



# TPS92511 500-mA, 65-V Common Anode Constant Current Buck LED Driver Without External Current Sensing Resistor

## 1 Features

- Wide Input Voltage Range: 4.5 V to 65 V
- Requires NO External Current Sensing Resistor
- Requires NO External Loop Compensation
- Ease of Use, Needs Minimum 5 Components
- 1000:1 Contrast Ratio Feasible
- Single Layer PCB Feasible
- Can Work as High Voltage Buck Regulators
- Can Work as Linear Current Shunt Regulators
- Integrated Low-side N-channel MOSFET
- LED Current Programmable up to 0.5 A
- Typically  $\pm 3.6\%$  LED Current Accuracy
- Switching Frequency Programmable From 50 kHz to 500 kHz
- Current Limit Protection
- VCC Under-voltage Lock-out
- Thermal Shutdown Protection
- Support Analog Dimming and Thermal Foldback
- Power Enhanced SOIC-8 Exposed Thermal Pad Package (HSOP-8)

## 2 Applications

- High Power LED Driver
- Architectural Lighting
- Office Troffer
- Automotive Lighting
- MR-16 LED Lamp

## 3 Description

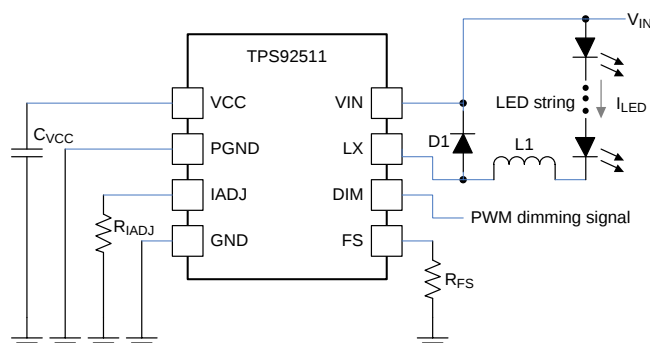
The TPS92511 is an easy to use 65V constant current buck converter for driving a single LED string with current up to 0.5A and efficiency up to 95%. Only 5 external components are required for basic operation and single layer PCB layout is feasible because of the integration of a N-MOSFET, no external current sensing resistor, no external compensation and the proper terminal assignment. A high-value external resistor programs the LED current so that fine tuning of the LED current can be achieved. Another high-value external resistor programs a constant switching frequency from 50kHz to 500kHz. EMI design becomes easier as a result of constant switching frequency. The TPS92511 provides a wide input voltage range from 4.5V to 65V. By adding simple external circuits, the device can handle applications with even higher input voltages.

The TPS92511 employs a proprietary control scheme to regulate the LED current without the need of sensing the LED current directly. It applies a floating buck topology with a low-side N-channel power MOSFET, which does not need boot-strapping capacitor. For multiple channel systems, the floating buck topology together with the proprietary control scheme allows a common-anode connection of the LED strings without an external current sensing network. This significantly reduces the number of wiring and as well as overall manufacturing cost.

The TPS92511 has very fast PWM dimming response time. For example, if the switching frequency is 500 kHz, the minimum DIM pulse width is 6 $\mu$ s and the dimming frequency is 150Hz, a contrast ratio of more than 1000:1 can be achieved.

The TPS92511 is available in the Power Enhanced SOIC-8 exposed thermal pad package.

**Simplified Application**



**Device Information<sup>(1)</sup>**

| PART NUMBER | PACKAGE  | BODY SIZE (NOM) |
|-------------|----------|-----------------|
| TPS92511    | HSOP (8) | 4.89mm × 3.90mm |

(1) For all available packages, see the orderable addendum at the end of the datasheet.



## Table of Contents

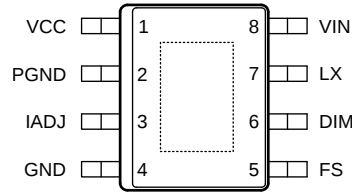
|                                                |          |                                                  |           |
|------------------------------------------------|----------|--------------------------------------------------|-----------|
| <b>1 Features</b> .....                        | <b>1</b> | 7.3 Feature Description.....                     | 10        |
| <b>2 Applications</b> .....                    | <b>1</b> | 7.4 Device Functional Modes.....                 | 17        |
| <b>3 Description</b> .....                     | <b>1</b> | <b>8 Application and Implementation</b> .....    | <b>18</b> |
| <b>4 Revision History</b> .....                | <b>2</b> | 8.1 Application Information.....                 | 18        |
| <b>5 Pin Configuration and Functions</b> ..... | <b>3</b> | 8.2 Typical Application .....                    | 18        |
| <b>6 Specifications</b> .....                  | <b>4</b> | <b>9 Power Supply Recommendation</b> .....       | <b>21</b> |
| 6.1 Absolute Maximum Ratings .....             | 4        | <b>10 Layout</b> .....                           | <b>22</b> |
| 6.2 Handling Ratings.....                      | 4        | 10.1 Layout Guidelines .....                     | 22        |
| 6.3 Recommended Operating Conditions .....     | 4        | 10.2 Layout Example .....                        | 22        |
| 6.4 Thermal Information .....                  | 4        | <b>11 Device and Documentation Support</b> ..... | <b>23</b> |
| 6.5 Electrical Characteristics.....            | 5        | 11.1 Trademarks .....                            | 23        |
| 6.6 Typical Characteristics.....               | 6        | 11.2 Electrostatic Discharge Caution.....        | 23        |
| <b>7 Detailed Description</b> .....            | <b>8</b> | 11.3 Glossary .....                              | 23        |
| 7.1 Overview .....                             | 8        | <b>12 Mechanical, Packaging, and Orderable</b>   |           |
| 7.2 Functional Block Diagram .....             | 9        | <b>Information</b> .....                         | <b>23</b> |

## 4 Revision History

| Changes from Original (March 2014) to Revision A | Page |
|--------------------------------------------------|------|
| • Corrected figure number sequencing .....       | 1    |
| • Updated the Device Information Table .....     | 1    |
| • Changed Terminal to Pin.....                   | 3    |

## 5 Pin Configuration and Functions

**DDA (SO THERMAL PAD) PACKAGE  
8 PINS  
(TOP VIEW)**



**Pin Functions**

| PIN         |     | DESCRIPTION                                                                                                                                                   |
|-------------|-----|---------------------------------------------------------------------------------------------------------------------------------------------------------------|
| NAME        | NO. |                                                                                                                                                               |
| DIM         | 6   | PWM Dimming Control. Apply logic level PWM signal to this pin dims the LED string. This pin is internally pulled up.                                          |
| FS          | 5   | Switching Frequency Setting. An external resistor $R_{FS}$ connecting the FS pin to ground programs the switching frequency from 50 kHz to 500 kHz.           |
| GND         | 4   | Analog Signal Ground.                                                                                                                                         |
| IADJ        | 3   | Average LED Current Setting. An external resistor $R_{IADJ}$ connecting the IADJ pin to ground programs the average LED current.                              |
| LX          | 7   | Integrated MOSFET Drain. Internally connected to the drain of the integrated MOSFET. Connect this pin to the output inductor and anode of the Schottky diode. |
| PGND        | 2   | Power Ground. Must be connected to the GND pin for normal operation. The PGND and GND pins are not internally shorted.                                        |
| VCC         | 1   | Internal Regulator Output. Typically regulated to 5.4 V. Connect a capacitor of larger than 1 $\mu$ F between the VCC and GND pins.                           |
| VIN         | 8   | Input Voltage. Supply pin to the device. The input voltage range is from 4.5 V to 65 V.                                                                       |
| Thermal pad |     | Thermal Connection Pad. Connect to a ground plane for heat dissipation.                                                                                       |

## 6 Specifications

### 6.1 Absolute Maximum Ratings <sup>(1)</sup>

Unless otherwise specified,  $T_J = T_A = 25^{\circ}\text{C}$

|                   |                                             | MIN     | NOM | MAX                | UNIT               |
|-------------------|---------------------------------------------|---------|-----|--------------------|--------------------|
| Pin voltage range | VIN to GND                                  | −0.3    |     | 65                 | V                  |
|                   | VIN to GND (Transient)                      | −0.3    |     | 67                 | V                  |
|                   | LX to PGND                                  | −0.3    |     | 65                 | V                  |
|                   | LX to PGND (Transient)                      | −3(2ns) |     | 67                 | V                  |
|                   | FS, IADJ to GND                             | −0.3    |     | 5                  | V                  |
|                   | DIM to GND                                  | −0.3    |     | 6                  | V                  |
|                   | VCC to GND                                  | −0.3    |     | 7                  | V                  |
| Temperature range | Operating junction temperature range, $T_J$ | −40     |     | Internally limited | $^{\circ}\text{C}$ |

- (1) Absolute Maximum Ratings are limits beyond which damage to the device may occur. Operating Ratings are conditions under which operation of the device is intended to be functional. For specified specifications and test conditions, see the Electrical Characteristics.

### 6.2 Handling Ratings

|                        |                                                              | MIN | MAX | UNIT               |
|------------------------|--------------------------------------------------------------|-----|-----|--------------------|
| $T_{\text{stg}}$       | Storage temperature range                                    | −65 | 150 | $^{\circ}\text{C}$ |
| $V_{\text{ESD}}^{(1)}$ | Human Body Model (HBM) ESD stress voltage <sup>(2)</sup>     |     | 1.5 | kV                 |
|                        | Charged Device Model (CDM) ESD stress voltage <sup>(3)</sup> |     | 1.5 | kV                 |

- (1) Electrostatic discharge (ESD) to measure device sensitivity and immunity to damage caused by assembly line electrostatic discharges in to the device.  
 (2) Level listed above is the passing level per ANSI, ESDA, and JEDEC JS-001. JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.  
 (3) Level listed above is the passing level per EIA-JEDEC JESD22-C101. JEDEC document JEP157 states that 250-V CDM allows safe manufacturing with a standard ESD control process.

### 6.3 Recommended Operating Conditions

|                 |                                | MIN | NOM | MAX | UNIT               |
|-----------------|--------------------------------|-----|-----|-----|--------------------|
| $V_{\text{IN}}$ | Supply voltage range           | 4.5 |     | 65  | V                  |
| $T_A$           | Operating free air temperature | −40 |     | 125 | $^{\circ}\text{C}$ |
| $T_J$           | Operating junction temperature | −40 |     | 125 | $^{\circ}\text{C}$ |

### 6.4 Thermal Information

| THERMAL METRIC <sup>(1)</sup> |                                              | TPS92511 | UNIT |
|-------------------------------|----------------------------------------------|----------|------|
|                               |                                              | DDA      |      |
|                               |                                              | 8 PINS   |      |
| R <sub>θJA</sub>              | Junction-to-ambient thermal resistance       | 59.9     | °C/W |
| R <sub>θJCTop</sub>           | Junction-to-case (top) thermal resistance    | 59.1     |      |
| R <sub>θJB</sub>              | Junction-to-board thermal resistance         | 30.6     |      |
| ψ <sub>JT</sub>               | Junction-to-top characterization parameter   | 11.0     |      |
| ψ <sub>JB</sub>               | Junction-to-board characterization parameter | 30.5     |      |
| R <sub>θJChot</sub>           | Junction-to-case (bottom) thermal resistance | 4.2      |      |

- (1) For more information about traditional and new thermal metrics, see the *IC Package Thermal Metrics* application report, [SPRA953](#).

