TI Designs
100-W, 0.1% Dimmable DC-DC LED Driver With Daylight Harvesting and Wireless Connectivity

Description

This TI Design is a tested DC-DC LED driver subsystem for high-power, high-efficiency dimmable LED luminaires. The design is built on a wireless system-on-chip (SoC) platform which can enable intensity adjustment through analog, PWM dimming, and control using any *Bluetooth*® low energy (BLE) smart device.

At the time of this writing, high-bay and low-bay LED lighting luminaires are replacing the fluorescent and HID lights because they cut energy consumption in half, and nearly eliminate maintenance costs. Daylight harvesting using the dimming feature, combined with an ambient light sensor, can provide up to an additional 50% in energy savings, depending on the application.

The TIDA-01095 TI Design provides high-efficiency DC-DC conversion, allows dimming and daylight harvesting, and enables wireless connected lighting control.

Resources

TIDA-01095	Design Folder
TPS92641	Product Folder
CSD18537NQ5A	Product Folder
CSD18563Q5A	Product Folder
OPA376	Product Folder
OPT3001	Product Folder
LMT84	Product Folder
LAUNCHXL-CC2650	Tools Folder

Features

- 100-W Synchronous Buck LED driver With Average of 97.3% Efficiency Over 100% to 50% Brightness With Analog Dimming
- 1:1000 Contrast Ratio With Analog Dimming, and PWM Dimming (200 Hz to 5 kHz)
- Ambient Light Sensor OPT3001-Based Light Measurement, Enabling Daylight Harvesting and Constant Lumen Implementations
- MCU PWM Used as 12-bit DAC for I_{ADJ} Setting in Analog Dimming
- Overcurrent and Overtemperature Protection for Driver and LED Module
- CC2650 SimpleLink™ Multi-Standard 2.4-GHz Ultra-Low-Power Wireless MCU Enables Connected Lighting With Bluetooth® Smart or ZigBee®

Applications

- Indoor LED Lighting (Industrial High-Bay, Low-Bay Lighting)
- Outdoor LED Lighting (Area Light, Street Light)
- Distributed DC Lighting

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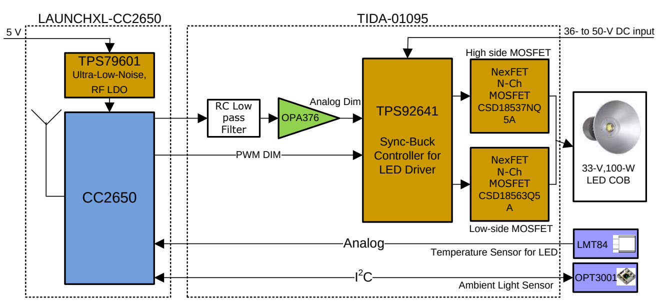

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1 System Overview

1.1 System Description

At the time of this writing, industrial indoor lighting is increasingly adopting light-emitting diodes (LEDs) for high-bay and low-bay lighting. LED lighting offers several advantages, such as energy savings greater than 50%, long lifetime, controllable light output, and extremely low maintenance. Integration of light sensors with connected lighting enables daylight harvesting, which increases the energy efficiency. Daylight harvesting is achieved by measuring the light conditions in the given work area, which could be partially from the light source and partially from the daylight. Based on that data, the lights are automatically dimmed when the daylight level increases.

Besides optical design and thermal management, LED luminaires must also ensure constant lumen output from the luminaire over its lifetime (as the light output from the LED is expected to reduce over a few years), and smooth and efficient dimming to enable daylight harvesting using light sensors.

Figure 1 shows an example of high-bay lighting in an industrial environment.

Figure 1. High-Bay Lighting in Industrial Environment

1.2 Key System Specifications

Table 1. Key System Specifications

PARAMETERS	TEST CONDITIONS AND NOTES	MIN	TYP	MAX	UNITS
INPUT CHARACTERISTICS					
Input Voltage	—	36	—	50 (1)	V
Input UVLO setting	—	30.25	31.9	33.55	V
OUTPUT CHARACTERISTICS					
Output (LED) Current	—	0	—	3	A
Inductor ripple current	Peak-to-peak	—	—	500	mA
LED ripple current	Peak-to-peak	—	—	350	mA
OVP Threshold	—	53.7	57.5	61.3	V
SYSTEMS CHARACTERISTICS					
Switching frequency	—	—	222	—	kHz
Current sensing resistor	—	—	0.05 (2)	—	Ω
LOAD CHARACTERISTICS (3)					
Forward voltage	at 1900 mA, T_C = 85°C	—	38.5	—	V
Forward voltage	at 1900 mA, T_C = 25°C	—	—	42	V
Forward current	—	—	—	2800	mA
Reverse current	—	—	—	0.1	mA

(1) Maximum input voltage is limited by the MOSFET voltage rating. The board can work with 60-V MOSFET with up to 50-V input, and it also can work with 100-V MOSFET with up to an 80-V input.
(2) For deep dimming or dimming in the range of less than 10 mA, the current sense resistor value must be around 0.25 Ω.
(3) LED load used is Cree CXA3070-0000-000N0HAB57F-ND.

1.3 Block Diagram

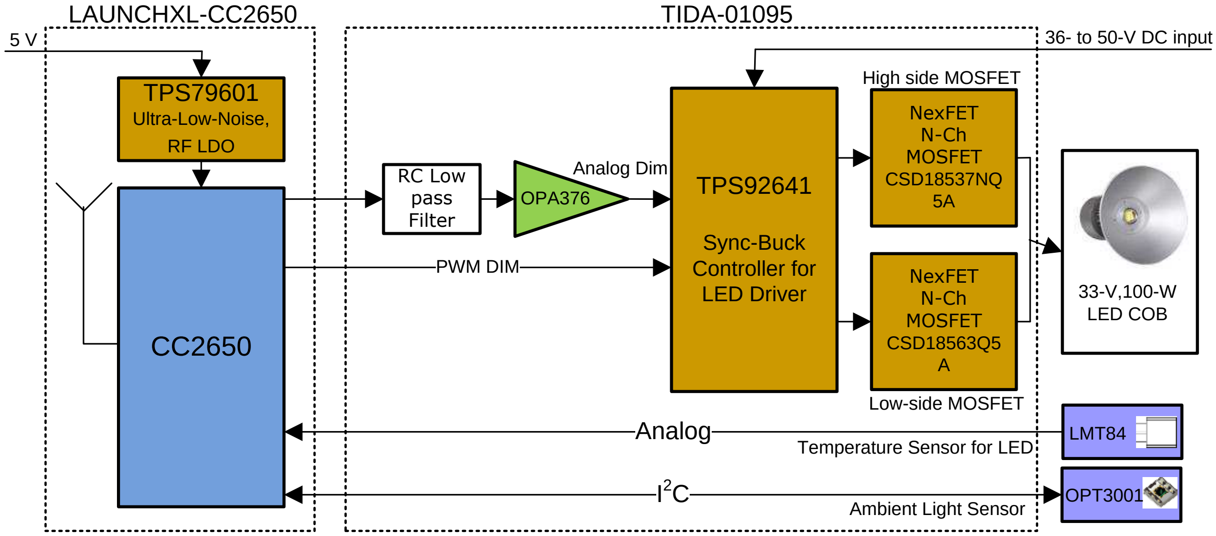

Figure 2. Block Diagram of Dimmable White LED Driver Augmented by CC2650 LaunchPad and Sensors

1.4 Highlighted Products

1.4.1 TPS92641

The TPS92640 and TPS92641 devices are high-voltage, synchronous NFET controllers for buck-current regulators (see Figure 3). Output current regulation is based on valley current-mode operation using a controlled on-time architecture. This control method eases the design of loop compensation while maintaining nearly constant switching frequency.

The TPS92640 and TPS92641 devices include a high-voltage start-up regulator that operates over a wide input range of 7 V to 85 V. The PWM controller is designed for high-speed capability, including an oscillator frequency range up to 1 MHz. The deadtime between the high-side and low-side gate driver is optimized to provide very high efficiency over a wide input operating voltage and output power range.

The TPS92640 and TPS92641 devices accept both analog and PWM input signals, resulting in exceptional dimming control range. Linear response characteristics between input command and LED current is achieved with true zero LED current using low off-set error amplifier and proprietary PWM dimming logic. Both devices also include precision reference capable of supplying current to a low-power microcontroller. Protection features include cycle-by-cycle current protection, overvoltage protection, and thermal shutdown. The TPS92641 device includes a shunt FET dimming input and MOSFET driver for high-resolution PWM dimming.

Features:

- V_{IN} range from 7 V to 85 V
- Wide dimming range
- 500:1 analog dimming
- 2500:1 standard PWM dimming
- 20000:1 shunt FET PWM dimming
- Adjustable LED current sense voltage
- 2-Ω, 1-A peak MOSFET gate drivers
- Shunt-dimming MOSFET gate driver (TPS92641)
- Programmable switching frequency
- Precision voltage reference 3 V ±2%

- Input UVLO and output OVP
- Low-power shutdown mode and thermal shutdown
- MSOP-10 package with PowerPAD™

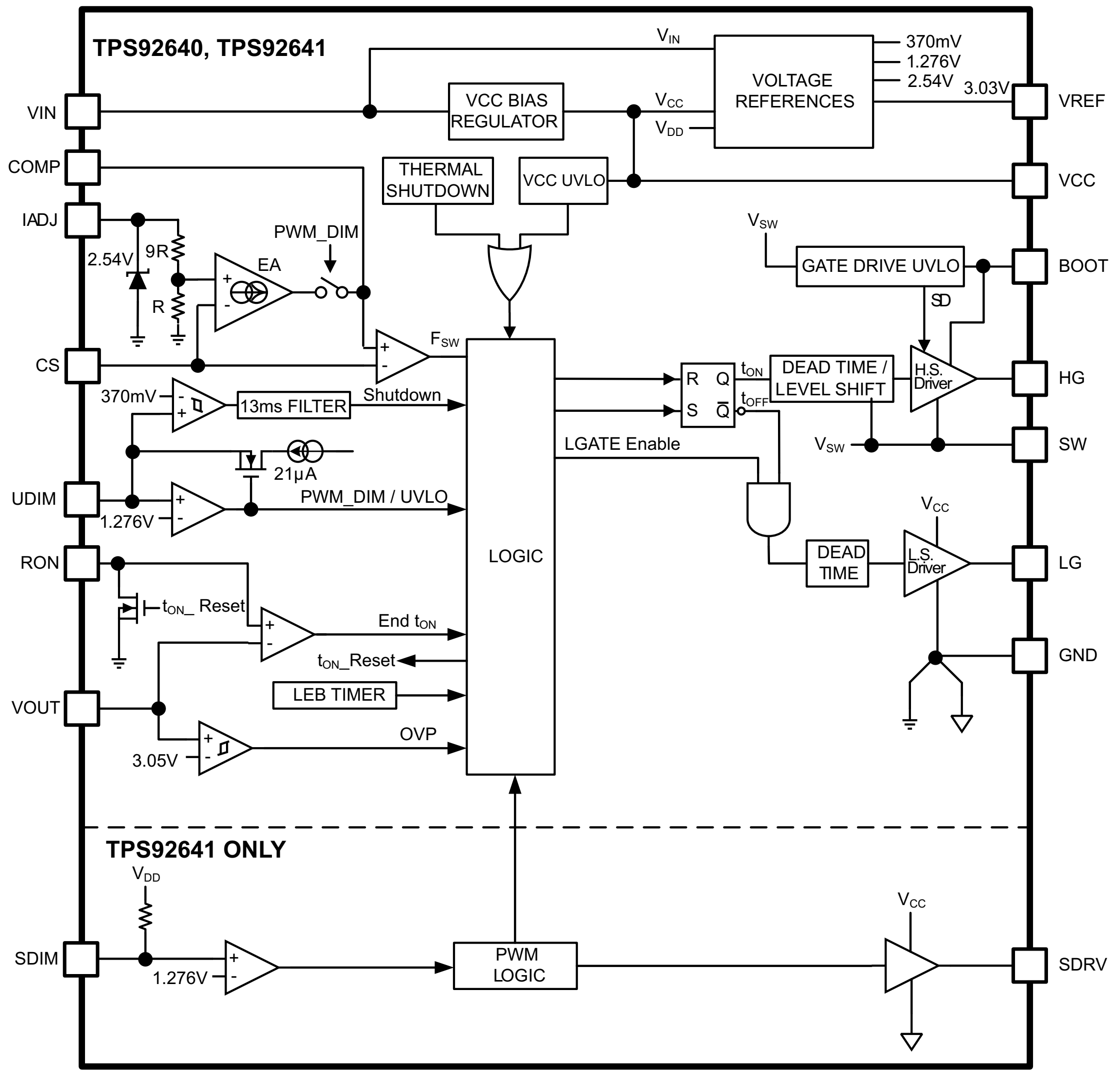

Figure 3. TPS92640, TPS92641 Block Diagram

1.4.2 TPS92640

The TPS92640 device is a high-voltage, synchronous NFET controller for buck-current regulators from the TPS9264x device family, and can be used instead of the TPS92641 in the same design. The TPS92641 device includes a shunt FET dimming input and MOSFET driver for high-frequency and high-resolution PWM dimming, in addition to all the features provided by the TPS92640. The TPS92640 can fit in end applications which do not exploit the shunt dimming feature of the TPS92641.

