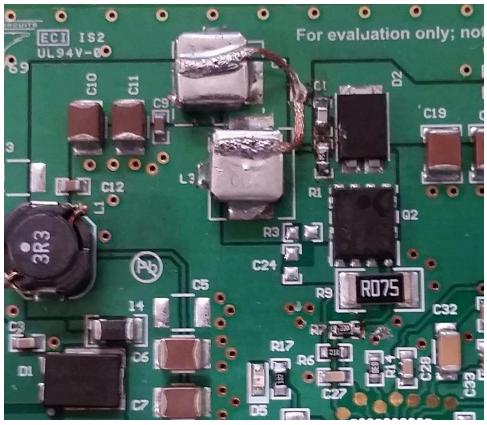

Figure 34. TIDA-01581 With Shielded Inductors Mounted (Cyntec VCMT053T-100MN5 Shielded)

Figure 35 shows an example of the results. Note the 2- to 3-dB improvement over some frequency ranges as compared to using unshielded inductors (see for comparison). Consider using shielded inductors if more margin is required between the test data and limit lines.

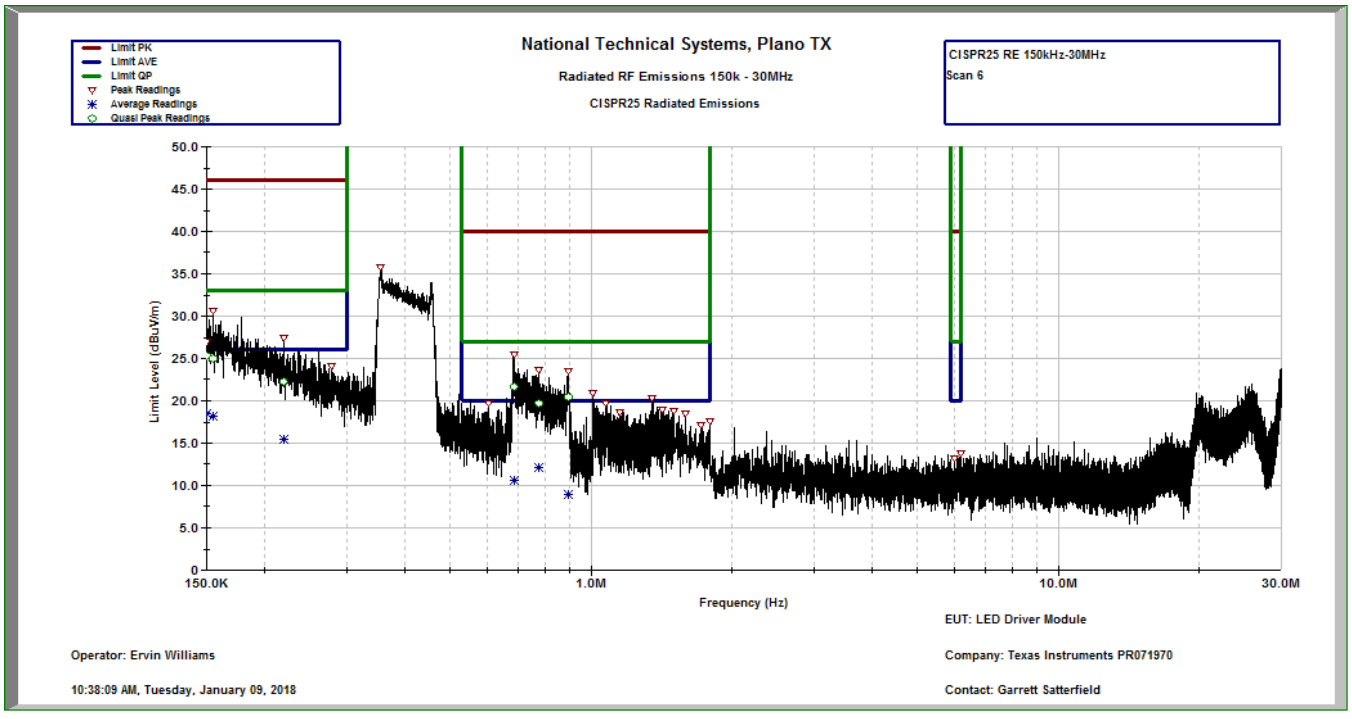

Figure 35. CISPR25 Class-5 Radiated Emissions: 150 kHz to 30 MHz With Shielded Inductors

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4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01581.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01581.

4.3 PCB Layout Recommendations

Use the following layout recommendations for optimal circuit and EMI performance:

- Use low equivalent series resistance (ESR) decoupling capacitors and place them as close to the IC pin as possible.
- Use copper pours in the boost converter component section instead of traces.
- Keep the output loop formed by the rectification diode, output capacitors, and low-side sense resistor as small as possible, as this is a discontinuous current path with high di/dt.
- Ensure that the traces cut as little as possible from the second-layer ground plane and that they do not cut in the path of the return current.
- Place the analog circuitry away from the switching power supply components.
- Keep the feedback traces that connect to CSP and CSN as short as possible.

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01581.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01581.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01581.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01581.

5 Software Files

To download the software files, see the design files at TIDA-01581.

6 Related Documentation

1. Texas Instruments, *Minimizing Ringing at the Switch Node of a Boost Converter* Application Report
2. Texas Instruments, *Driving Daytime Running Lights LEDs With Thermal Foldback Reference Design*
3. Texas Instruments, *0-W, Dual-Stage LED Driver Reference Design With Pre- Boost Control for Automotive Headlights*

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7 Terminology

CMOS— Complementary metal–oxide–semiconductor

'DRL'— Full brightness mode

EMI— Electromagnetic interference

ESR— Equivalent series resistance

FET— Field-effect transistor

LED— Light-emitting diode

MCU— Microcontroller unit

MOSFET— Metal-oxide-semiconductor field-effect transistor

NTC— Negative temperature coefficient

Op Amp—Operational amplifier

PCB— Printed-circuit board

'Position'— PWM dimming mode

PWM— Pulse-width modulation

SMPS— Switched-mode power supply

8 About the Author

GARRETT SATTERFIELD is an applications engineer at Texas Instruments where he is responsible for developing reference designs for automotive systems. Garrett received his BSEE from The Georgia Institute of Technology in 2016.

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