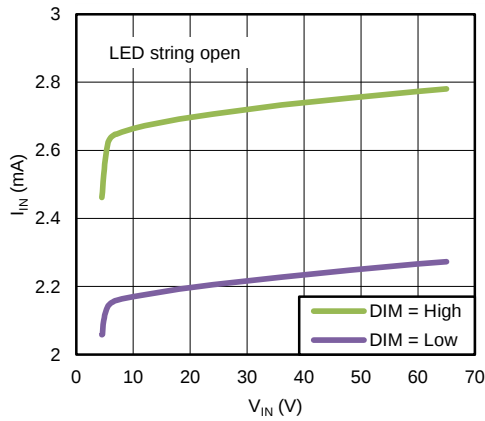
## 6.5 Electrical Characteristics

Unless otherwise specified,  $-40^{\circ}\text{C} \leq T_J = T_A \leq 125^{\circ}\text{C}$ ,  $V_{IN} = 48\text{ V}$

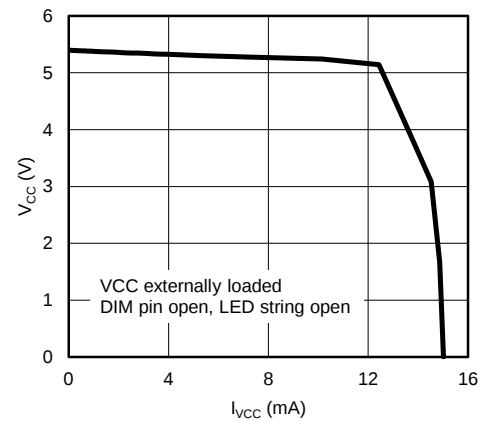
| PARAMETER                 |                              | CONDITIONS                                                                                            | MIN   | TYP  | MAX   | UNIT               |
|---------------------------|------------------------------|-------------------------------------------------------------------------------------------------------|-------|------|-------|--------------------|
| <b>SYSTEM</b>             |                              |                                                                                                       |       |      |       |                    |
| $I_{IN-DIM-HIGH}$         | VIN Operating Current        | $4.5\text{ V} \leq V_{IN} \leq 65\text{ V}$ , $R_{IADJ} = 3\text{ k}\Omega$ , $V_{DIM} = \text{High}$ |       | 2.8  | 3.15  | mA                 |
| $I_{IN-DIM-LOW}$          | VIN Standby Current          | $4.5\text{ V} \leq V_{IN} \leq 65\text{ V}$ , $R_{IADJ} = 3\text{ k}\Omega$ , $V_{DIM} = \text{Low}$  |       | 2.3  | 2.7   | mA                 |
| $I_{LX-OFF}$              | LX Pin Current               | Main switch turned OFF, $V_{LX} = V_{IN} = 65\text{ V}$                                               |       | 0.1  | 1.0   | $\mu\text{A}$      |
| $I_{LED}$                 | Average LED Current          | $V_{FS} = 4.6\text{V}$ , $R_{IADJ} = 3\text{ k}\Omega$ , $T_A = 25^{\circ}\text{C}$                   | 484   | 502  | 520   | mA                 |
|                           |                              | $V_{FS} = 4.6\text{V}$ , $R_{IADJ} = 3\text{ k}\Omega$                                                | 477   | 502  | 528   | mA                 |
|                           |                              | $V_{FS} = 4.6\text{V}$ , $R_{IADJ} = 6\text{ k}\Omega$ , $T_A = 25^{\circ}\text{C}$                   | 236   | 249  | 262   | mA                 |
|                           |                              | $V_{FS} = 4.6\text{V}$ , $R_{IADJ} = 6\text{ k}\Omega$                                                | 233   | 249  | 268   | mA                 |
|                           |                              | $V_{FS} = 4.6\text{V}$ , $R_{IADJ} = 10\text{ k}\Omega$ , $T_A = 25^{\circ}\text{C}$                  | 138   | 149  | 160   | mA                 |
|                           |                              | $V_{FS} = 4.6\text{V}$ , $R_{IADJ} = 10\text{ k}\Omega$                                               | 133   | 149  | 166   | mA                 |
| $V_{IADJ}$                | IADJ Pin voltage             |                                                                                                       | 1.224 | 1.25 | 1.278 | V                  |
| $V_{DIM-ON}$              | DIM Pin Upper Threshold      | $V_{DIM}$ Increasing                                                                                  | 0.85  | 1.0  | 1.25  | V                  |
| $V_{DIM-OFF}$             | DIM Pin Lower Threshold      | $V_{DIM}$ Decreasing                                                                                  | 0.44  |      |       | V                  |
| $V_{DIM-HYS}$             | DIM Pin Threshold Hysteresis |                                                                                                       |       | 325  |       | mV                 |
| $f_{SW}$                  | Switching frequency          | $R_{FS} = 20\text{ k}\Omega$                                                                          | 450   | 500  | 550   | kHz                |
| $t_{on(min)}$             | Minimum On-time              |                                                                                                       |       | 250  | 400   | ns                 |
| <b>INTERNAL REGULATOR</b> |                              |                                                                                                       |       |      |       |                    |
| $V_{CC}$                  | VCC Regulated Output Voltage | $C_{VCC} = 1\text{ }\mu\text{F}$ , no load                                                            | 4.7   | 5.4  | 6.0   | V                  |
|                           |                              | $C_{VCC} = 1\text{ }\mu\text{F}$ , $V_{IN} = 4.5\text{V}$ , 2 mA load                                 | 3.7   | 4.1  |       | V                  |
| $V_{CC-UVLO-ON}$          | VCC UVLO Upper Threshold     | $V_{CC}$ rising                                                                                       | 3.50  | 3.75 | 4.00  | V                  |
| $V_{CC-UVLO-OFF}$         | VCC UVLO Lower Threshold     | $V_{CC}$ falling                                                                                      | 3.05  |      |       | V                  |
| $V_{CC-UVLO-HYS}$         | VCC UVLO Hysteresis          |                                                                                                       |       | 275  |       | mV                 |
| <b>INTEGRATED MOSFET</b>  |                              |                                                                                                       |       |      |       |                    |
| $R_{LX}$                  | Resistance Across LX and GND | Main Switch Turned ON, $T_A = 25^{\circ}\text{C}$                                                     |       | 1.4  | 2.15  | $\Omega$           |
| <b>THERMAL SHUTDOWN</b>   |                              |                                                                                                       |       |      |       |                    |
| $T_{SD}$                  | Thermal shutdown temperature | $T_J$ Rising                                                                                          |       | 165  |       | $^{\circ}\text{C}$ |
| $T_{SD-HYS}$              | Thermal shutdown hysteresis  | $T_J$ Falling                                                                                         |       | 10   |       |                    |

## 6.6 Typical Characteristics

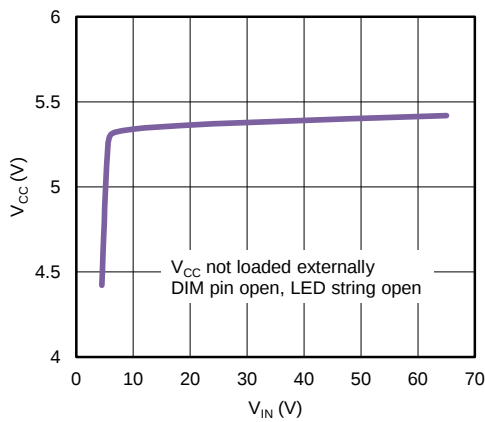
Unless otherwise specified, all curves are taken at  $V_{IN} = 48V$  with configuration in the application circuit for driving 12 LEDs with  $I_{LED} = 0.5A$  and  $f_{SW} = 300\text{ kHz}$  as shown in this datasheet, and  $T_A = 25^\circ C$ .



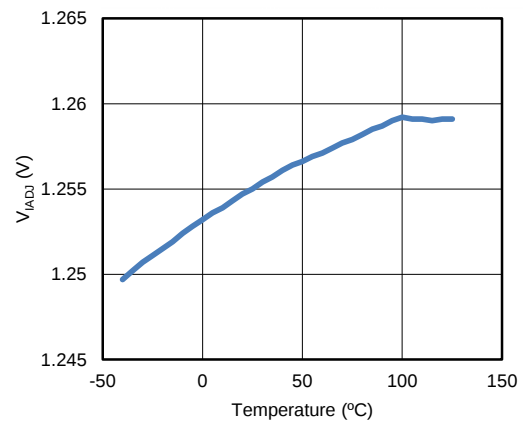
**Figure 1.  $I_{IN}$  vs  $V_{IN}$**



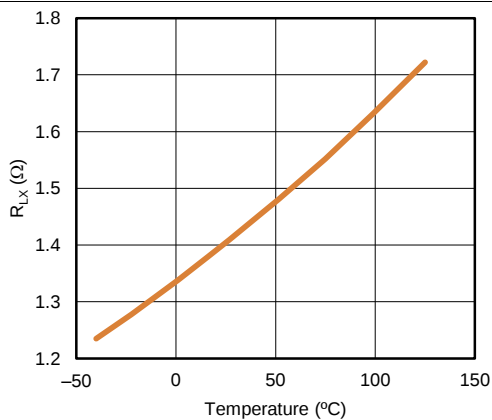
**Figure 2.  $V_{CC}$  vs  $I_{VCC}$**



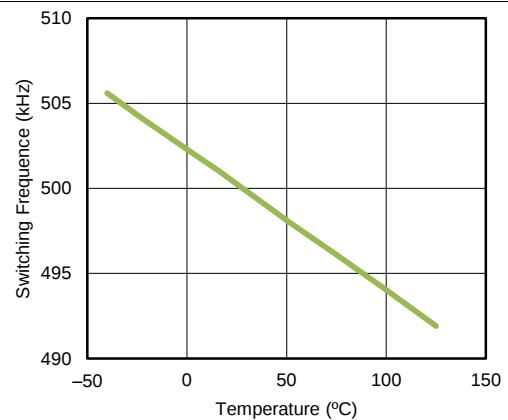
**Figure 3.  $V_{CC}$  vs  $V_{IN}$**



**Figure 4.  $V_{IADJ}$  vs Temperature**



**Figure 5.  $R_{LX}$  vs Temperature**



**Figure 6.  $f_{SW}$  vs Temperature**

## Typical Characteristics (continued)

Unless otherwise specified, all curves are taken at  $V_{IN} = 48V$  with configuration in the application circuit for driving 12 LEDs with  $I_{LED} = 0.5A$  and  $f_{SW} = 300\text{ kHz}$  as shown in this datasheet, and  $T_A = 25^\circ C$ .

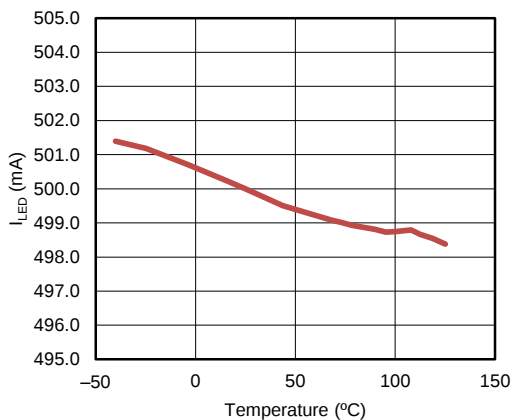


Figure 7.  $I_{LED}$  at 500 mA vs Temperature

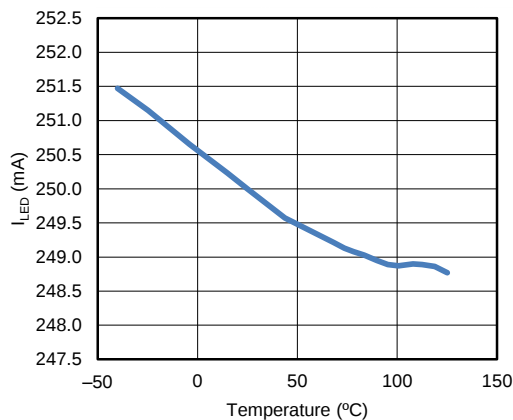


Figure 8.  $I_{LED}$  at 250 mA vs Temperature

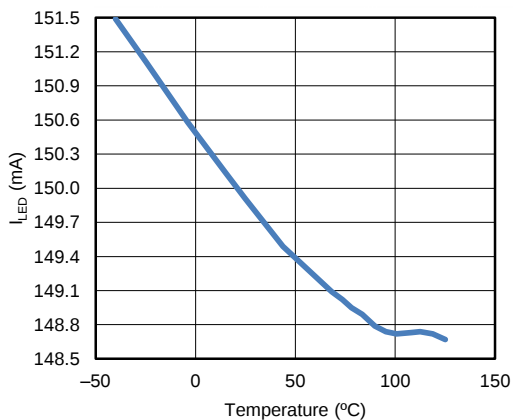


Figure 9.  $I_{LED}$  at 150 mA vs Temperature

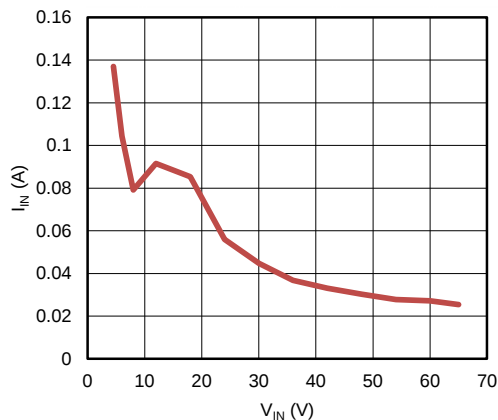


Figure 10.  $I_{IN}$  vs  $V_{IN}$  at LED Short

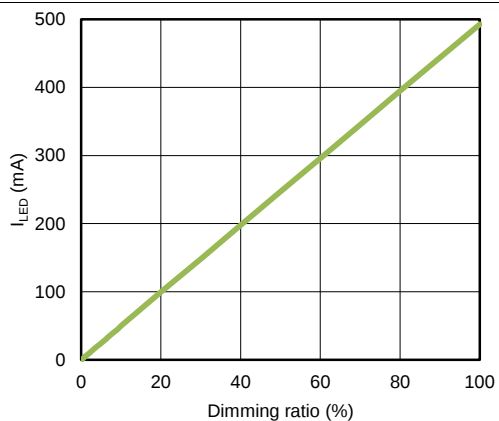


Figure 11. PWM Dimming Linearity (0-100%) ( $f_{SW} = 500\text{kHz}$ ,  $L1 = 68\text{ }\mu\text{H}$ )