1.4.3 CSD18537NQ5A

This 10-mΩ, 60-V, SON 5×6-mm NexFET™ power MOSFET from TI is designed to minimize losses in power conversion applications. This MOSFET is recommended to be used as the high-side MOSFET in synchronous buck converter applications.

Features:

- Ultra-low Q_g and Q_{gd}
- Low thermal resistance
- Avalanche rated
- Pb-free terminal plating
- RoHS compliant

1.4.4 CSD18563Q5A

This 5.7-mΩ, 60-V SON 5×6-mm NexFET power MOSFET is designed to pair with the CSD18537NQ5A control FET, and act as the sync FET for a complete industrial buck-converter chipset solution.

Features:

- Ultra-low Q_g and Q_{gd}
- Soft body diode for reduced ringing
- Low thermal resistance
- Avalanche rated
- Logic level
- Pb-free terminal plating
- RoHS compliant
- Halogen free
- SON 5×6-mm plastic package

1.4.5 CSD18563Q5A

This 100-V, 12.6-mΩ, SON 5x6-mm NexFET power MOSFET is designed to minimize losses in power conversion applications.

Features:

- Ultra-low Q_g and Q_{gd}
- Low thermal resistance
- Avalanche rated
- Pb-free terminal plating
- RoHS compliant
- Halogen free
- SON 5×6-mm plastic package

1.4.6 OPT3001

The OPT3001 is a sensor that measures the intensity of visible light. The spectral response of the sensor tightly matches the photopic response of the human eye, and includes significant infrared rejection (see Figure 4).

The OPT3001 is a single-chip LUX meter that measures the intensity of light as visible by the human eye. The precision spectral response and strong IR rejection of the device enables the OPT3001 device to accurately meter the intensity of light as seen by the human eye, regardless of the light source. The strong infrared (IR) rejection also aids in maintaining high accuracy when industrial design calls for mounting the sensor under dark glass for aesthetics. The OPT3001 is designed for systems that create light-based experiences for humans, and an ideal preferred replacement for photodiodes, photoresistors, or other ambient light sensors with less human eye matching and IR rejection.

Measurements can be made from 0.01 lux up to 83k lux without manually selecting full-scale ranges, by using the built-in, full-scale setting feature. This capability allows light measurement over a 23-bit effective dynamic range.

The digital operation is flexible for system integration. Measurements can be either continuous or single-shot. The control and interrupt system features autonomous operation, allowing the processor to sleep while the sensor searches for appropriate wake-up events to report through the interrupt pin. The digital output is reported over an I^2C- and SMBus-compatible, two-wire serial interface.

The low-power consumption and low-power-supply voltage capability of the OPT3001 enhances the battery life of battery-powered systems.

Features:

- Precision optical filtering to match human eye
- Rejects > 99% (typ) of IR
- Automatic full-scale setting feature simplifies software and ensures proper configuration
- Measurements: 0.01 lux to 83k lux
- 23-bit effective dynamic range with automatic gain ranging
- 12 binary-weighted full-scale range settings
- < 0.2% (typ) matching between ranges
- Low operating current: 1.8 µA (typ)
- Operating temperature range: –40°C to +85°C
- Wide power-supply range: 1.6 V to 3.6 V
- 5.5-V tolerant I/O
- Flexible interrupt system
- Small-form factor: 2.0 mm × 2.0 mm × 0.65 mm

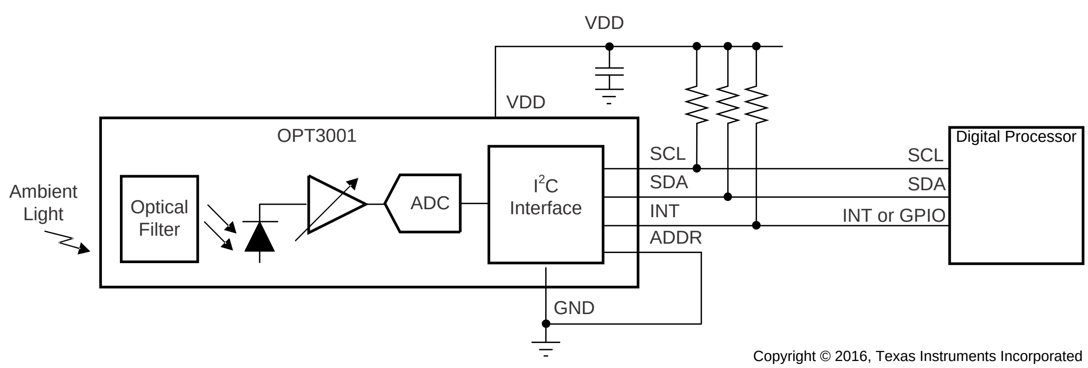

Figure 4. OPT3001 Block Diagram

1.4.7 CC2650

The CC2650 device is a wireless MCU targeting Bluetooth® Smart, ZigBee®, 6LoWPAN, and ZigBee RF4CE remote control applications (see Figure 5).

The device is a member of the CC26xx family of cost-effective, ultra-low-power, 2.4-GHz RF devices. Very-low active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin cell batteries and in energy-harvesting applications.

The CC2650 device contains a 32-bit ARM Cortex™-M3 processor that runs at 48 MHz as the main processor, and a rich peripheral feature set that includes a unique ultra-low-power sensor controller. This sensor controller is ideal for interfacing external sensors, and for collecting analog and digital data autonomously while the rest of the system is in sleep mode. Thus, the CC2650 device is ideal for applications within a whole range of products including industrial, consumer electronics, and medical.

The BLE controller and the IEEE 802.15.4 MAC are embedded into ROM, and are partly running on a separate ARM Cortex-M0 processor. This architecture improves overall system performance and power consumption, and frees up flash memory for the application.

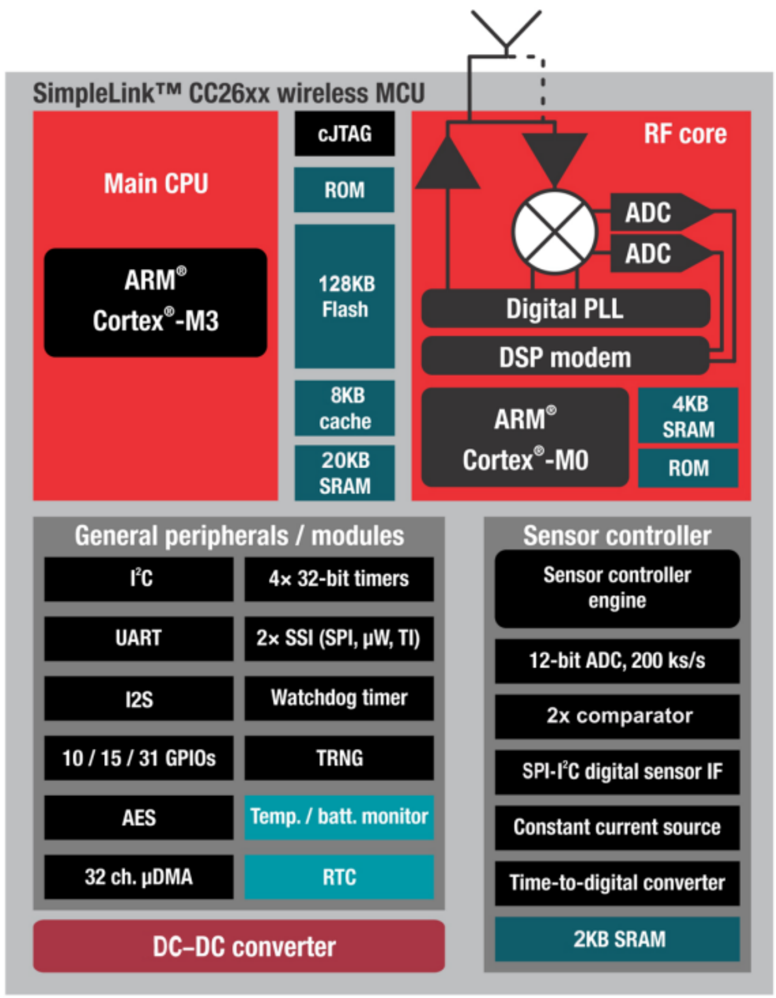

Figure 5. CC2650 Block Diagram

1.4.8 OPA376

The OPA376 family represents a new generation of low-noise operational amplifiers with e-trim™, offering outstanding DC precision and AC performance. Rail-to-rail input and output, low offset (25 µV maximum), low noise (7.5 nV/√Hz), quiescent current of 950 µA (maximum), and a 5.5-MHz bandwidth make this part attractive for a variety of precision and portable applications. In addition, this device has a reasonably-wide supply range with excellent power supply rejection ratio (PSRR), which makes it desirable for applications that run directly from batteries without regulation.

The OPA376 (single version) is available in MicroSIZE SC70-5, SOT-23-5, and SOIC-8 packages. The OPA2376 (dual) is offered in the DSBGA-8, VSSOP-8, and SOIC-8 packages. The OPA4376 (quad) is offered in a TSSOP-14 package. All versions are specified for operation from –40°C to +125°C.

Features:

- Low noise: 7.5 nV/√Hz at 1 kHz
- 0.1 Hz to 10 Hz noise: 0.8 µV_{PP}
- Quiescent current: 760 µA (typical)
- Low offset voltage: 5 µV (typ)
- Gain bandwidth product: 5.5 MHz
- Rail-to-rail input and output
- Single-supply operation
- Supply voltage: 2.2 V to 5.5 V
- Space-saving packages: SC70, SOT-23, DSBGA, VSSOP, TSSOP

1.4.9 LMT84

The LMT84 and LMT84-Q1 are precision CMOS integrated-circuit temperature sensors with an analog output voltage that is linearly and inversely proportional to temperature. The sensor features make it suitable for many general temperature-sensing applications. The LMT84 can operate down to a 1.5-V supply with 5.4-µA power consumption, making it ideal for battery-powered devices.

Package options, including the through-hole TO-92 package, allows the LMT84 to be mounted onboard, off-board, to a heat sink, or on multiple locations in the same application. A class-AB output structure gives the LMT84/LMT84-Q1 strong output source and sink current capability that can directly drive up to 1.1-nF capacitive loads. The LMT84 is well suited to drive an ADC sample-and-hold input with its transient load requirements. The device has accuracy specified in the operating range of −50°C to 150°C. The accuracy, three-lead package options, and other features also make the LMT84/LMT84-Q1 an alternative to thermistors.