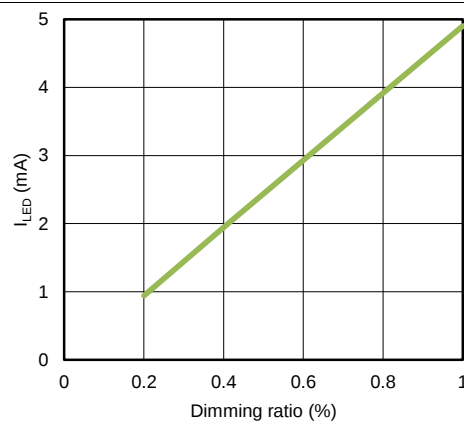


Figure 12. PWM Dimming Linearity (under 1%) ( $f_{SW} = 500\text{kHz}$ ,  $L1 = 68\text{ }\mu\text{H}$ )

## 7 Detailed Description

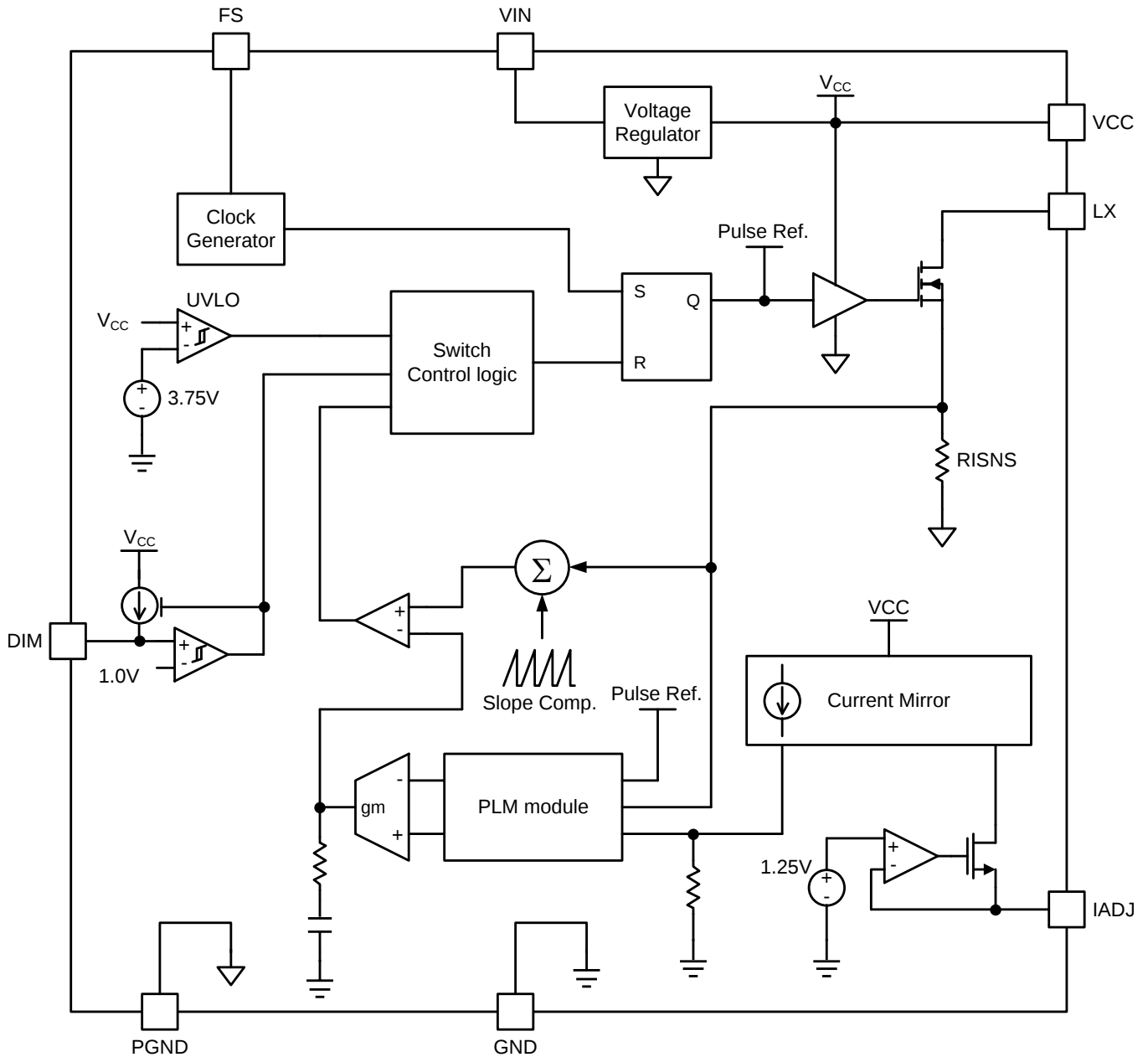
### 7.1 Overview

The TPS92511 is an easy to use constant current buck converter for driving a single LED string with current up to 0.5A and efficiency up to 95%. Only 5 external components are required for basic operation and single layer PCB layout is feasible because of the integration of a N-MOSFET, no external current sensing resistor, no external compensation and the proper pin assignment. A high-value external resistor programs the LED current so that fine tuning of the LED current can be achieved. Another high-value external resistor programs a constant switching frequency from 50kHz to 500kHz. As a result of constant switching frequency, EMI design becomes easy. The TPS92511 provides a wide input voltage range from 4.5V to 65V. By adding simple external circuits, it can handle applications with even higher input voltages.

The TPS92511 employs a proprietary Pulse-Level-Modulation (PLM) control scheme under continuous conduction mode (CCM) to regulate the LED current without the need of sensing the LED current directly. It applies a floating buck topology with a low-side N-channel power MOSFET, which does not need boot-strapping capacitor, so that driving LED string under drop-out conditions and very high input voltages are feasible. For multiple channel systems, the floating buck topology without external current sensing network together with the proprietary control scheme allows a common-anode connection of the LED strings without external current sensing network. This saves high-side current sensing wirings for separate driver boards and LED board systems and significantly reduces the number of wiring, which can lower overall manufacturing cost.

The TPS92511 has very fast PWM dimming response time. There is almost no delay between the DIM pin voltage rising edge and the start of the LED current conduction, so it can dim down to nearly zero current. In order to maintain good dimming linearity, the minimum LED current pulse width is suggested to be three switching cycles. For example, if the switching frequency is 500 kHz, the minimum DIM pulse width is 6 $\mu$ s and the dimming frequency is 150Hz, a contrast ratio of more than 1000:1 can be achieved.

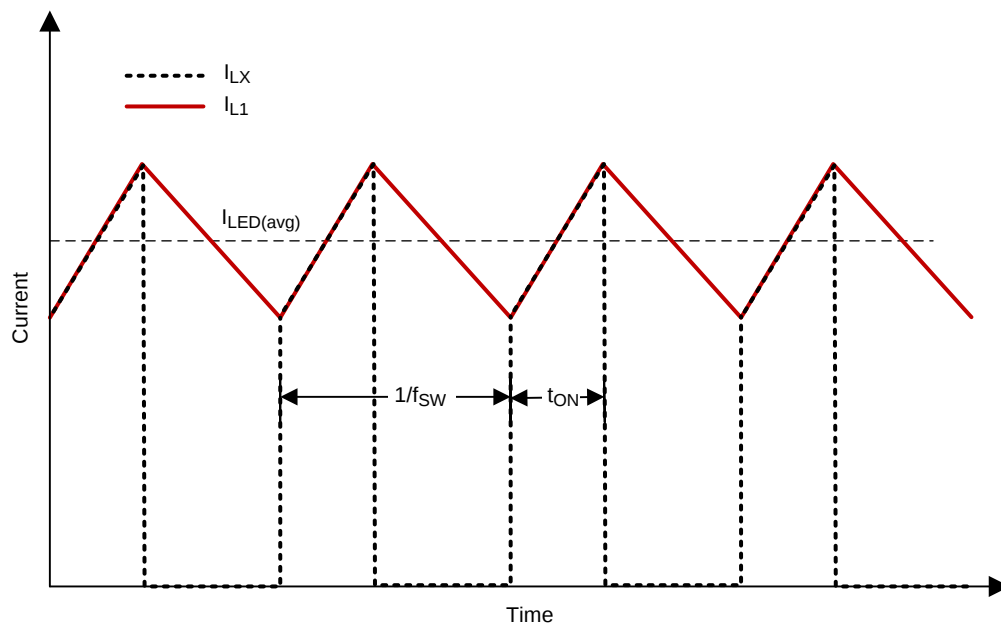
## 7.2 Functional Block Diagram



## 7.3 Feature Description

### 7.3.1 Pulse Level Modulation (PLM) Control

A proprietary Pulse-Level-Modulation (PLM) control method is used in the TPS92511. It can regulate the average LED current by sensing only the inductor current at the on-period (Figure 13). The integrated MOSFET and the sensing and control circuits in the TPS92511 implement the whole PLM control internally so the control does not suffer from tolerance and noise issues that may be coming from external components. As compared with the conventional method which regulates average LED current by sensing the current over the entire switching cycle, the power dissipation on the sensing circuit in PLM is much lower. For example, consider a duty cycle of 0.5, the power dissipation on current sensing in PLM can be reduced by half. PLM requires no external loop compensation circuit. Besides, the accuracy of the regulated LED current is high (typically  $\pm 3.5\%$  in the TPS92511).



**Figure 13. Waveforms of a Floating Buck LED Driver with PLM**

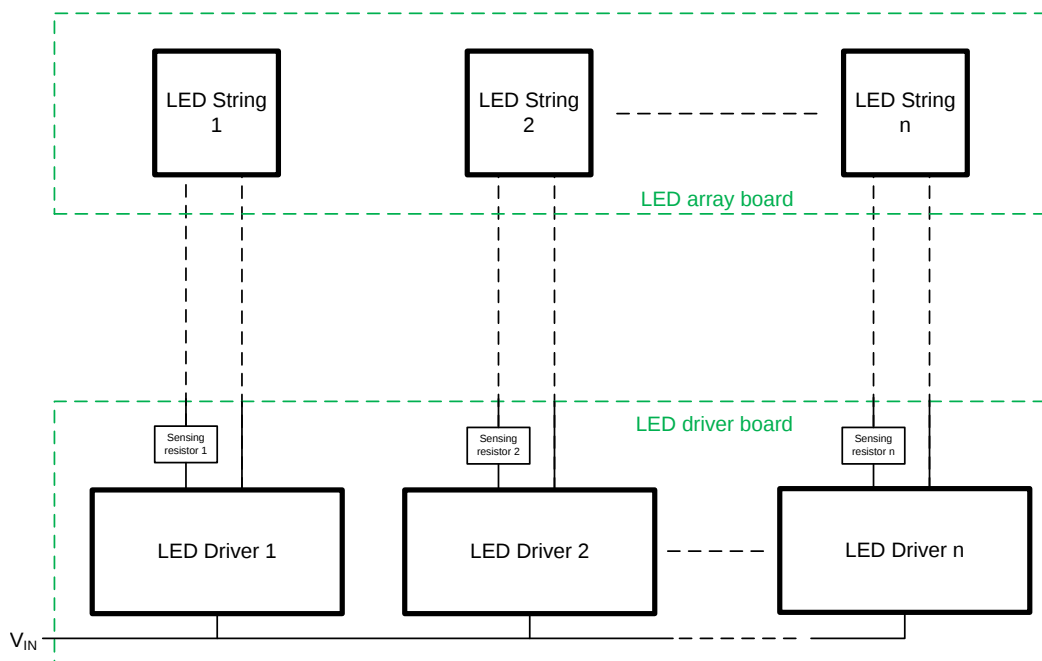
### 7.3.2 Pulse Level Modulation (PLM) Operation Principles

The Pulse-Level-Modulation is a patented method to ensure an accurate average output current regulation without the need of direct output current sensing. Figure 13 shows the current waveforms of a typical buck converter under steady state, where,  $I_{L1}$  is the inductor current and  $I_{LX}$  is the current flowing into the LX pin. For a buck converter operating in steady state, the mid-point of the RAMP portion of  $I_{L1}$  equals to the average value of  $I_{L1}$  and hence the average LED current  $I_{LED(avg)}$ . In short, by regulating the mid-point with respect to a precise reference level, PLM achieves LED current regulation by sensing the main MOSFET current solely, instead of the entire cycle of  $I_{L1}$ .

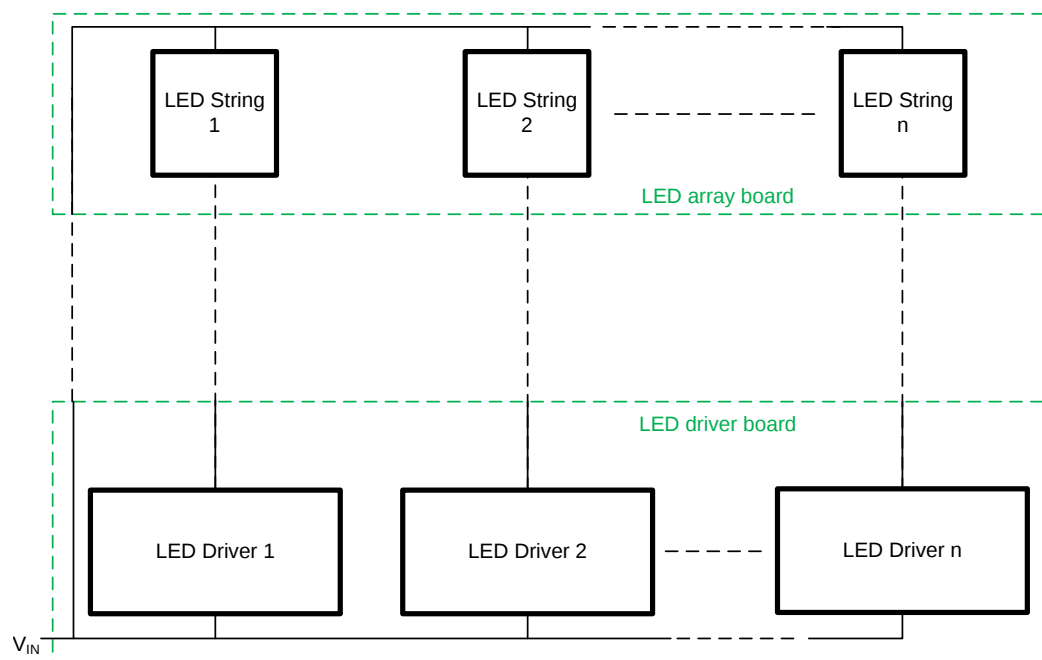
### 7.3.3 PLM Control enable Common-Anode Low-Side Sensing (CALS) Technique to Save Wiring

For multi-channel systems with separated driver boards and LED array boards, the Pulse-Level-Modulation (PLM) control scheme enable Common-Anode Low-Side Current Sensing to save inter-board wirings. Figure 14 shows a conventional configuration with a Low-side switching and High-Side Current Sensing. For an n channel system with separated driver and an LED array boards, 2n inter-board wirings are required. For example, an 128-channel system needs 256 inter-board wirings, which implies a high material and manufacturing cost. Figure 15 shows the PLM configuration with Low-side switching and Low-Side Current Sensing. A Common-Anode configuration is used for the LED array board. As shown in the figure, an n channel system with separated driver and LED array boards requires only n+1 inter-board wirings. For an 128-channel system, only 129 inter-board wirings are required. The wiring cost is cut by half, and the cost of the end product can be reduced.

## Feature Description (continued)



**Figure 14. Conventional Configuration with Low-Side Switching and High-Side Current Sensing Requires 2xn Inter-Board Wirings**



**Figure 15. PLM Configuration with Common-Anode Low-Side Switching Requires n+1 Inter-Board Wirings**

## Feature Description (continued)

### 7.3.4 Internal Regulator

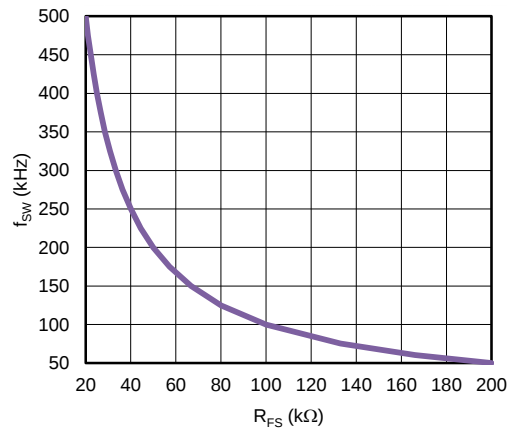
The TPS92511 integrates an internal voltage regulator for powering internal circuitry. For stability, an external capacitor  $C_{VCC}$  of at least 1  $\mu\text{F}$  should be connected between the VCC and PGND pins. The output of the internal regulator  $V_{CC}$  is 5.4V when  $V_{IN}$  is larger than 6V. If  $V_{IN}$  is lower than 6V,  $V_{CC}$  decreases. The TPS92511 will trigger the VCC under-voltage lock-out if  $V_{CC}$  falls below typically 3.5V.  $V_{CC}$  can be used to bias external circuits subject to a loading of maximum 2 mA, while it has a short circuit current limit at typically 16 mA.

### 7.3.5 Setting The Switching Frequency

The switching frequency  $f_{SW}$  of the TPS92511 is programmable in the range of 50 kHz to 500 kHz by a single resistor  $R_{FS}$  connecting the FS pin and ground. The following equation shows the relationship between  $f_{SW}$  and  $R_{FS}$ :

$$f_{SW} = \frac{10 \times 10^6}{R_{FS}} \text{ kHz} \quad (1)$$

Figure 16 plots  $f_{SW}$  against  $R_{FS}$ . Table 1 shows values of  $R_{FS}$  for commonly used switching frequencies.



**Figure 16. Switching Frequency vs  $R_{FS}$**

**Table 1. Commonly Used  $f_{SW}$  And  $R_{FS}$**

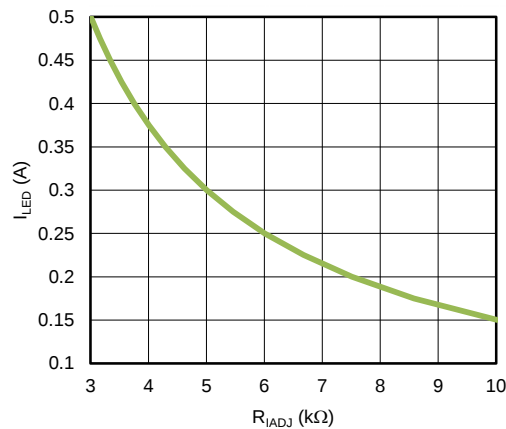
| $f_{SW}$ (kHz) | $R_{FS}$ (kΩ) |
|----------------|---------------|
| 50             | 200           |
| 100            | 100           |
| 300            | 33.2          |
| 500            | 20            |

### 7.3.6 Setting The LED Current

The LED current  $I_{LED}$  of the TPS92511 is programmable by a single resistor  $R_{IADJ}$  connecting the IADJ pin and ground. The IADJ pin is internally biased to 1.25 V. Equation 2 shows the relationship between  $I_{LED}$  and  $R_{IADJ}$ :

$$I_{LED} = \frac{1500}{R_{IADJ}} \text{ A} \quad (2)$$

To ensure stability,  $R_{IADJ}$  must be less than 30 kΩ, implying a minimum  $I_{LED}$  of 50 mA can be programmed. The tolerance of  $I_{LED}$  of 150 mA is shown in the ELECTRICAL CHARACTERISTICS. Larger tolerance should be expected for lower  $I_{LED}$ . Figure 17 plots  $I_{LED}$  against  $R_{IADJ}$ . Table 2 shows values of  $R_{IADJ}$  for commonly used  $I_{LED}$ .



**Figure 17. LED Current vs R<sub>IADJ</sub>**

**Table 2. Commonly Used I<sub>LED</sub> And R<sub>IADJ</sub>**

| I <sub>LED</sub> (mA) | R <sub>IADJ</sub> (kΩ) |
|-----------------------|------------------------|
| 150                   | 10                     |
| 350                   | 4.32                   |
| 500                   | 3.01                   |

### 7.3.7 Integrated MOSFET

The TPS92511 integrates a N-channel power MOSFET, the drain of which is connected to the LX pin. When the integrated MOSFET is turned on, the resistance across the LX and GND pins is typically 1.4Ω. The integrated MOSFET has a fixed current limit of 1.2A to protect the application circuit during critical operation conditions like short circuit of the LED string. Once the limit is hit, the integrated MOSFET turns off immediately for 34 μs to let the inductor discharge.

The minimum on-time of the integrated MOSFET is 400 ns. It may be hit at a high switching frequency and a high V<sub>IN</sub>/V<sub>LED</sub> ratio. Once hit, the I<sub>LED</sub> regulation may be affected. In the worst case, I<sub>LED</sub> may be boost up to a level higher than the programmed value, and the LED string and/or the inductor may be damaged as a result. Hence, it is recommended that the ratio between V<sub>IN</sub> and V<sub>LED</sub> should be designed under the following constraint:

$$\frac{V_{LED}}{V_{IN}} \geq 400\text{ns} \times f_{SW} \quad (3)$$

### 7.3.8 Inductor Selection

Operating in the continuous conduction mode (CCM) is required in the TPS92511 application circuit. In the CCM, considering the on-period, the peak-to-peak inductor current ripple (2ΔI<sub>L1</sub>) is shown in Equation 4.

$$2\Delta I_{L1} = \frac{t_{on}(V_{IN} - V_{LED})}{L_1} \quad (4)$$

Because

$$\frac{V_{LED}}{V_{IN}} = t_{on}f_{SW} \quad (5)$$

L<sub>1</sub> can be a function of V<sub>IN</sub>, V<sub>LED</sub>, f<sub>SW</sub> and ΔI<sub>L1</sub> as shown in Equation 6 .

$$L_1 = \frac{(V_{IN} - V_{LED})V_{LED}}{2\Delta I_{L1}V_{IN}f_{SW}} \quad (6)$$

The value of L<sub>1</sub> is selected by designers with the consideration of all above parameters. The minimum L<sub>1</sub> calculated by the following equation is a good starting point for designing L<sub>1</sub>:

$$L_1 > 1\mu\text{H}\Omega^{-1} \times \frac{R_{\text{FS}}R_{\text{IADJ}}}{10^6} \quad (7)$$

The following table shows some typical examples of using  $R_{\text{FS}}$  and  $R_{\text{IADJ}}$  to estimate the minimum  $L_1$ :

**Table 3. Estimation Of Minimum  $L_1$  Using  $R_{\text{FS}}$  And  $R_{\text{IADJ}}$**

| $R_{\text{FS}}$ (k $\Omega$ ) | $R_{\text{IADJ}}$ (k $\Omega$ ) | Estimated Minimum $L_1$ ( $\mu\text{H}$ ) | Recommended $L_1$ ( $\mu\text{H}$ ) |
|-------------------------------|---------------------------------|-------------------------------------------|-------------------------------------|
| 100                           | 10                              | 1000                                      | 1000                                |
| 33.2                          | 3.01                            | 100                                       | 100                                 |
| 20                            | 4.32                            | 86                                        | 100                                 |
| 20                            | 3.01                            | 60                                        | 68                                  |

To maintain the CCM,  $\Delta I_{L1}$  must be smaller than the average LED current  $I_{\text{LED(avg)}}$ . Hence, the minimum inductance used is:

$$L_{1(\text{min})} = \frac{(V_{\text{IN}} - V_{\text{LED}})V_{\text{LED}}}{2I_{\text{LED(avg)}}V_{\text{IN}}f_{\text{SW}}} \quad (8)$$

In the absence of output capacitors, the TPS92511 can maintain a continuous  $I_{\text{LED}}$  throughout the entire switching cycle because in such case the inductor current is the same as  $I_{\text{LED}}$  (floating buck topology operating in the CCM). However, the LED peak current must not exceed the rated current of the LED. The peak LED current can be found by the following equation:

$$I_{\text{LED(peak)}} = I_{\text{LED(avg)}} + \frac{(V_{\text{IN}} - V_{\text{LED}})V_{\text{LED}}}{2L_1V_{\text{IN}}f_{\text{SW}}} \quad (9)$$

### 7.3.9 Integrated MOSFET Current Limit

The current limit of the integrated MOSFET is internally fixed at 1.2A to protect the LED string, the inductor and the integrated MOSFET from overdriven. Once triggered, the integrated MOSFET turns off immediately for 34  $\mu\text{s}$  to let the inductor to discharge. The triggering of the current limit cycles repetitively until all overdriven conditions disappear.