Features:

- LMT84-Q1 is AEC-Q100 Grade 0 qualified and is manufactured on an automotive grade flow
- Low 1.5-V operation
- Very accurate: ±0.4°C typical
- Wide temperature range of –50°C to 150°C
- Low 5.4-µA quiescent current
- Average sensor gain of –5.5 mV/°C
- Output is short-circuit protected
- Push-pull output with ±50-µA drive capability
- Footprint compatible with the industry-standard LM20/19 and LM35 temperature sensors
- Cost-effective alternative to thermistors

2 System Design Theory

LEDs require constant current drive, and, in most cases, the current must be adjustable to enable dimming. Thus the user must have a regulated AC-DC power supply and adjustable current controller to facilitate dimming. For DC lighting systems, low-voltage DC is directly available, and thus a current controller with dimming capability is adequate. To enable dimming and control, use a wireless control or wired control system. Wireless lighting controls are becoming more common because of their ease of use and availability.

The TIDA-01095 platform uses TPS92641, a synchronous buck controller for a precision dimming LED drive. The controller requires two external MOSFETs that must be sized based on the power requirements. The TPS92641 is designed for high-speed capability, including an oscillator frequency range of up to 1 MHz. The dead time between high-side and low-side gate drivers is optimized to provide very high efficiency over a wide input operating voltage and output power range. The TPS92641 device accepts both analog and pulse width modulation (PWM) input signals, resulting in exceptional dimming control range. Linear response characteristics between the input command and LED current is achieved with true zero LED current, using a low off-set error amplifier and proprietary PWM dimming logic. For dimming control and wireless connectivity, the SimpleLink™ technology, multi-standard, 2.4-GHz ultra-low-power wireless MCU CC2650 is used. Besides 2.4-Ghz RF connectivity, the built-in peripherals such as an analog-to-digital converter (ADC) and PWMs are useful in this lighting application. The SimpleLink CC2650 Wireless MCU LaunchPad™ kit generates one PWM for the PWM dimming and another PWM, followed by a four-stage low-pass filter and low-offset operational amplifier (op amp) as a buffer-generated variable voltage as I_{ADJ}, to enable analog dimming. Dimming through I_{ADJ} is more efficient and produces less electromagnetic interference (EMI). However, at very low currents, there is slight variation in the color temperature of the LEDs, which may not be desirable. The PWM dimming method avoids this issue and allows higher resolution dimming. However, both dimming methods can be combined through software to achieve both high efficiency and wider dimming resolution.

The OPT3001 Digital Ambient Light Sensor (ALS) with high-precision human eye response is interfaced with the CC2650 MCU and thus features, such as constant lumen output and daylight energy harvesting by automatic dimming of LEDs with the presence of sun light, can easily be implemented in the software. The CC2650 SimpleLink multi-standard, 2.4-GHz ultra-low-power wireless MCU lets the user implement any of the various radio frequency (RF) connectivity standards, such as Bluetooth Smart, ZigBee, 6LoWPAN, and ZigBee RF4CE for remote control applications. The LMT84 1.5 V-capable, 10-µA analog output temperature sensor in the TO-92 package allows the user to measure the temperature of the LED heatsink, which enables automatic foldback dimming in the case of overtemperature, and enables LED string or LED COB protection.

2.1 Design Equations

2.1.1 Undervoltage Lockout (UVLO)

The UDIM pin of the TPS92641 is a dual-function input that features an accurate 1.276-V threshold with programmable hysteresis. This pin functions as both the PWM dimming input of the LEDs and as an input UVLO with built-in hysteresis. When the pin voltage rises and exceeds the 1.276-V threshold, 21 µA (typical) of current is driven out of the UDIM pin into the resistor divider (R_{UDIM1}, R_{UDIM2}) providing programmable hysteresis. The UVLO turnon threshold, V_{TURN_ON}, is defined in Equation 1:

$$V_{TURN\_ON} = 1.276 \times \left(\frac{(R_{UDIM1} + R_{UDIM2})}{R_{UDIM2}} \right) \quad (1)$$

To set an undervoltage lockout threshold of 31.9 V (typical), chose R_{UDIM1} and R_{UDIM2} as R_{UDIM1} = 120 k and R_{UDIM2} = 5 k. The minimum and maximum threshold values can be calculated based on the corresponding values specified in the TPS92641 data sheet, as in Equation 2 and Equation 3.

$$V_{TURN\_ON\_MIN} = 1.21 \times \left(\frac{(R_{UDIM1} + R_{UDIM2})}{R_{UDIM2}} \right) = 30.25\ V \quad (2)$$

$$V_{TURN\_ON\_MAX} = 1.342 \times \left(\frac{(R_{UDIM1} + R_{UDIM2})}{R_{UDIM2}} \right) = 33.55\ V \quad (3)$$

2.1.2 Overvoltage Protection (OVP)

The TPS92641 has programmable overvoltage protection by using the resistor divider at the VOUT pin. The OVP limit, V_{OVP_ON}, is defined as in Equation 4.

$$V_{OVP\_ON} = 3.05 \times \left(\frac{(R_{UDIM1} + R_{UDIM2})}{R_{UDIM2}} \right) \tag{4}$$

The values of R_{VOUT1} and R_{VOUT2} have been chosen to set the limit at 57.5, that is, R_{VOUT1} = 100 k and R_{VOUT2} = 5.6 k. If the output voltage reaches V_{OVP_ON}, the HG, LG, and SDRV pins are pulled low to prevent damage to the LEDs or the rest of the circuit. The OVP circuit has a fixed hysteresis of 100 mV before the driver attempts to switch again.

2.1.3 Switching Frequency

The switching frequency, f_{SW}, can be calculated using the following equation from the TPS92641 data sheet, as in Equation 5.

$$f_{SW} = \left(\frac{(R_{VOUT1} + R_{VOUT2})}{(R_{VOUT2} \times R_{ON} \times C_{ON})} \right) \tag{5}$$

For setting f_{SW} = 220 kHz, the following values of the resistance and capacitance can be used: R_{ON} = 47k, C_{ON} = 1.8 nF.

$$f_{SW} = \left(\frac{(100 + 5.6)}{(5.6 \times 47 \times 1.8)} \right) \text{MHz} = 222.89 \text{ kHz} \tag{6}$$

2.1.4 Adjustable LED Current (I_{ADJ})

The average LED current regulation is set using a sense resistor in series with the LEDs. The internal error amplifier regulates the voltage across the sense resistor (V_{CS}) to the I_{ADJ} voltage divided by 10. I_{ADJ} can be set to any value up to 2.54 V, by connecting it to V_{REF} through a resistor divider for static output current settings. I_{ADJ} can also be used to change the regulation point, if connected to a controlled voltage source or potentiometer, to provide analog dimming. I_{ADJ} can also be configured for thermal foldback functions.

The set LED current depends on R_{CS} and V_{CS}, as shown in Equation 7 and Equation 8.

$$I_{LED} = \frac{V_{CS}}{R_{CS}} \tag{7}$$

$$V_{CS} = \frac{V_{IADJ}}{10} \tag{8}$$

This controllable analog voltage is generated by a buffered, four-pole, RC low-pass filter, which in turn takes a variable PWM input from the CC2650 MCU. The maximum analog output voltage is 3.3 V (logic high) at 100% duty cycle. To match this with 2.54 V, a resistor divider is placed following the output of the buffer. The chosen values of the resistors are 174 Ω at the buffer side and 542 Ω at the ground side, giving a full scale output voltage of ≈2.596 V.

2.1.5 Fourth-Order Passive Low-Pass Filter

To utilize the analog dimming feature of the TPS92641, a variable analog voltage is required. This voltage is achieved by low-pass filtering the PWM generated by the CC2650 device to obtain its average value. The passive RC low-pass filter gives an analog voltage output with 12 bits of resolution, as in Equation 9.

$$\text{Resolution} = \frac{V_{PWM}}{2^n}$$

where

- Resolution is the minimum incremental change in the analog output voltage with a change in PWM duty cycle
- V_{PWM} is the amplitude of the PWM signal
- n is the resolution in bits for the analog signal (12 in this case) (9)

$$\text{Minimum Ripple} = \frac{\text{Resolution}}{2} = \frac{V_{PWM}}{2 \times 2^n} \quad (10)$$

$$\text{Ripple} = \frac{V_{PWM}}{10^{Order}} \quad (11)$$

$$\frac{V_{PWM}}{10^{Order}} = \frac{V_{PWM}}{2 \times 2^n} \quad (12)$$

$$\text{Order} = (n + 1)\log(2) \quad (13)$$

Therefore, the order = 13 × 0.3 = 3.9.

Round up the order to the next highest integer, if it is fractional, to achieve a higher performance than the goal. Thus, the order = 4.

The equation that sets the cutoff frequency for a simple first-order, RC low-pass filter is given as Equation 14.

$$R_1 = \frac{1}{(2\pi \times f_{CUTOFF} \times C_1)} = \frac{1}{(2\pi \times 391\ \text{Hz} \times 470\ \text{nF})} = 866\ \Omega$$

where

- $f_{CUTOFF} = \frac{f_{PWM}}{10} = \frac{3.91\ \text{kHz}}{10} = 391\ \text{Hz}$
- R_1 and C_1 = first-stage low-pass RC filter
- C_1 is selected arbitrarily as a standard value; choose near 1 uF as the capacitance in each subsequent stage divided by 10 (14)

The RC filter loads the microcontroller. The load current is at a maximum when the PWM signal makes a logic level transition (such as low-to-high or high-to-low). The transient current can be estimated as shown in Equation 15.

$$I_{TRANSIENT} = \frac{V_{CC}}{R_1} = \frac{3.3}{866} = 3.8\ \text{mA} \quad (15)$$

The transient current is 3.8 mA, which is a reasonable load for the CC2650 device. To obtain a higher-order filter, additional stages of the filter can be cascaded. However, ensure that subsequent stages do not load the initial stage. A simple approach to prevent the loading is to increase the impedance of each subsequent stage by a factor of ten, as shown in Table 2.