### 7.3.10 PWM Dimming Control

The TPS92511 implements PWM dimming by applying a PWM dimming signal to the DIM pin. A low input applying to the DIM pin disables the switching of the integrated MOSFET, and as a result discharges the inductor and then turns off the LED string. To turn on the LED string, the DIM pin should be connected to high or left open (since it is internally pulled high by a current of typically 40  $\mu\text{A}$  and 90  $\mu\text{A}$  when the DIM pin is low and high respectively). The PWM dimming frequency is recommended to be lower than  $0.1f_{\text{SW}}$  to ensure normal operation.

### 7.3.11 Analog Dimming

Analog dimming can be implemented by injecting a current to  $R_{\text{IADJ}}$  (Figure 18) and as a result reduces the current of the IADJ pin,  $I_{\text{ADJ}}$ , which is controlled internally by the TPS92511 to bias the voltage on the IADJ pin to be 1.25V. If the CCM can be maintained, the minimum  $I_{\text{ADJ}}$  can achieve 15  $\mu\text{A}$ , which refers to an  $I_{\text{LED}}$  of 18 mA. If  $I_{\text{ADJ}}$  is further decreased,  $I_{\text{LED}}$  may not follow due to the presence of the minimum on-time of the integrated MOSFET. If the CCM cannot be maintained,  $I_{\text{LED}}$  can still decrease monotonically with  $I_{\text{ADJ}}$ . However, if good line and load regulations are required, the CCM should be maintained by using a large inductance.

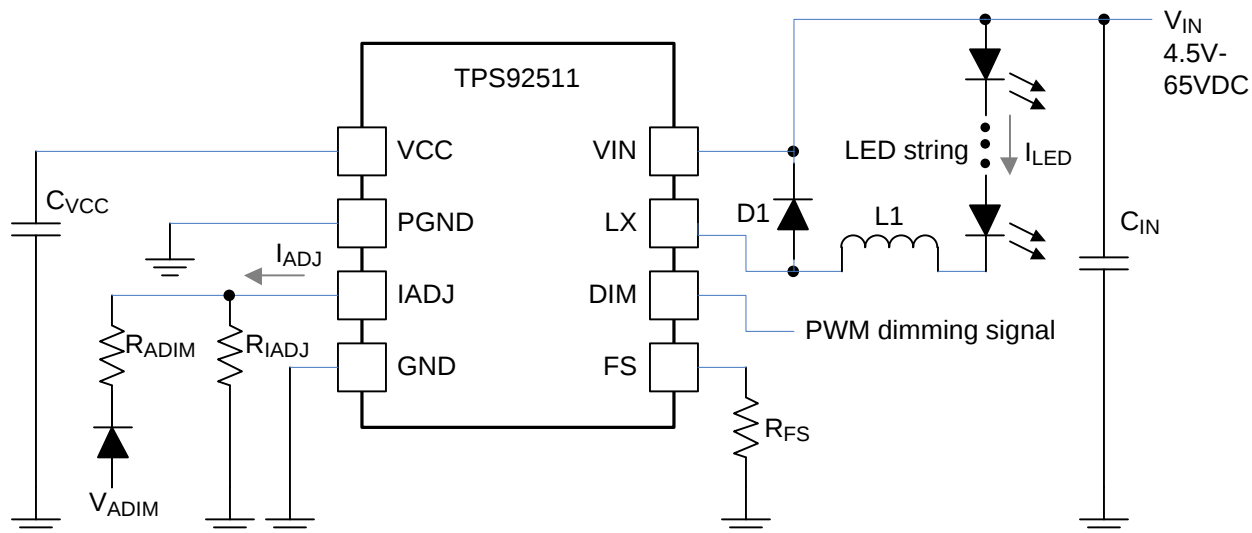


Figure 18. Circuit Configuration for Analog Dimming

### 7.3.12 High Voltage Buck Configuration

The TPS92511 can handle applications with an input voltage higher than 65V, which is the maximum  $V_{IN}$  of the recommended operating condition of the TPS92511, by adding an external high voltage N-channel MOSFET to the application circuit as shown in Figure 19. PWM dimming can be implemented in this circuit without additional efforts, and analog dimming is also feasible by referencing to additional circuits shown in Figure 18.

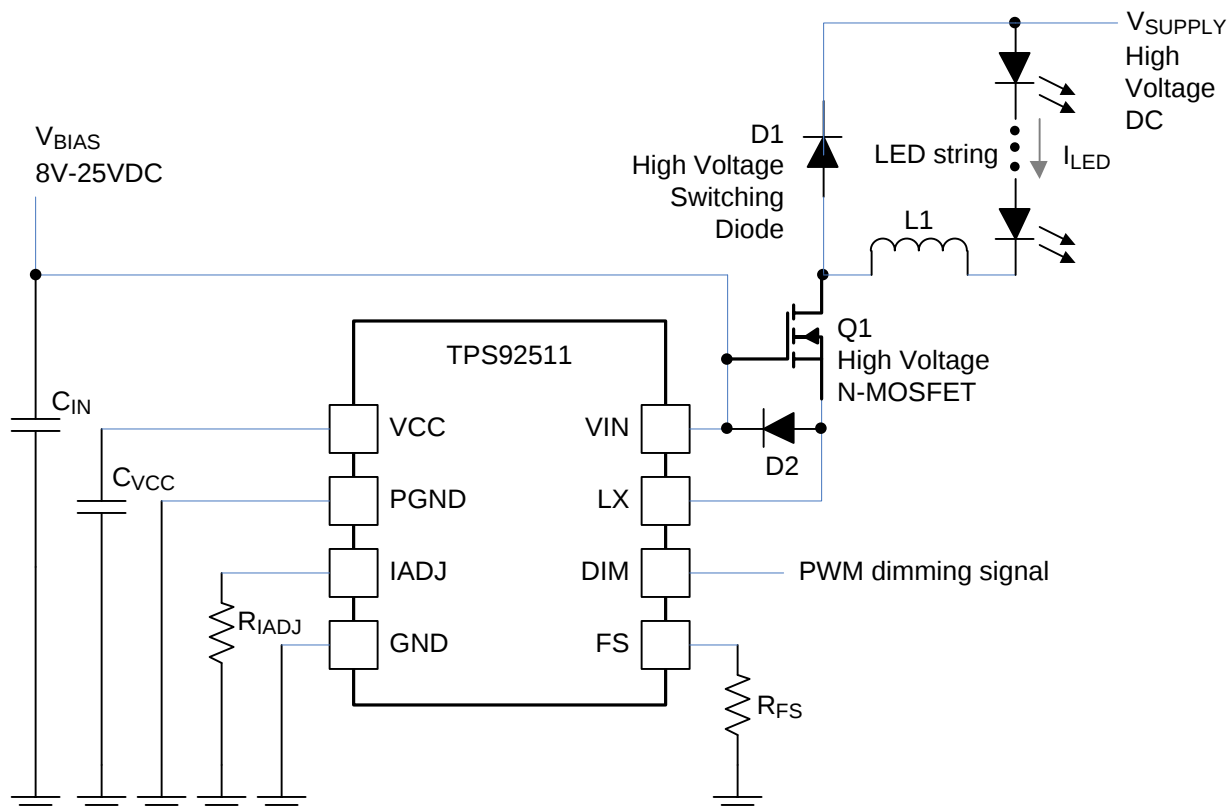
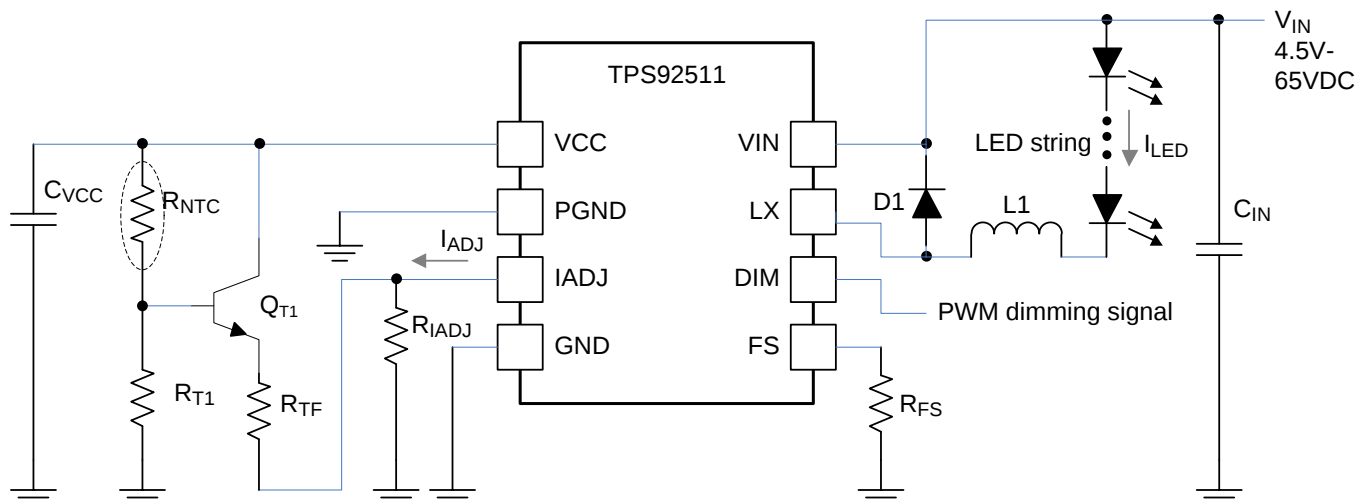


Figure 19. Circuit Configuration for Very High Voltage Buck

### 7.3.13 Thermal Foldback

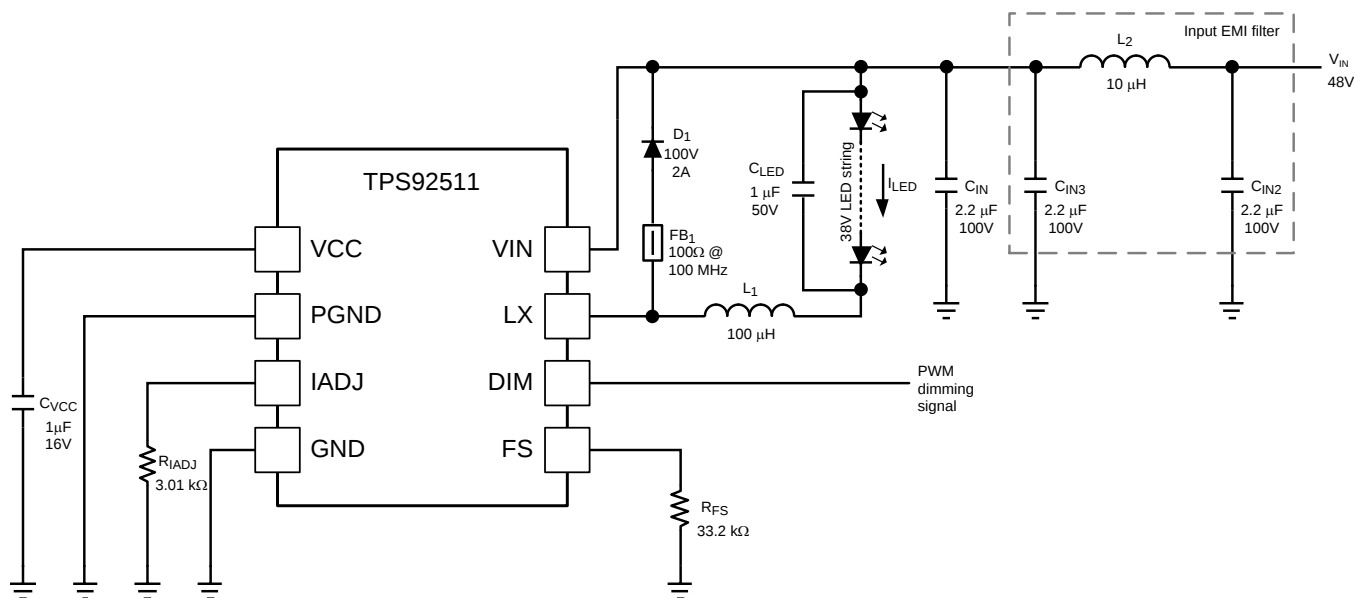
Thermal foldback is useful to prevent over-temperature of LEDs during operation by sensing the temperature of LEDs and, if the sensed temperature is high, reducing  $I_{LED}$  to decrease the power and as well as the temperature of LEDs. Thanks to the feature of analog dimming, thermal foldback can be implemented by embedding a negative temperature coefficient (NTC) resistor,  $R_{NTC}$ , into a circuit as shown in Figure 20. When the sensed temperature increases,  $R_{NTC}$  decreases and thus the emitter current of  $Q_{T1}$  increases to reduce  $I_{LED}$  by means of analog dimming. The resistor  $R_{TF}$  can adjust the loop gain of the thermal foldback control loop, which should be high enough to avoid oscillation and maintain stability.



**Figure 20. Circuit Configuration for Thermal Foldback**

### 7.3.14 EMI Consideration

Conductive and radiative EMI can be major concerns for lighting applications. The TPS92511 application circuit can be designed for the EN 55022 class B standard by adding a few external components, as shown in Figure 21. The input filter which consists of an inductor  $L_2$  and two capacitors  $C_{IN2}$  and  $C_{IN3}$  takes care of the conductive EMI, while the output capacitor  $C_{LED}$  and the ferrite bead  $FB_1$  which inserts between the LX pin and  $D_1$  take care of the radiative EMI.



**Figure 21. Circuit Configuration with EMI Design Consideration**

## 7.4 Device Functional Modes

### 7.4.1 Operation with $V_{IN} < 4.5\text{ V}$ (minimum $V_{IN}$ )

For the typical application circuit, when the input voltage drops so that the VCC voltage regulator is under drop-out mode, and the VCC voltage drops below the “VCC UVLO Lower Threshold” (typically 3.48V), the switching of the main MOSFET is stopped, and the LED current will become zero. At the same time, the voltages of both the FS and IADJ pins will become zero.

When the input voltage increases from zero and the VCC voltage is increased to cross over the “VCC UVLO Upper Threshold” (typically 3.75V), the voltages on the FS and IADJ pins will rise to their regulation voltage (typically 1.25V), the switching of the main MOSFET is started upon the DIM pin voltage is HIGH, and the LED current will ramp up to its preset value set by  $R_{IADJ}$ .

### 7.4.2 Operation with DIM control

For the typical application circuit, when the VCC voltage is not under UVLO condition, the switching of the main MOSFET is enabled and the LED current is conducted if the DIM pin voltage is higher than the “DIM Pin Upper Threshold” (typically 1V).

Alternatively, the switching is disabled and the LED current is cut off if the voltage of the DIM pin is lower than the “DIM Pin Lower Threshold” (typically 0.675V).

### 7.4.3 Linear Mode

When the VCC voltage is not under UVLO condition and the voltage on the FS pin is forced to be higher than 4.2V but lower than 5V, the switching of the main MOSFET is disabled, and the TPS92511 is working in the Linear Mode. In the Linear Mode, if the voltage on the DIM pin is higher than the “DIM Pin Upper Threshold” (typically 1V), the TPS92511 will regulate the LX pin in-going current according to the preset value set by  $R_{IADJ}$ . Alternatively, if the voltage on the DIM pin is lower than the “DIM Pin Lower Threshold” (typically 0.675V), the LX pin will open and its in-going current will become zero.

Below is the simple configuration to have the TPS92511 working as a linear current shunt regulator.

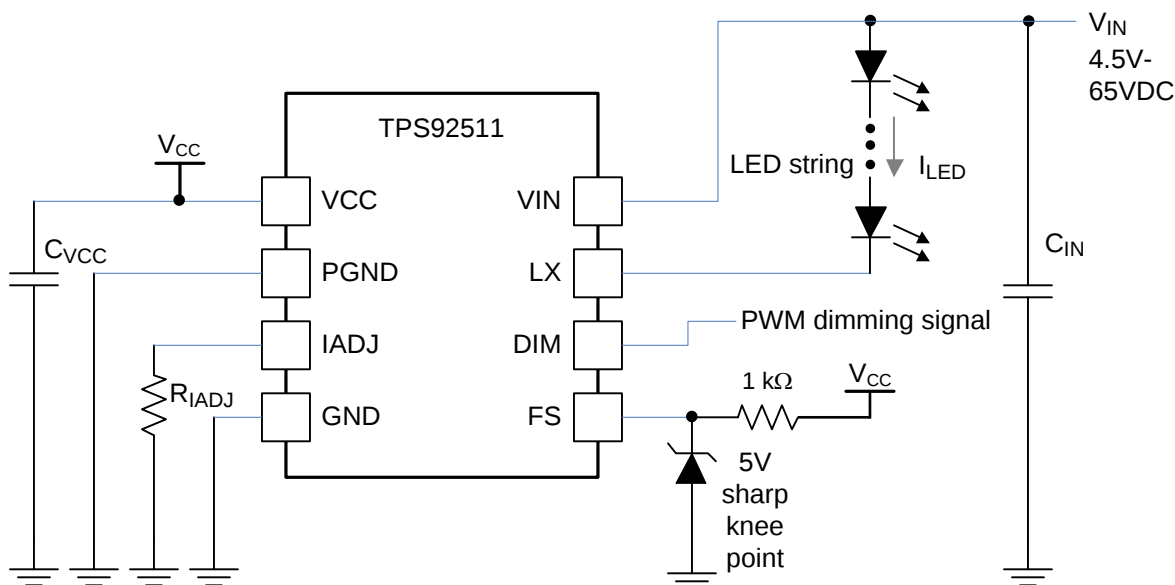


Figure 22. Circuit Configuration for Working as a Linear Current Shunt Regulator

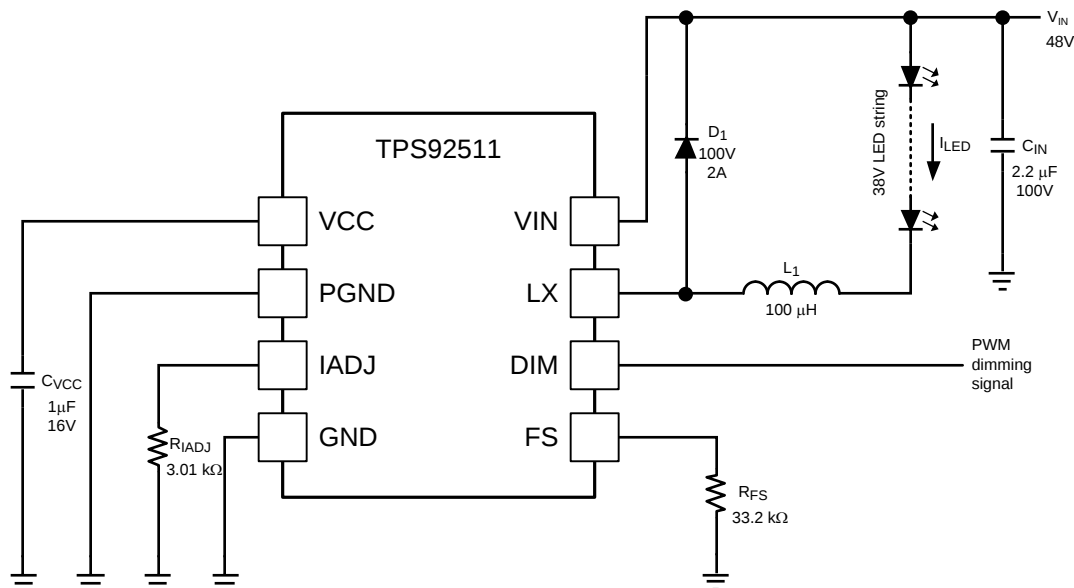
## 8 Application and Implementation

### 8.1 Application Information

The TPS92511 is an LED driver which provides a regulated output current to drive a single string of LED with the forward voltage lower than the input voltage. The following procedures design a TPS92511 application circuit with an input voltage of 48V, driving an LED string of 38V at an LED current of 0.5A. The switching frequency is 300 kHz.

### 8.2 Typical Application

#### 8.2.1 TPS92511 LED driver for 12 LEDs at 0.5A



**Figure 23. Application Circuit of TPS92511 ( $f_{sw} = 300$  kHz and  $I_{LED} = 0.5A$ )**

## Typical Application (continued)

### 8.2.1.1 Design Requirements

**Table 4. Design Parameters**

| DESIGN PARAMETER           | EXAMPLE VALUE |
|----------------------------|---------------|
| Input voltage range        | 43V to 53V    |
| LED current                | 0.5A          |
| LED string forward voltage | 38V           |
| Operating frequency        | 300 kHz       |

### 8.2.1.2 Detailed Design Procedure

**C<sub>IN</sub>** : The function of the input capacitor C<sub>IN</sub> is to reduce the input voltage ripple. Ceramic capacitors are recommended owing to the concern of product lifetime. A 100V 2.2  $\mu$ F ceramic capacitor is selected in this circuit.

**C<sub>VCC</sub>** : The capacitor on the VCC pin provides noise filtering and stabilizes the internal regulator. It also prevents false triggering of the VCC UVLO. C<sub>VCC</sub> is recommended to be a 1  $\mu$ F good quality and low ESR ceramic capacitor.

**D<sub>1</sub>** : The diode D<sub>1</sub> should have a reverse voltage larger than V<sub>IN</sub> in the floating buck topology. In this circuit, a 100V diode is selected.

**R<sub>FS</sub> and R<sub>IADJ</sub>** : In this circuit, the switching frequency and LED current are designed to be 300 kHz and 0.5A. From [Table 1](#) and [Table 2](#), R<sub>FS</sub> is 33.2 k $\Omega$  and R<sub>IADJ</sub> is 3.01 k $\Omega$ .

**L<sub>1</sub>** : The selection of inductor mainly affects the inductor current ripple. In this circuit, we design the peak to peak inductor current ripple to be 50% of I<sub>LED</sub>, i.e. 0.25A. From (6), L<sub>1</sub> is calculated to be 106  $\mu$ H, and a 100  $\mu$ H inductor is selected.

### 8.2.1.3 Application Curves

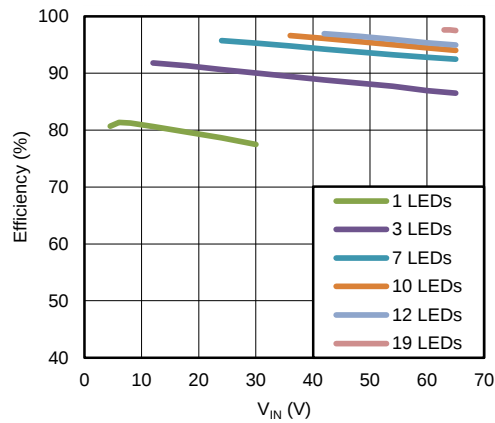


Figure 24. Efficiency vs  $V_{IN}$

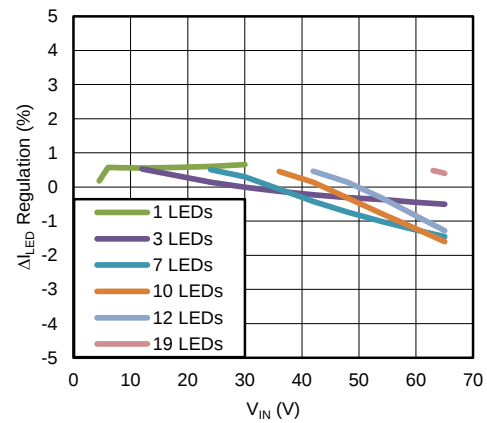


Figure 25. LED Current Regulation vs  $V_{IN}$

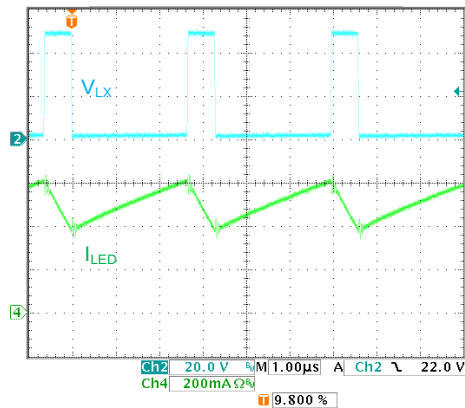


Figure 26. Steady State Operation

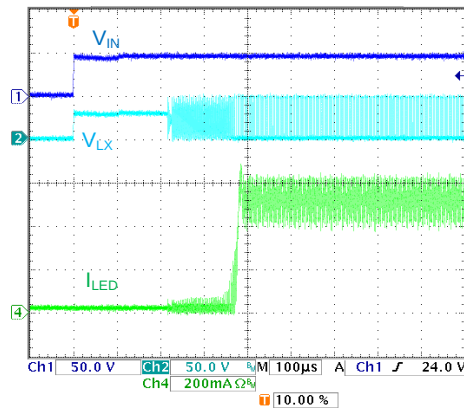


Figure 27. Power Up

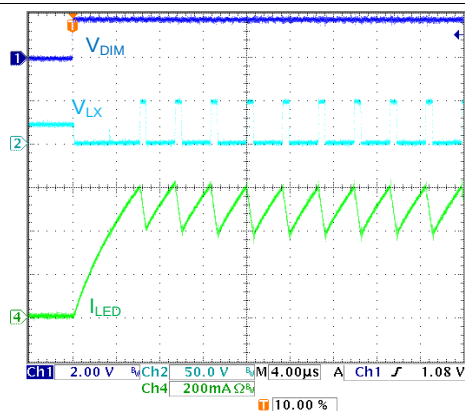


Figure 28. PWM Dimming ( $V_{DIM}$  Rising)