Table 2. Impedance Stages

LOW-PASS FILTER STAGE	RESISTOR DESIGNATOR	RESISTOR VALUE	CAPACITOR DESIGNATOR	CAPACITOR VALUE
Stage 1	R15	866 Ω	C14	0.47 µF
Stage 2	R16	8.66 KΩ	C15	0.047 µF
Stage 3	R17	86.6 KΩ	C16	0.0047 µF
Stage 4	R18	866 KΩ	C17	470 pF

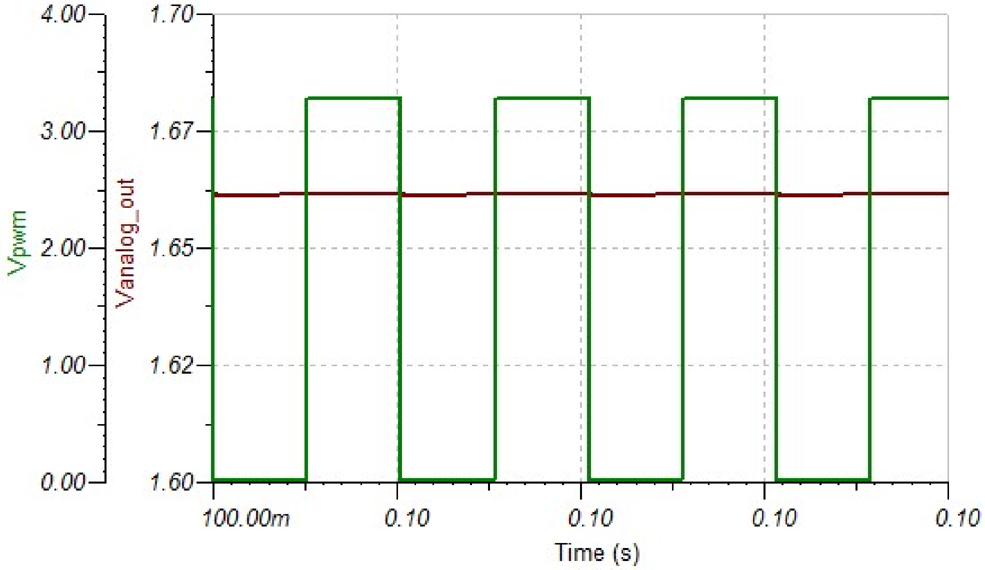

Figure 6. V_{PWM} versus Time (1 of 2)

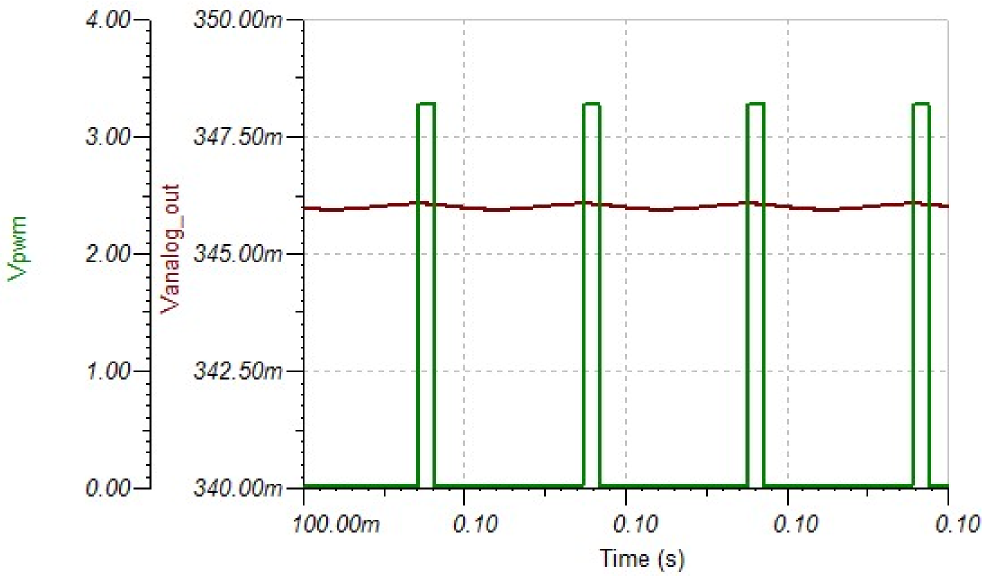

Figure 7. V_{PWM} versus Time (2 of 2)

2.1.6 Control Loop Compensation (COMP)

Compensating the TPS92641 is relatively simple for most applications. The only compensation required is a compensation capacitor, C_{COMP} across the COMP pin, and a ground to place a low-frequency dominant pole in the system. The pole must be placed low enough to ensure adequate phase margin at the crossover frequency. For most applications, a C_{COMP} of 100 nF to 470 nF is adequate, and a 100-nF capacitor has been selected for this application. Additionally, TI recommends a high-quality ceramic capacitor with an X7R dielectric rated for 25 V.

2.1.7 Inductor Selection

Because this is a PWM-dimming application, too much output capacitance is not recommended for faster current rise and fall times, so the inductor ripple current must be close to the 500-mA peak-to-peak. The governing equation which relates the inductor value (L), inductor ripple current (I_L), f_{SW}, V_{IN}, and V_{OUT} is shown in Equation 16.

$$L = \left(\frac{(V_{IN} - V_{OUT}) \times D}{\Delta I_L \times f_{SW}} \right)$$

where

- In this application, V_{IN} = 48 V
- f_{SW} = 222 kHz
- $V_{OUT} = V_{LED} + V_{CS}$ = 38.5 + 0.15 = 38.65
- $$D = \frac{V_{OUT}}{V_{IN}} = \frac{38.65}{48} = 0.81 \quad (16)$$

Thus, solve for L: $$L = \frac{(9.35 \times 0.81)}{(0.5 \times 0.222)} = 68.23\ \mu H$$

Choose the standard inductor value 68 µH, which results in an ΔI_L of 501 mA.

2.1.8 LED Ripple Current Selection

LED ripple current, ΔI_{LED}, in an LED driver is the equivalent of output voltage ripple, ΔV_O, in a voltage regulator. In general, the requirements for ΔI_{LED} are not as tight as the output voltage ripple. A ripple of a few mV to 4% P-P of V_O is typical for ΔV_O, whereas ripple currents for LED drivers range from 10% to 40% P-P of the average forward current. Allowing larger ripple current means lower inductance and capacitance for the output filter, which in turn translates to smaller printed-circuit board (PCB) footprints and lower bill of material (BOM) costs. For this reason, ΔI_{LED} can generally be made as large as the application permits. This application is designed for an LED peak-to-peak ripple current equal to 1/8th or 12.5% of the maximum forward current (2800 mA = 2.8 A), ΔI_{LED} = 350 mA.

2.1.9 Dynamic Resistance of LED

Load resistance is an important parameter in power supply design, particularly for the control loop. In LED drivers, load resistance is used to select the output capacitance required to achieve the desired LED ripple current. When the load is an LED or string of LEDs, however, the load resistance is replaced with the dynamic resistance, r_D, and the current sense resistor. Typical dynamic resistance at a specified forward current is provided by some manufacturers, but in most cases it must be calculated using I-V curves.

The dynamic resistance calculation for the selected LED load is done as shown in Table 3, based upon the IV measurements.

Table 3. Forward Current and Voltage

FORWARD CURRENT (A)	FORWARD VOLTAGE (V)
2.748	41.80
2.462	40.77
2.169	39.75
1.872	38.74
1.578	37.74
1.284	36.72
0.991	35.68
0.700	34.58
0.409	33.29

A least square trend line can be fit in the above data to calculate the dynamic resistance. The equation of the trend line is V = 3.5691I + 32.038. Therefore, the dynamic resistance, r_D, comes out to 4.34 Ω.

2.1.10 Output Capacitor Selection

The LED manufacturers generally recommend values of current ripple, ΔI_{LED}, to achieve optimal optical efficiency. The peak-to-peak current ripple values typically range from ±10% to ±40% of DC current, I_{LED}. A capacitor placed in parallel with the LED or array of LEDs can be used to reduce ΔI_{LED} while keeping the same average current through both the inductor and the LED array. With this topology, the inductance can be lowered, making the magnetics smaller and less expensive.

$$\Delta I_{LED} = \frac{\Delta I_L}{\left(1 + \left(\frac{r_D}{Z_{COUT}}\right)\right)} \tag{17}$$

$$Z_{COUT} = \frac{1}{\left(2\pi \times f_{SW} \times C_{OUT}\right)} \tag{18}$$

Rearranging Equation 17 and Equation 18 shows the relation for the required value of C_{OUT} shown in Equation 19.

$$C_{OUT} = \frac{\left(\Delta I_L - \Delta I_{LED}\right)}{\left(2\pi \times f_{SW} \times r_D \times \Delta I_{LED}\right)} = \frac{(0.501 - 0.35)}{(2\pi \times 0.222 \times 3.5691 \times 0.35)}\ \mu F = 87\ nF \tag{19}$$

Therefore, choose C_{OUT} to be 0.1 uF. The actual value of ΔI_{LED} for 0.1 uF turns out to be 334 mA.

For low dimming currents of up to 100 uA, a higher output capacitance is required to reduce the output voltage ripple, and thus the LED ripple current. For this purpose, a 1-uF capacitor is placed in parallel with the calculated 0.1-uF capacitor. If low dimming currents are not required, then this component can be left unpopulated.

2.1.11 Minimum Input Capacitance

Input capacitance is necessary to provide instantaneous current to the discontinuous portions of the circuit during the high side NFET on-time. The allowable input voltage ripple ($\Delta V_{IN\text{-}PP}$) is specified at approximately 4 V peak-to-peak of V_{IN} = 48 V. The minimum required capacitance ($_{CIN\_MIN}$) to achieve this specification is as in Equation 20.

$$C_{IN\_MIN} = \frac{\left(I_{LED} \times D\right)}{\left(\Delta V_{IN-PP} \times f_{SW}\right)} = \frac{(2.8 - 0.81)}{(4 \times 0.222)} = 2.55\ \mu F \tag{20}$$

TI recommends that a higher capacitance be chosen than the value calculated above, especially for PWM applications. Thus, two capacitors, one each of 1 uF and 2.2 uF, are placed in parallel to jointly make up an equivalent capacitance of 3.2 uF.

2.1.12 MOSFET Selection

The TPS92640 and TPS92641 devices require two external NFETs for the switching regulator. The FETs should have a voltage rating at least 20% higher than the maximum input voltage to ensure safe operation during the ringing of the switch node. In practice, all switching converters have some ringing at the switch node, due to the diode parasitic capacitance and the lead inductance. The NFETs should also have a current rating at least 50% higher than the average transistor current. Once NFETs are chosen, the power rating is verified by calculating the power loss.

The suggested minimum voltage rating, V_{T_MAX} and current rating, I_{T_MAX} are as in Equation 21 and Equation 22.

$$V_{T\_MAX} = 1.2 \times V_{IN\_MAX} = 1.2 \times 50 = 60\ V \tag{21}$$

$$I_{T\_MAX} = 1.5 \times D_{MAX} \times I_{LED} = 1.5 \times \left(\frac{42}{48}\right) \times 2.8 = 3.675\ A \tag{22}$$

The MOSFETs chosen in this application are CSD18537NQ5A (60-V, 50-A N-Channel NexFET™ Power MOSFET) for the high side and CSD18563Q5A (60-V, 50-A N-Channel NexFET Power MOSFET, logic level compatible) for the low side. These pair of MOSFETs are designed to minimize losses for power conversion applications. Specifically, the CSD18563Q5A was designed to pair with the CSD18537NQ5A control FET and act as the sync FET for a complete industrial buck converter chipset solution.

NOTE: The TIDA-01095 board is also tested with 100-V MOSFETs to enable DC-DC driver operating voltage up to 80 V. Texas Instruments CSD19534Q5A 100 V N-Channel NexFET Power MOSFETs are used for both high-side and low-side switch.

2.1.13 High-Side Gate Resistor

As the performance of power devices has improved, the control FET has the ability to switch voltages at rates greater than 10 kV/µs. However, the fast switching faces a common challenge of dealing with switching noise. In particular, when the Control FET turns on and the Sync FET is off, the loop inductor, the loop resistor, and the output capacitor of the sync FET form a series RLC loop and resonate at a resonant frequency. This resonance results in voltage overshoot and ringing at the switch node. Using a resistor in series with the gate of the high-side FET is an effective way to reduce ringing. Similar to the boot-resistor method, this resistor slows down the turnon of the high-side FET. However, because this resistor is in series with the gate, it is also in the discharge path, so it slows down the turnoff as well. To reduce the ringing for this design, a 24-Ω gate resistor is used.

The following waveforms in Figure 8, Figure 9, Figure 10, and Figure 11 show the effect of the gate resistor on the switch node ringing.