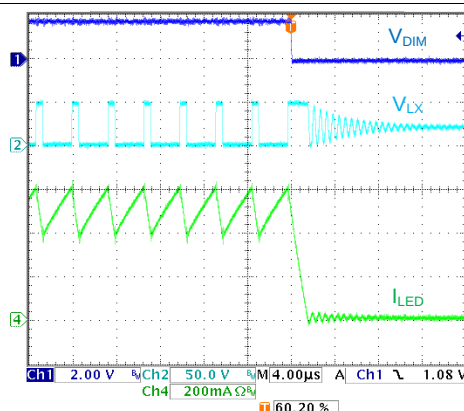


Figure 29. PWM Dimming ( $V_{DIM}$  Falling)

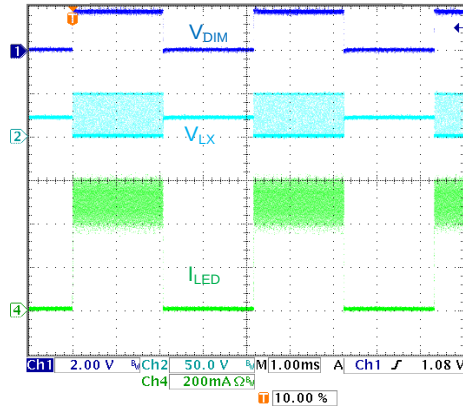


Figure 30. PWM Dimming ( $f_{DIM} = 1 \text{ kHz}$ , 50% Duty Cycle)

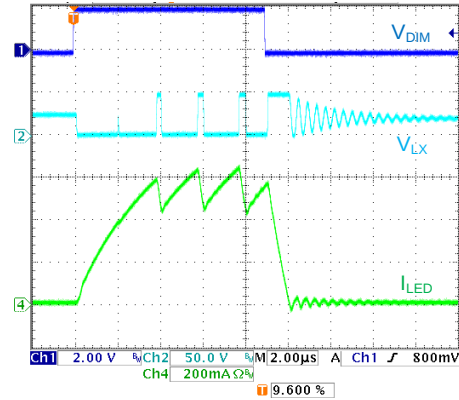


Figure 31. PWM Dimming (9  $\mu\text{s}$  dimming pulse) ( $f_{SW} = 500\text{kHz}$ ,  $L_1 = 68 \mu\text{H}$ )

## 9 Power Supply Recommendation

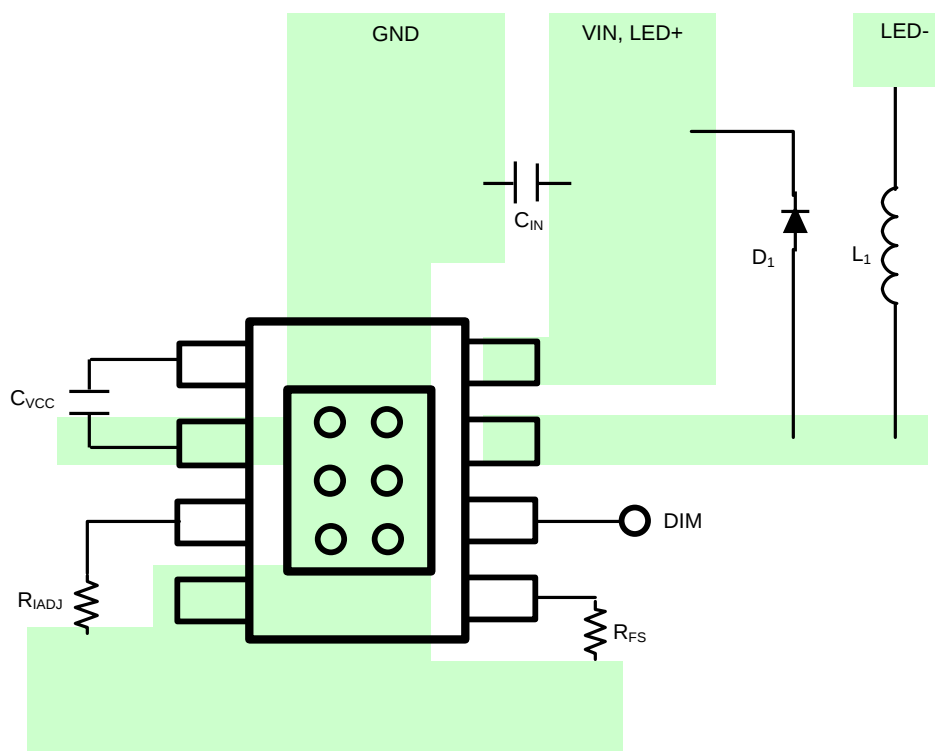
This device is designed to operate from an input voltage supply range between 4.5 V and 65 V. The input supply should be well regulated. If the input supply is located more than a few inches from the TPS92511 application board, additional bulk capacitance may be required in addition to the input capacitor. A ceramic capacitor with a value of 2.2  $\mu\text{F}$  is a typical choice.

## 10 Layout

### 10.1 Layout Guidelines

- The PCB layout of the TPS92511 application circuit plays an important role in optimizing the performance.
- The external components should be placed as close to the TPS92511 as possible to minimize resistance and parasitic inductance of copper traces.
- For example,  $D_1$  and  $L_1$  should be near the LX pin, and  $C_{VCC}$  should be near the VCC pin, and the connecting copper traces are short and thick.
- The exposed pad of the TPS92511, which is internally connected to the die substrate, should be connect to a ground plane, and the plane should be extended as much as possible on the same copper layer around the TPS92511.
- Using numerous vias beneath the exposed pad to dissipate heat to another copper layer is also a good practice.

### 10.2 Layout Example



**Figure 32. TPS92511 Board Layout**

#### 10.2.1 Thermal Consideration

$\Psi_{JT}$  (shown in session 6.4 Thermal Information) is a relatively small value for package with exposed pad since most of the heat is dissipated through the exposed pad to the copper plate of the PCB (assuming optimized PCB layout), relatively little heat goes to the top of the device. The top of the device mold compound temperature is physically close to the device junction temperature.

For example, a 30W output TPS92511 end system at 95% power efficiency (can be estimated from the efficiency curves of Figure 13), power loss is 1.6W. Assuming all the heat is generated from the TPS92511 (which is true for high  $V_{LED}$ ), and assuming half of the heat generated is dissipated through the top of the device. Now  $\Psi_{JT}$  is 11 °C/W, the device junction temperature is estimated to be higher than the package's top-surface temperature by  $11 \times 1.6 \times 0.5 = 8.8$  (°C). If the package top-surface temperature is measured to be 90 °C (for example by an IR camera), the device junction temperature is around 99 °C, which is within the 125°C maximum junction temperature requirement with margin.

## 11 Device and Documentation Support

### 11.1 Trademarks

All trademarks are the property of their respective owners.

### 11.2 Electrostatic Discharge Caution



These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

### 11.3 Glossary

[SLYZ022](#) — *TI Glossary*.

This glossary lists and explains terms, acronyms and definitions.

## 12 Mechanical, Packaging, and Orderable Information

The following pages include mechanical packaging and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

## PACKAGING INFORMATION

| Orderable part number        | Status<br>(1) | Material type<br>(2) | Package   Pins           | Package qty   Carrier | RoHS<br>(3) | Lead finish/<br>Ball material<br>(4) | MSL rating/<br>Peak reflow<br>(5) | Op temp (°C) | Part marking<br>(6) |
|------------------------------|---------------|----------------------|--------------------------|-----------------------|-------------|--------------------------------------|-----------------------------------|--------------|---------------------|
| <a href="#">TPS92511DDA</a>  | Active        | Production           | SO PowerPAD<br>(DDA)   8 | 95   TUBE             | Yes         | SN                                   | Level-3-260C-168 HR               | -40 to 125   | 92511               |
| TPS92511DDA.A                | Active        | Production           | SO PowerPAD<br>(DDA)   8 | 95   TUBE             | Yes         | SN                                   | Level-3-260C-168 HR               | -40 to 125   | 92511               |
| <a href="#">TPS92511DDAR</a> | Active        | Production           | SO PowerPAD<br>(DDA)   8 | 2500   LARGE T&R      | Yes         | SN                                   | Level-3-260C-168 HR               | -40 to 125   | 92511               |
| TPS92511DDAR.A               | Active        | Production           | SO PowerPAD<br>(DDA)   8 | 2500   LARGE T&R      | Yes         | SN                                   | Level-3-260C-168 HR               | -40 to 125   | 92511               |

<sup>(1)</sup> **Status:** For more details on status, see our [product life cycle](#).

<sup>(2)</sup> **Material type:** When designated, preproduction parts are prototypes/experimental devices, and are not yet approved or released for full production. Testing and final process, including without limitation quality assurance, reliability performance testing, and/or process qualification, may not yet be complete, and this item is subject to further changes or possible discontinuation. If available for ordering, purchases will be subject to an additional waiver at checkout, and are intended for early internal evaluation purposes only. These items are sold without warranties of any kind.

<sup>(3)</sup> **RoHS values:** Yes, No, RoHS Exempt. See the [TI RoHS Statement](#) for additional information and value definition.

<sup>(4)</sup> **Lead finish/Ball material:** Parts may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead finish/Ball material values may wrap to two lines if the finish value exceeds the maximum column width.

<sup>(5)</sup> **MSL rating/Peak reflow:** The moisture sensitivity level ratings and peak solder (reflow) temperatures. In the event that a part has multiple moisture sensitivity ratings, only the lowest level per JEDEC standards is shown. Refer to the shipping label for the actual reflow temperature that will be used to mount the part to the printed circuit board.

<sup>(6)</sup> **Part marking:** There may be an additional marking, which relates to the logo, the lot trace code information, or the environmental category of the part.

Multiple part markings will be inside parentheses. Only one part marking contained in parentheses and separated by a "~" will appear on a part. If a line is indented then it is a continuation of the previous line and the two combined represent the entire part marking for that device.

**Important Information and Disclaimer:** The information provided on this page represents TI's knowledge and belief as of the date that it is provided. TI bases its knowledge and belief on information provided by third parties, and makes no representation or warranty as to the accuracy of such information. Efforts are underway to better integrate information from third parties. TI has taken and continues to take reasonable steps to provide representative and accurate information but may not have conducted destructive testing or chemical analysis on incoming materials and chemicals. TI and TI suppliers consider certain information to be proprietary, and thus CAS numbers and other limited information may not be available for release.

In no event shall TI's liability arising out of such information exceed the total purchase price of the TI part(s) at issue in this document sold by TI to Customer on an annual basis.