60-V MOSFETs:

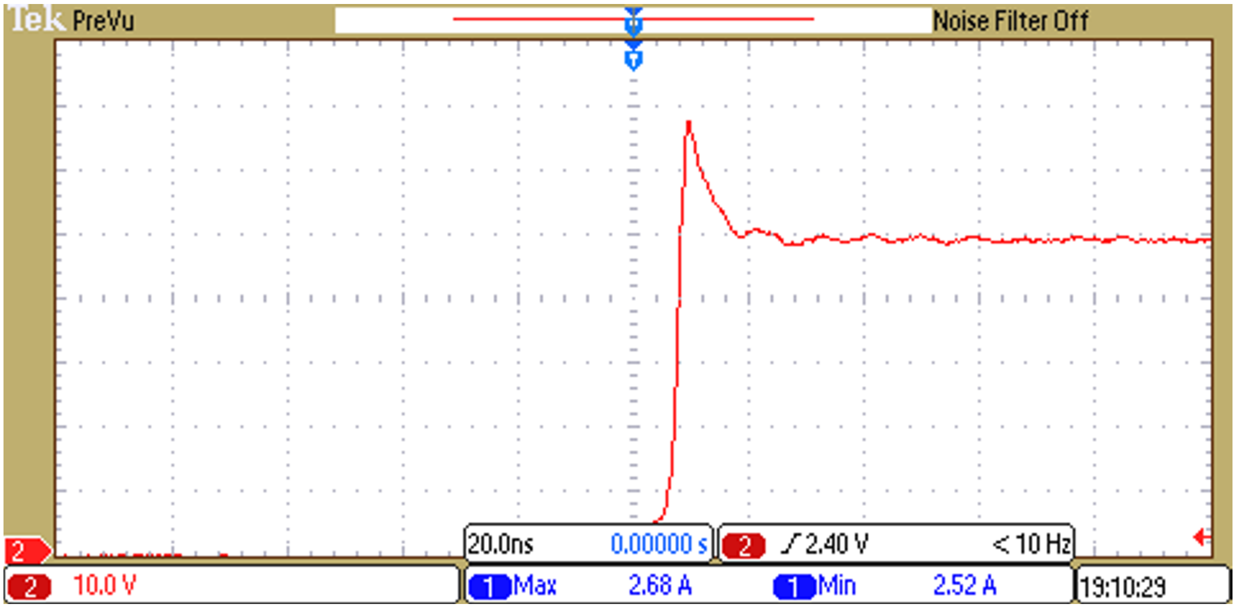

Figure 8. Voltage Waveform Across Drain Source of Low-Side MOSFET Without Any Gate Resistor, Peaking Around 68 V

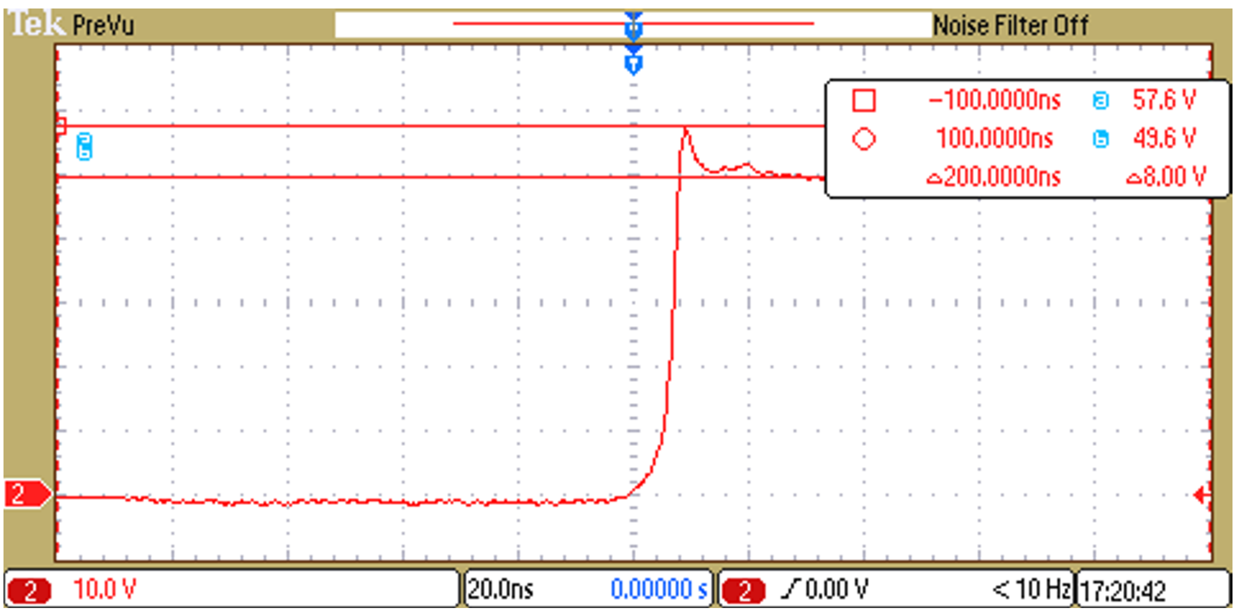

Figure 9. Voltage Waveform Across Drain Source of Low-Side MOSFET With 25-Ω Gate Resistor, Peaking at 57.6 V

100-V MOSFETs:

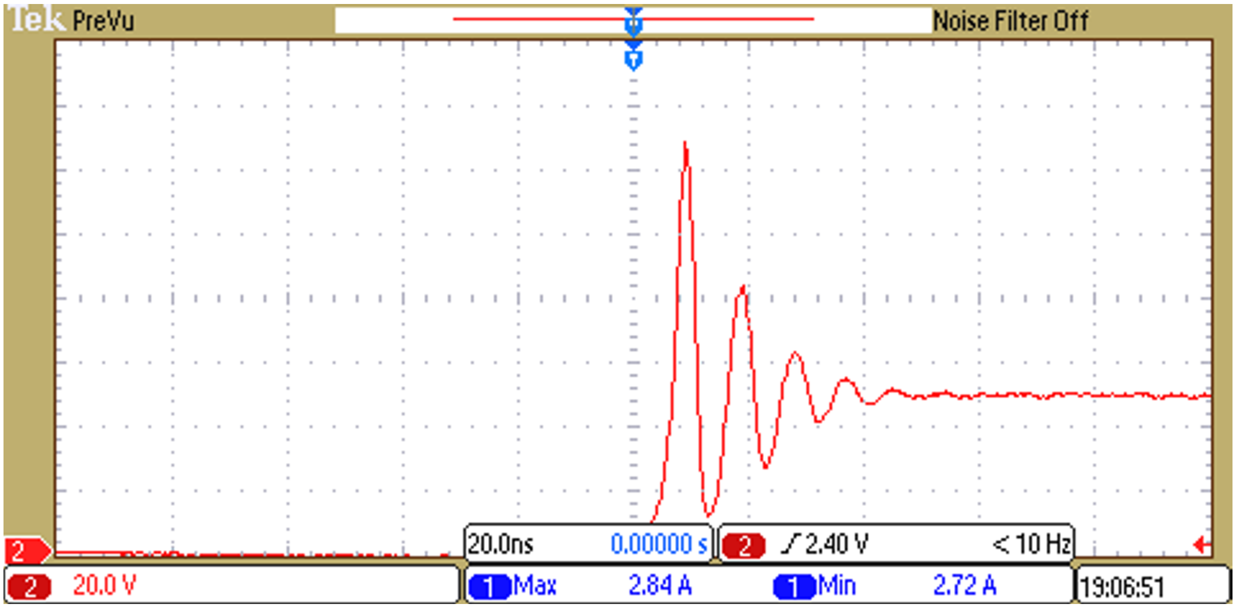

Figure 10. Voltage Waveform Across Drain Source of Low-Side MOSFET Without Any Gate Resistor, Peaking Around 124 V

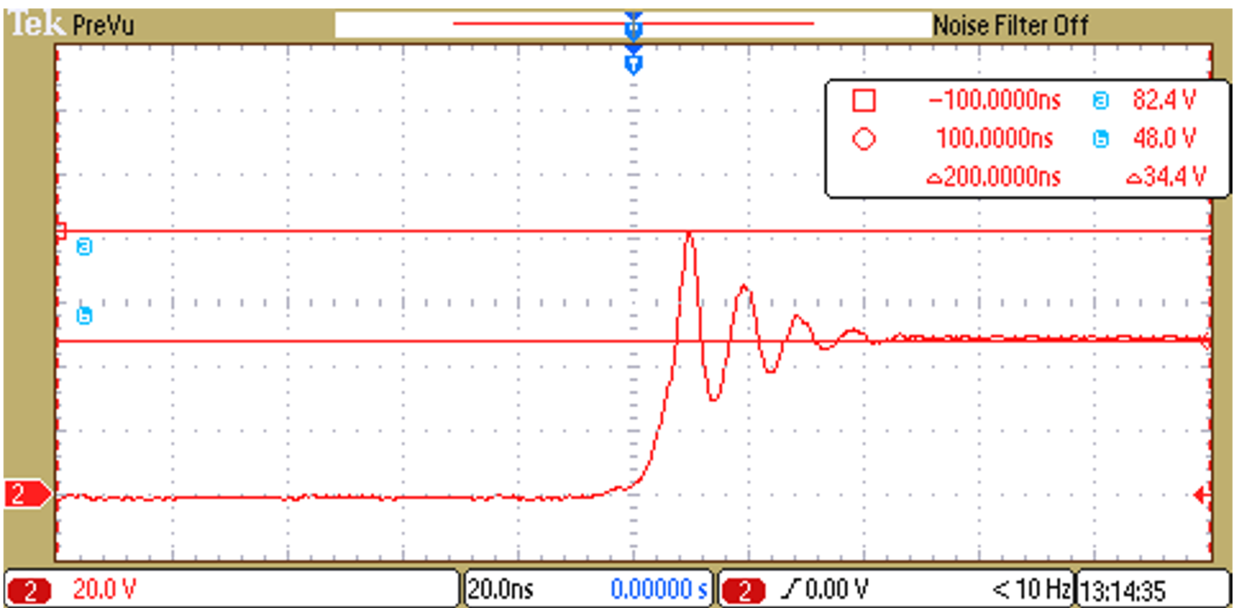

Figure 11. Voltage Waveform Across Drain Source of Low-Side MOSFET Without 25-Ω Gate Resistor, Peaking at 82.4 V

2.2 Dimming Techniques

2.2.1 Analog Dimming Using I_{ADJ}

The LED current can be set and controlled dynamically by using the IADJ pin of the TPS92641 device. In this application, the V_{IADJ} voltage is obtained from a fourth-order passive LPF followed by an OPA376 operational amplifier used as a voltage follower. This low-pass filter converts the digital PWM waveform (logic high – 3.3 V and logic low – 0 V) from the CC2650 to an analog voltage equal to the average value of the PWM waveform. The output of the op-amp feeds a resistor divider to scale the maximum possible input voltage from 3.3 V to 1.57 V as desired, and to not let the LED current exceed 3 A, the set maximum value. Refer to Section 4 for the set of measurements taken using this feature.

The fourth-order low pass filter is designed for PWM frequencies of 3.91 kHz and above. The operating frequency of the CC2650 MCU is f_{MCU} = 48 MHz. This corresponds to the cycle time of:
T_{MCU} = 125 / 6 = 20.83 ns. The desired PWM frequency is generated by counting these cycles.
To generate a PWM frequency of f_{PWM}, the MCU cycles must be counted until T_{PWM} / T_{MCU}, where T_{PWM} = 1 / f_{PWM}.

The following list provides more details:

- For the counts: $N_{PWM} = T_{PWM} / T_{MCU} = f_{MCU} / f_{PWM} = 48,000,000 / f_{PWM}$.
- For any chosen f_{PWM}, the minimum possible duty cycle (resolution of the PWM) can be obtained by keeping the corresponding I/O pin high for the duration of only 1 MCU cycle, that is, 1 count.
- The PWM resolution = 1 / N_{PWM} × 100%.
- For f_{PWM} = 4 kHz, the PWM resolution is 0.0083%. Thus, one count results in an incremental output voltage of 0.0083% of 3.3 V = 0.275 mV at the output of the buffer.