## TAPE AND REEL INFORMATION



\*All dimensions are nominal

| Device       | Package Type | Package Drawing | Pins | SPQ  | Reel Diameter (mm) | Reel Width W1 (mm) | A0 (mm) | B0 (mm) | K0 (mm) | P1 (mm) | W (mm) | Pin1 Quadrant |
|--------------|--------------|-----------------|------|------|--------------------|--------------------|---------|---------|---------|---------|--------|---------------|
| TPS92511DDAR | SO PowerPAD  | DDA             | 8    | 2500 | 330.0              | 12.4               | 6.5     | 5.4     | 2.0     | 8.0     | 12.0   | Q1            |

## TAPE AND REEL BOX DIMENSIONS



\*All dimensions are nominal

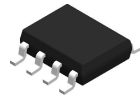
| Device       | Package Type | Package Drawing | Pins | SPQ  | Length (mm) | Width (mm) | Height (mm) |
|--------------|--------------|-----------------|------|------|-------------|------------|-------------|
| TPS92511DDAR | SO PowerPAD  | DDA             | 8    | 2500 | 356.0       | 356.0      | 36.0        |

## TUBE



\*All dimensions are nominal

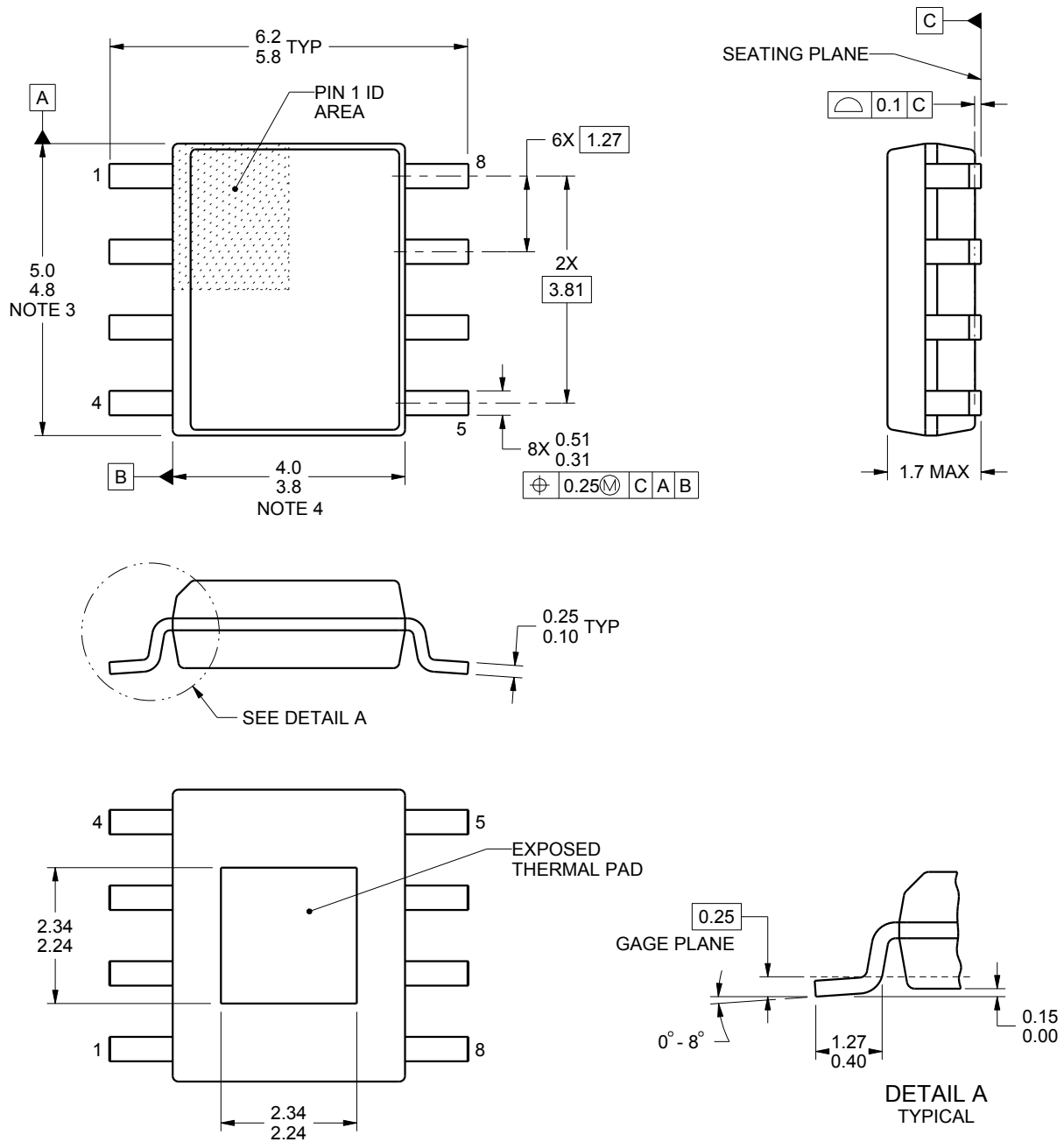
| Device        | Package Name | Package Type | Pins | SPQ | L (mm) | W (mm) | T (μm) | B (mm) |
|---------------|--------------|--------------|------|-----|--------|--------|--------|--------|
| TPS92511DDA   | DDA          | HSOIC        | 8    | 95  | 495    | 8      | 4064   | 3.05   |
| TPS92511DDA.A | DDA          | HSOIC        | 8    | 95  | 495    | 8      | 4064   | 3.05   |

**DDA0008A**

# PACKAGE OUTLINE

## PowerPAD™ SOIC - 1.7 mm max height

PLASTIC SMALL OUTLINE



4218825/A 05/2016

PowerPAD is a trademark of Texas Instruments.

**NOTES:**

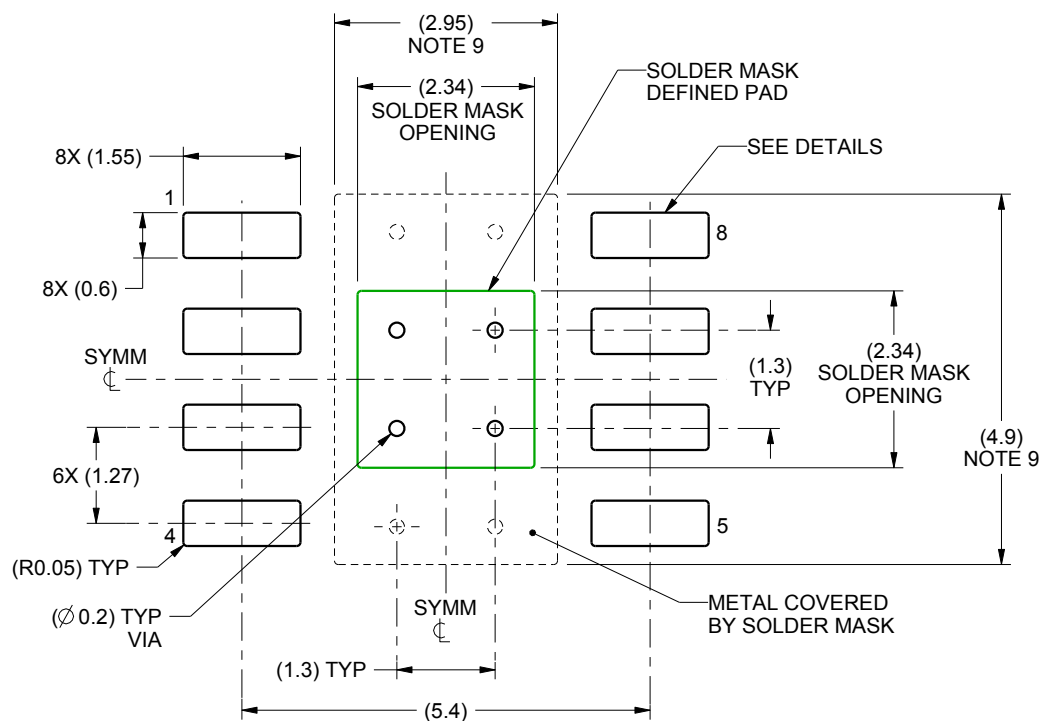
1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 mm per side.
4. This dimension does not include interlead flash. Interlead flash shall not exceed 0.25 mm per side.
5. Reference JEDEC registration MS-012.

# EXAMPLE BOARD LAYOUT

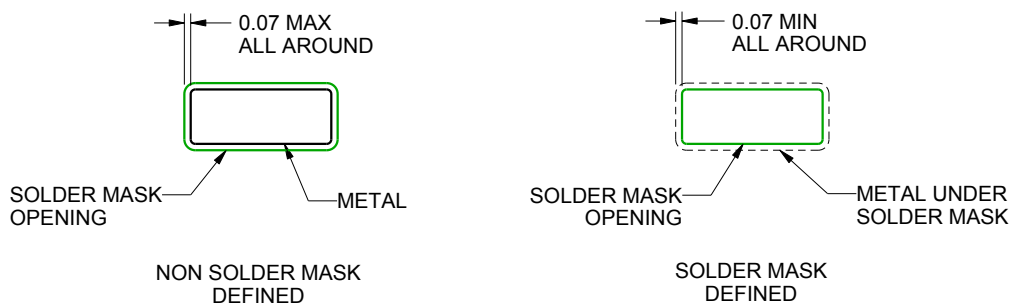
DDA0008A

PowerPAD™ SOIC - 1.7 mm max height

PLASTIC SMALL OUTLINE



LAND PATTERN EXAMPLE  
SCALE:10X



SOLDER MASK DETAILS

4218825/A 05/2016

NOTES: (continued)

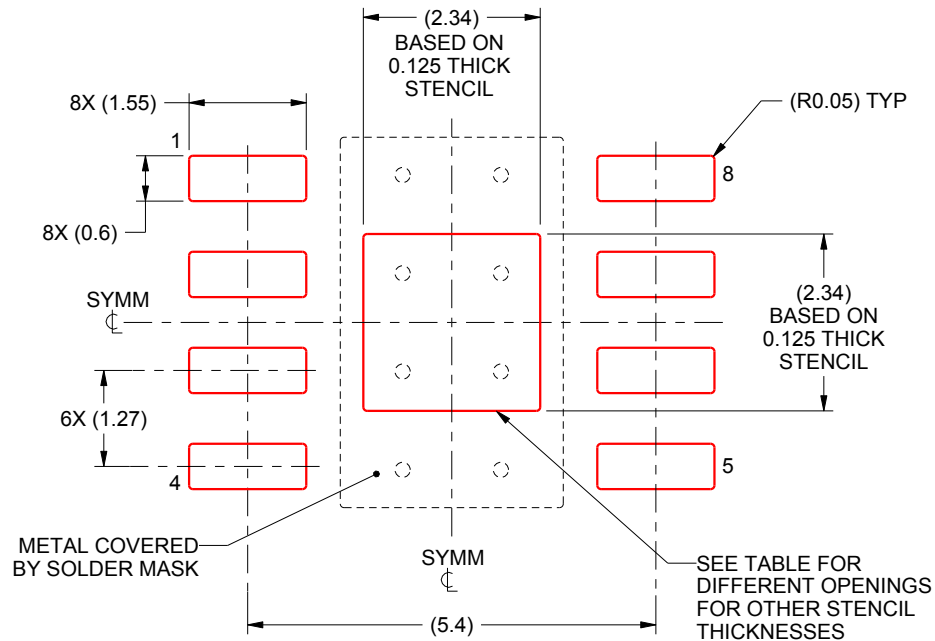
6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.
8. This package is designed to be soldered to a thermal pad on the board. For more information, see Texas Instruments literature numbers SLMA002 ([www.ti.com/lit/slma002](http://www.ti.com/lit/slma002)) and SLMA004 ([www.ti.com/lit/slma004](http://www.ti.com/lit/slma004)).
9. Size of metal pad may vary due to creepage requirement.
10. Vias are optional depending on application, refer to device data sheet. If any vias are implemented, refer to their locations shown on this view. It is recommended that vias under paste be filled, plugged or tented.

# EXAMPLE STENCIL DESIGN

DDA0008A

PowerPAD™ SOIC - 1.7 mm max height

PLASTIC SMALL OUTLINE



**SOLDER PASTE EXAMPLE**  
EXPOSED PAD  
100% PRINTED SOLDER COVERAGE BY AREA  
SCALE:10X

| STENCIL THICKNESS | SOLDER STENCIL OPENING |
|-------------------|------------------------|
| 0.1               | 2.62 X 2.62            |
| 0.125             | 2.34 X 2.34 (SHOWN)    |
| 0.150             | 2.14 X 2.14            |
| 0.175             | 1.98 X 1.98            |

4218825/A 05/2016

NOTES: (continued)

11. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
12. Board assembly site may have different recommendations for stencil design.

## IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you fully indemnify TI and its representatives against any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to [TI's Terms of Sale](#), [TI's General Quality Guidelines](#), or other applicable terms available either on [ti.com](#) or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products. Unless TI explicitly designates a product as custom or customer-specified, TI products are standard, catalog, general purpose devices.

TI objects to and rejects any additional or different terms you may propose.

Copyright © 2026, Texas Instruments Incorporated

Last updated 10/2025