2.2.2 Digital PWM Dimming Using UDIM

The UDIM pin can be driven with a PWM signal, which controls the synchronous NFET operation. The brightness of the LEDs can be varied by modulating the duty cycle (D_{DIM}) of this signal using a Schottky diode with an anode connected to the UDIM pin. The resulting dimmed LED current (I_{DIM_LED}) is given as in Equation 23.

$$I_{DIM\_LED} = D_{DIM} \times I_{LED} \quad (23)$$

This PWM is generated using the CC2650 MCU, and the operation of this feature has been tested for PWM frequencies of 1 kHz and 5 kHz. Refer to Section 4 for the set of measurements taken using this feature.

2.2.3 100-µA Flicker-Free Dimming

The TIDA-01095 can be used to achieve 100-µA flicker-free output LED current by modifying the value of the current sensing resistor from 50 mΩ to 250 mΩ. This increases the voltage at the CS pin seen by the TPS92640/1 device. The LED current measurements (with the 250-mΩ CS resistor and 60-V MOSFEts) in the range 49 µA to 1 mA are as shown in Table 4.

Table 4. LED Current Measurements

V_{IN} (V)	I_{IN} (mA)	V_{OUT} (V)	I_{OUT} (mA)	V_{IADJ} (V)
48.50	0.021	28.53	0.049	0.0697
48.50	0.021	28.71	0.073	0.0703
48.50	0.021	28.86	0.103	0.0709
48.50	0.021	28.96	0.125	0.0713
48.50	0.021	29.01	0.251	0.0717
48.50	0.021	29.16	0.360	0.0725
48.50	0.021	29.27	0.457	0.0731
48.50	0.021	29.36	0.561	0.0737
48.50	0.021	29.42	0.640	0.0741
48.50	0.021	29.51	0.758	0.0747
48.50	0.021	29.56	0.846	0.0752
48.50	0.021	29.63	0.975	0.0758
48.50	0.021	29.66	1.020	0.0760

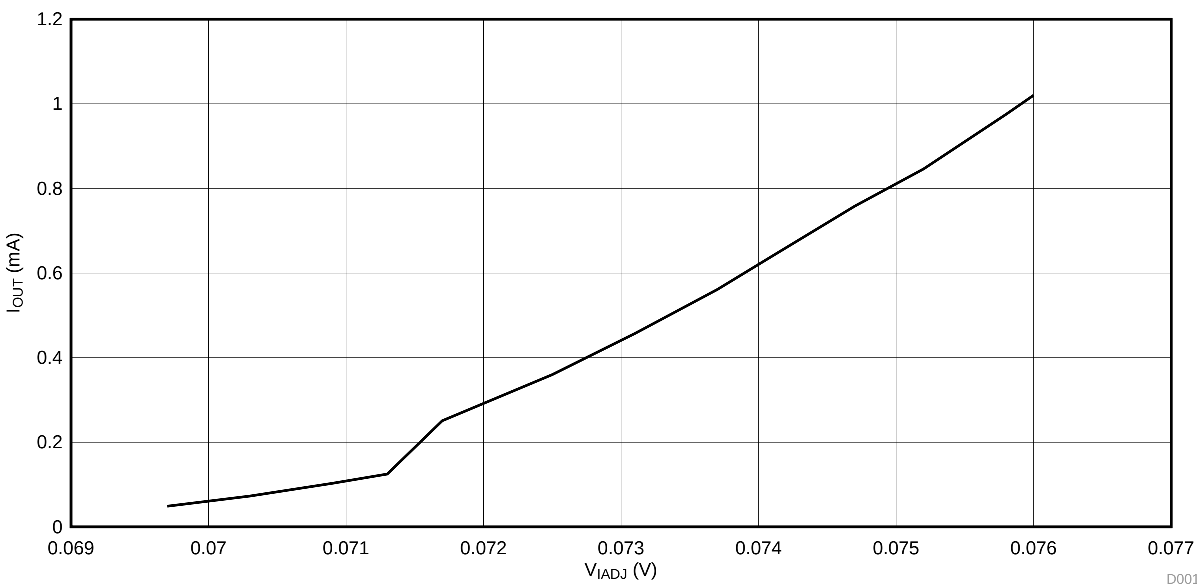

Figure 12. I_{OUT} (mA) versus V_{IADJ} (V)

3 Getting Started Hardware and Software

3.1 Hardware Connections

Figure 13 shows the hardware interconnections and wireless connections required for the TIDA-01095 to work as expected. As mentioned earlier, the TIDA-01095 connects as a BoosterPack™ Plug-in Module upon the CC2650 LaunchPad. Both of these boards should be assembled as shown in Figure 14.

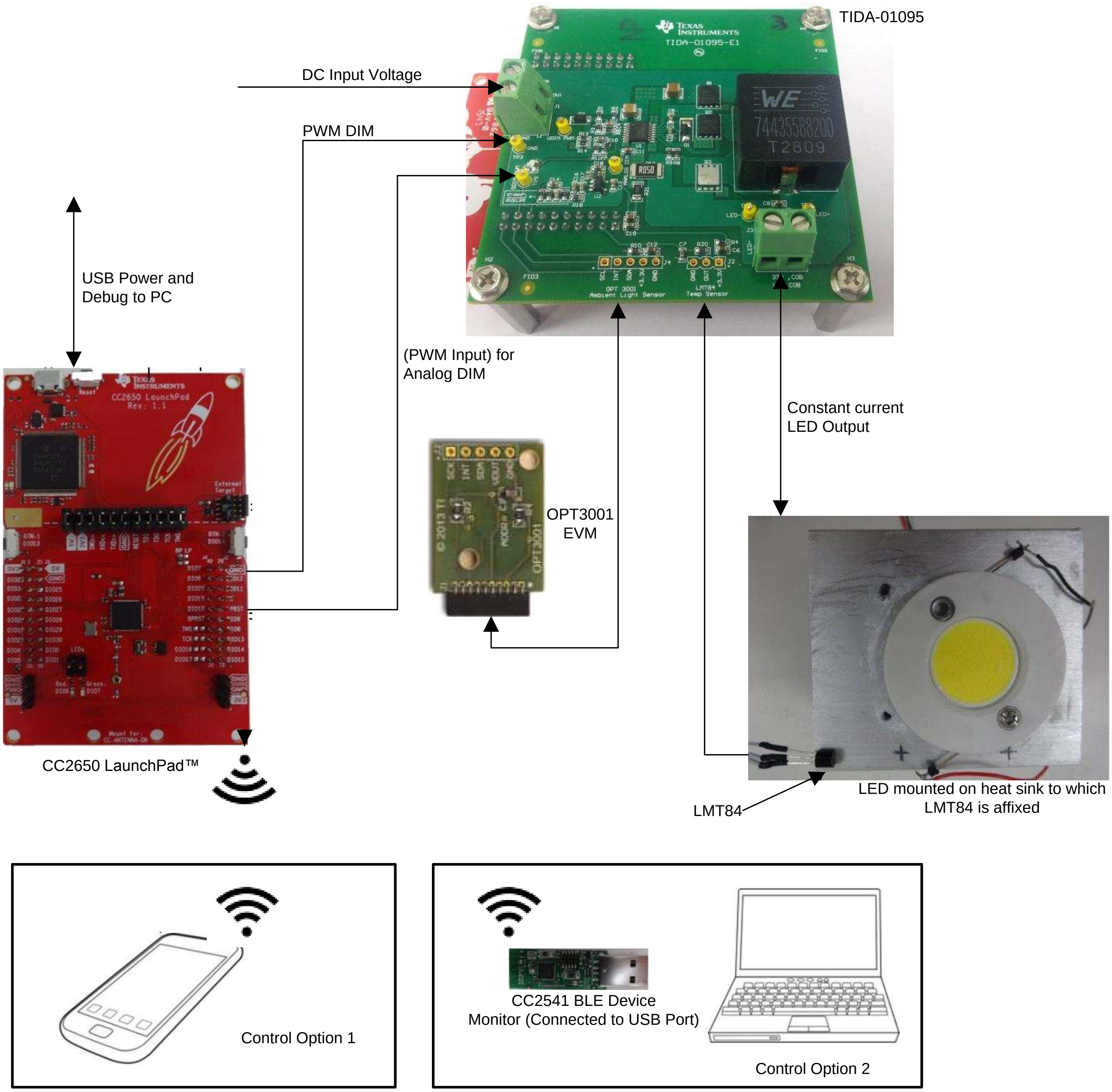

Figure 13. Hardware Connections

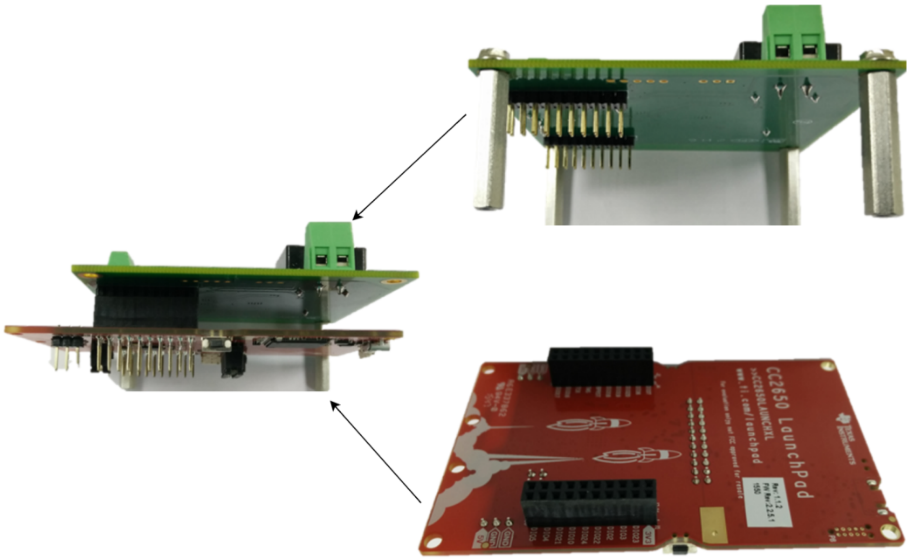

Figure 14. Board Assembly

Along with the TIDA-01095 and CC2650, either a BLE dongle—the TI CC2540 USB dongle has been used in this design—or a Bluetooth-enabled phone (with a BLE scanner application) is required to control the dimming setting of the LED.

3.2 Firmware

3.2.1 Compiling Project in CCS™ Software

The provided project files require TI's Code Composer Studio™ (CCS) software (verified with v6) and the BLE software stack (BLE-STACK V2.1.0, which must be downloaded from the BLE software stack archive at http://www.ti.com/tool/BLE-STACK-ARCHIVE. Any other installed versions of BLE software stack will require uninstallation). After installing CCS and BLE Stack, the compilation can be done as follows. The following instructions assume that CCS and BLE Stack are installed in the directory C:\ti\, the default installation directory.

1. Download the project from <URL>.
2. Open CCS and select (create) an existing (new) workspace.
3. Import the example project SimpleBLEPeripheral from *C:\ti\simplelink\ble_cc26xx_2_01_01_44627\Projects\ble\SimpleBLEPeripheral\CC26xx\CCS\SimpleBLEPeripheral*.
4. Import the example project SimpleBLEPeripheralStack from *C:\ti\simplelink\ble_cc26xx_2_01_01_44627\Projects\ble\SimpleBLEPeripheral\CC26xx\CCS\SimpleBLEPeripheralStack*.
5. Build SimpleBLEPeripheralStack.
6. After the SimpleBLEPeripheralStack builds successfully without any error:
   - Click on SimpleBLEPeripheral → Application (under the Project Explorer tab), and right-click on simpleBLEPeripheral.C to select properties. Select Resource on the left pane, and click on Edit to edit the Location. Then, click on File and browse to <directory-name>, and select simpleBLEPeripheral.C.
   - Similarly, click on SimpleBLEPeripheral → Startup, and right-click on main.C to select properties. Select Resource on the left pane, and click on Edit to edit the Location. Then, click on File and browse to <directory-name>, and select main.C.
7. Click on SimpleBLEPeripheral → Startup and open Board.C. Modify the file by adding the following two lines at line number 64 below the comment.

   ```
   64 #if defined(LED_Dimmer_CC2650LP)
   65    #include "LED_Dimmer/Board.c"
   ```

   Change the #if directive in the following line (number 66) to #elif. Save the file.
8. Right-click on SimpleBLEPeripheral to open properties.
   (a) Select the General option in the left pane. Under the Main tab, tick Manage the project's target-configuration automatically and select Texas Instruments XDS110 USB Debug Probe as Connection.
   (b) Click on Include Options under ARM Compiler in the left pane. Click on the Add icon to add the directory path. Click on Browse and add the path to the <directory-name>. Similarly, add <directory-name>\LED_Dimmer.
   (c) Select Advanced Options → Predefined Symbols from the left pane in the Properties dialogue box. Add the symbol TI_DRIVERS_I2C_INCLUDED (if not already present in the list) by clicking on the Add icon, typing in TI_DRIVERS_I2C_INCLUDED, and clicking OK. Also, in the same list, modify the TI_DRIVERS_LCD_INCLUDED entry (if present) by clicking on the Edit icon and typing xTI_DRIVERS_LCD_INCLUDED.
   (d) Finally, click OK to close the Properties dialogue box.
9. Right-click on SimpleBLEPeripheral → Drivers and select New → Folder. Click on Advanced, and then Link to alternate location (Linked Folder). Browse to <directory-name>\i2c and Finish.
10. Right-click on SimpleBLEPeripheral and navigate to Folder under New to create a new folder. Leave the default parent folder SimpleBLEPeripheral unchanged, type in the Folder Name as LEDService, and click OK.
11. Right-click on SimpleBLEPeripheral and select Add Files.
12. Navigate to <directory-name>\LED_Dimmer. Select all the .C files except Board.C. Select Copy Files in the next dialogue box and click OK. Move all the added files to LEDService by first selecting all the files and then right-clicking to select Move to SimpleBLEPeripheral → LEDService.

13. Right-click on SimpleBLEPeripheral and Clean Project.
14. Build the project.

3.2.2 Using the BLE Device Monitor

The Bluetooth low energy (BLE) Device Monitor is a Windows® application that displays services, characteristics, and attributes of any BLE device. The BLE Device Monitor requires a CC2540USB dongle with a HostTestApplication to work. The BLE Device Monitor has been tested on Windows 7 and Windows 8. BLE Device Monitor is used to connect to the CC2650 LaunchPad to read OPT3001 and LMT84 sensor values, as well as giving the PWM inputs for controlling the LED dimming level. Refer to the *BLE Device Monitor User Guide* [1] to get started with the BLE Device Monitor and using it to connect to other BLE devices.

Figure 15 is a screenshot of the BLE Device Monitor showing the SimpleBLEPeripheral in the BLE Network tab.

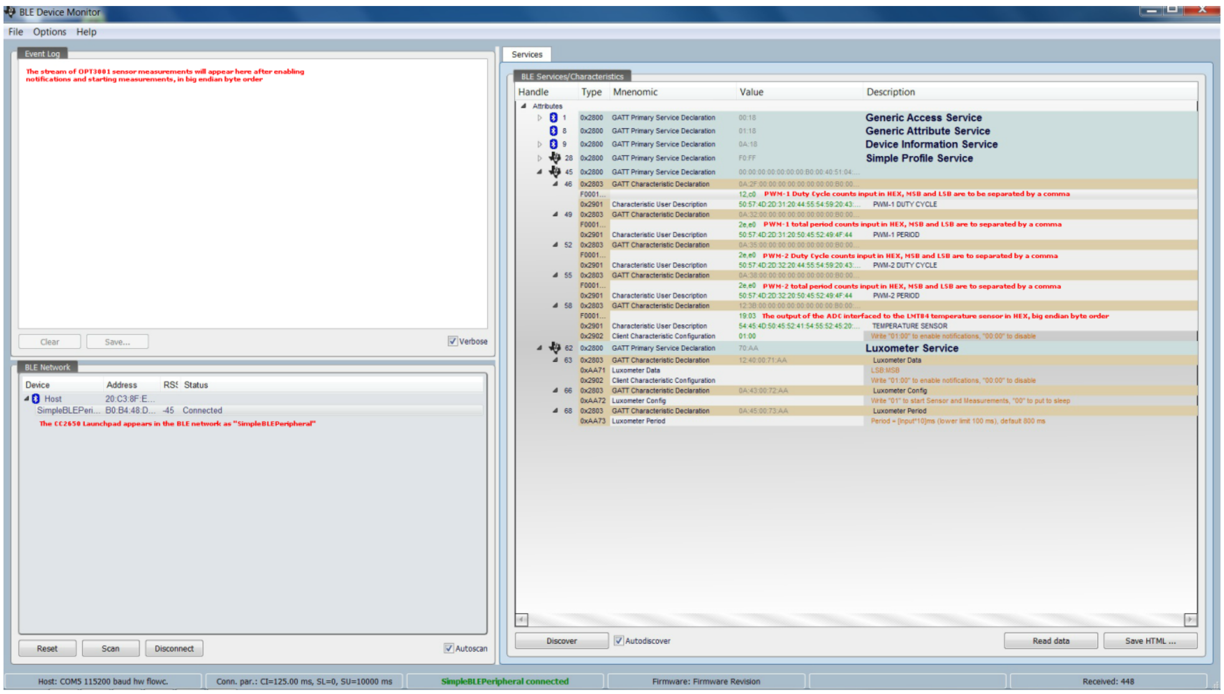

Figure 15. SimpleBLEPeripheral in BLE Network Tab

From the BLE Device Monitor, the frequency and the duty cycle of the two PWMs can be controlled. These values are required to be given in the HEX format. For setting the time period (frequency) of the PWM, the total counts (as mentioned in Section 2.2.1) should be entered; for example, 48000, which is BB,80 in HEX, for 1 kHz. Similarly, the duty cycle should be in proportion to the counts, such as 24000, which is 5D,C0 in HEX, for 50% duty cycle at 1 kHz.

The temperature sensor characteristic is a read-only characteristic, and shows the output of the ADC onboard the CC2650 after converting the analog output of the LMT84 in big-endian format. If the characteristic shows 06:03, then the output of the ADC is 0306, which evaluates to 774 in decimal. The CC2650 ADC has a 12-bit ADC with a reference voltage of 4.3 V. Thus, the analog voltage value this corresponds to is $4.3 \times 774 / (2^{12} - 1) = 0.812$ V. From the mapping table in the LMT84 data sheet, the temperature is 41°C.

The OPT3001 is interfaced to the CC2650 using I^2C. From the BLE Device Monitor, the sensor can be enabled or put to sleep. As shown in Figure 15, enabling the OPT3001 notifications causes the sensor values to appear in the *Event Log*. The duration after which the OPT3001 value is read can also be controlled.

4 Test Data (With 60-V MOSFETs)

In this section, the measurements have been performed with 60-V MOSFETs used for Q1 and Q2, as mentioned in Section 2.1.12.

4.1 Efficiency and Output Current With I_{ADJ} Feature

NOTE: The µC duty is the duty cycle of the PWM input fed into the DAC filter circuit (see Table 5).

Table 5. Efficiency and Output Current

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	EFFICIENCY	V_{IADJ} (V)
47.86	2.380	113.907	41.55	2.699	112.143	98.45%	1.508
47.94	2.078	99.619	40.56	2.416	97.993	98.37%	1.358
48.01	1.790	85.938	39.60	2.132	84.427	98.24%	1.208
48.08	1.513	72.745	38.64	1.845	71.291	98.00%	1.057
48.15	1.248	60.091	37.68	1.557	58.668	97.63%	0.907
48.22	0.994	47.931	36.69	1.269	46.560	97.14%	0.756
48.28	0.752	36.307	35.66	0.979	34.911	96.16%	0.605
48.34	0.520	25.137	34.58	0.689	23.826	94.78%	0.454
48.40	0.299	14.472	33.32	0.400	13.328	92.10%	0.302
48.45	0.094	4.554	31.71	0.112	3.552	77.98%	0.15151
48.45	0.074	3.585	31.52	0.083	2.616	72.97%	0.13622
48.46	0.055	2.665	31.24	0.055	1.718	64.47%	0.12113
48.46	0.037	1.793	30.87	0.028	0.864	48.21%	0.10605
48.47	0.028	1.357	30.68	0.015	0.460	33.91%	0.09842
48.47	0.021	1.018	30.16	0.005	0.139	13.63%	0.09099
48.47	0.018	0.872	28.98	0.00022	0.006	0.73%	0.09056
48.47	0.018	0.872	26.96	0.00000	0.000	0.00%	0.07590

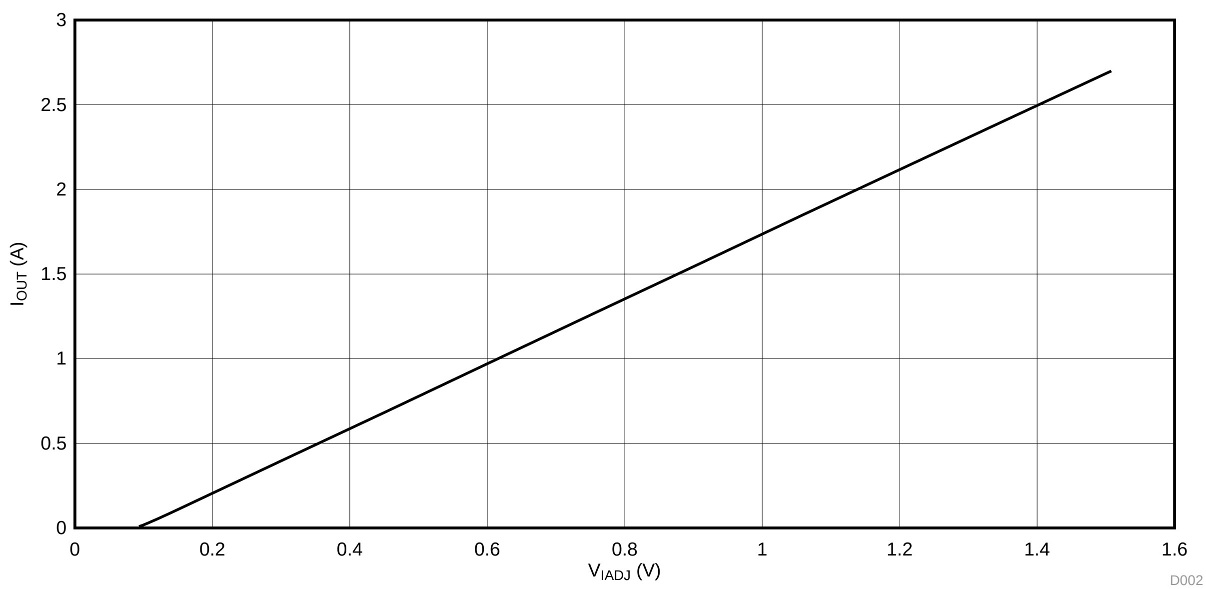

Figure 16. I_{OUT} (A) versus V_{IADJ} (V)

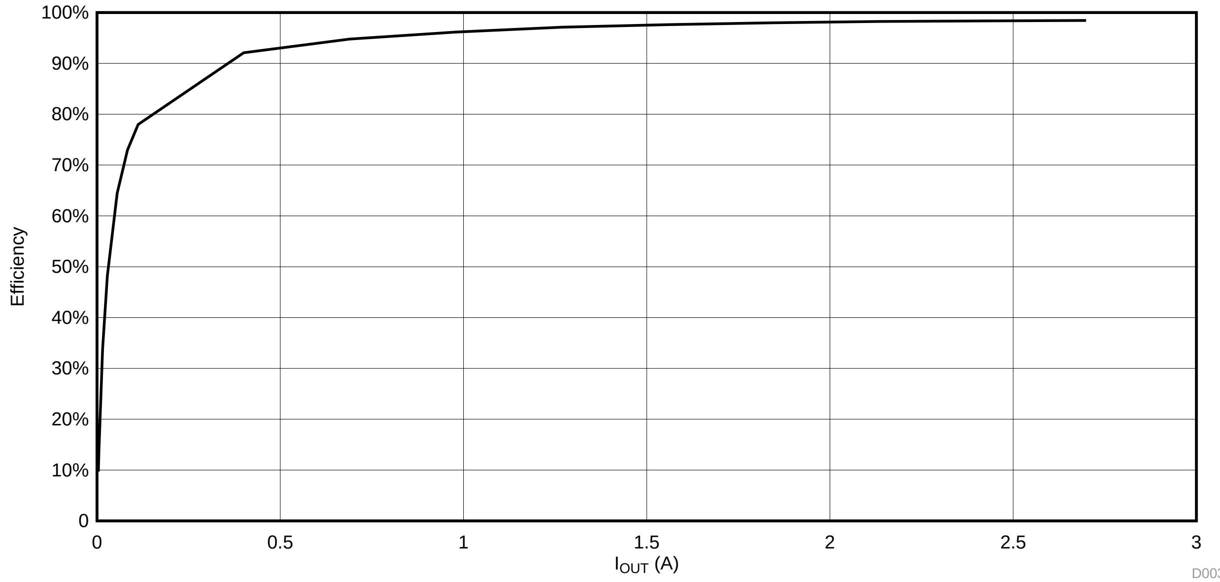

Figure 17. Efficiency versus I_{OUT} (A)

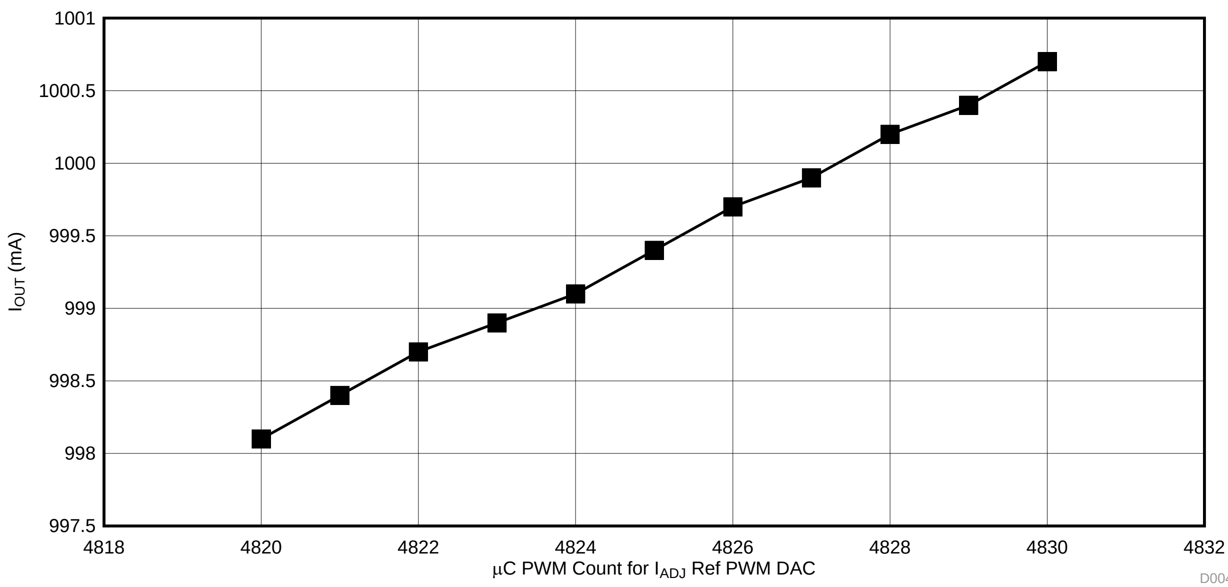

Figure 18. I_{OUT} (A) versus µC Counts

4.2 Efficiency and Output Current With UDIM Feature

4.2.1 At 1-kHz UDIM Frequency

V_{OUT} = 41.8 V is the forward voltage drop for I_{OUT} = 2.764 A (see Table 6).

Table 6. Efficiency and Output Current at 1-kHz UDIM Frequency

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	I_{OUT} (A)	P_{OUT} (W)	EFFICIENCY	UDIM DUTY CYCLE
47.86	2.451	117.305	2.764	115.535	98.49%	100%
47.93	2.196	105.254	2.476	103.497	98.33%	90%
47.99	1.956	93.868	2.200	91.960	97.97%	80%
48.05	1.715	82.406	1.924	80.423	97.59%	70%
48.11	1.472	70.818	1.647	68.845	97.21%	60%
48.18	1.229	59.213	1.371	57.308	96.78%	50%
48.24	0.984	47.468	1.094	45.729	96.34%	40%
48.30	0.738	35.645	0.818	34.192	95.92%	30%
48.37	0.490	23.701	0.540	22.572	95.24%	20%
48.43	0.239	11.575	0.262	10.952	94.62%	10%
48.46	0.114	5.524	0.123	5.141	93.07%	5%
48.47	0.089	4.314	0.096	4.013	93.02%	4%
48.48	0.063	3.054	0.068	2.842	93.06%	3%
48.48	0.035	1.697	0.038	1.588	93.61%	2%
48.49	0.013	0.630	0.013	0.543	86.20%	1%
48.49	0.006	0.291	0.003	0.125	43.10%	0.5%
48.49	0.002	0.097	0.00000	0.000	0.00%	0.1%

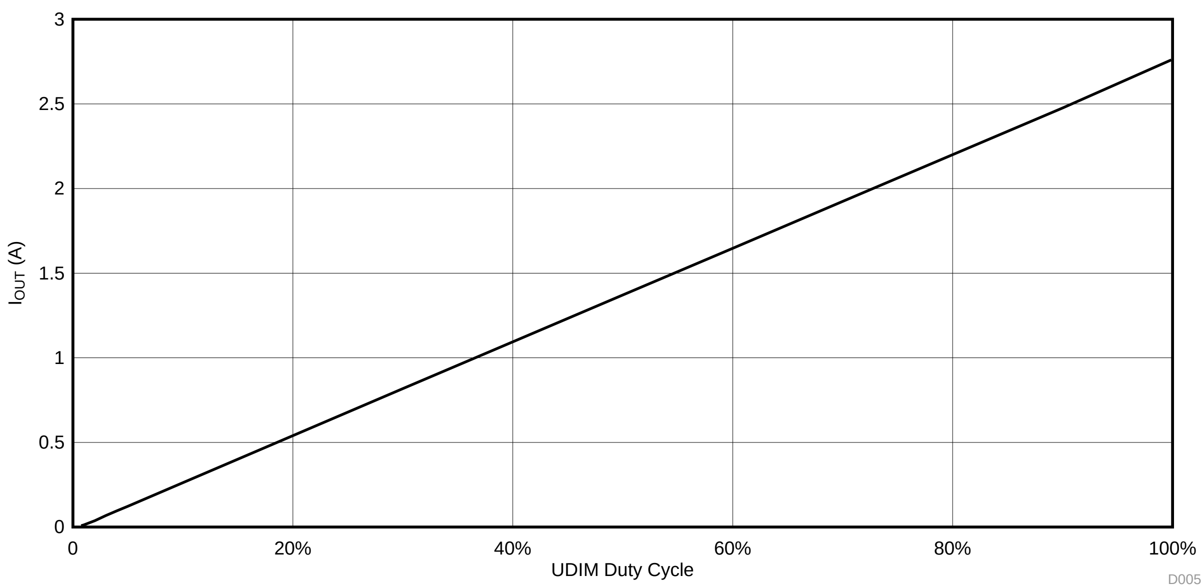

Figure 19. I_{OUT} (A) versus UDIM Duty Cycle

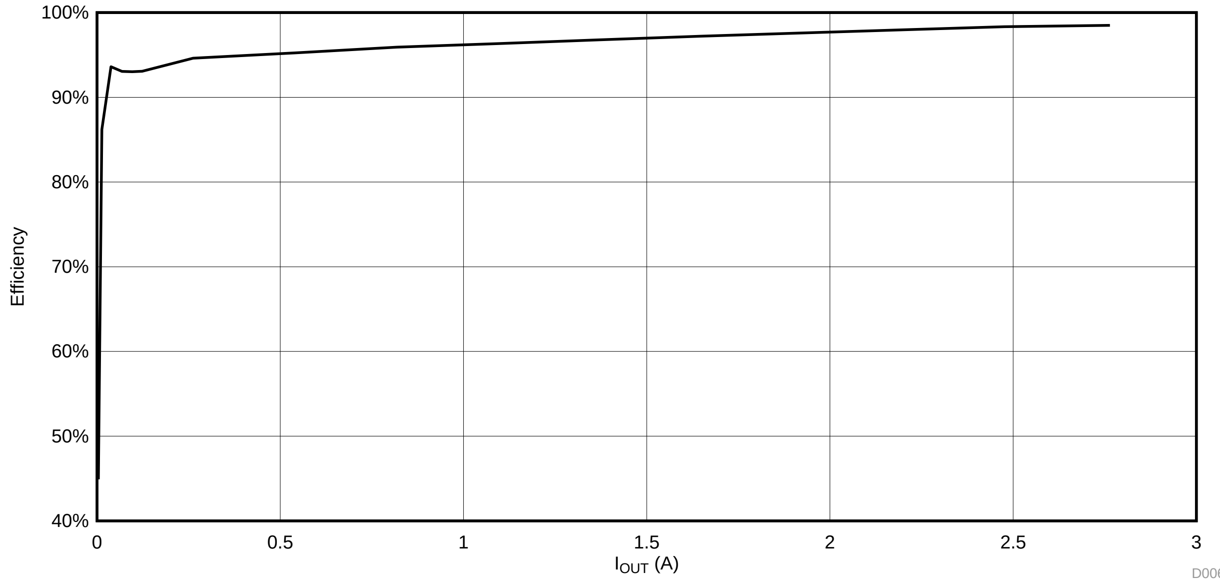

Figure 20. Efficiency versus I_{OUT} (A)

4.2.2 At 5-kHz UDIM Frequency

V_{OUT} = 41.59 V is the forward voltage drop for I_{OUT} = 2.701 A (see Table 7).

Table 7. Efficiency and Output Current at 5-kHz UDIM Frequency

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	I_{OUT} (A)	P_{OUT} (W)	EFFICIENCY	UDIM DUTY CYCLE
47.86	2.377	113.763	2.701	112.335	98.74%	100%
47.93	2.092	100.270	2.375	98.776	98.51%	90%
47.99	1.853	88.925	2.098	87.256	98.12%	80%
48.06	1.616	77.665	1.825	75.902	97.73%	70%
48.12	1.383	66.550	1.560	64.880	97.49%	60%
48.18	1.145	55.166	1.288	53.568	97.10%	50%
48.24	0.903	43.561	1.013	42.131	96.72%	40%
48.31	0.665	32.126	0.747	31.068	96.71%	30%
48.37	0.420	20.315	0.472	19.630	96.63%	20%
48.43	0.165	7.991	0.193	—	—	10%
48.44	0.141	6.830	0.164	—	—	9%
48.45	0.116	5.620	0.137	—	—	8%
48.45	0.094	4.554	0.111	—	—	7%
48.46	0.072	3.489	0.087	—	—	6%
48.46	0.054	2.617	0.065	—	—	5%
48.46	0.038	1.841	0.046	—	—	4%
48.47	0.023	1.115	0.028	—	—	3%
48.47	0.013	0.630	0.014	—	—	2%
48.47	0.006	0.291	0.0041	—	—	1%
48.47	0.005	0.242	0.0033	—	—	0.9%
48.47	0.002	0.097	0.00000	—	—	0.1%

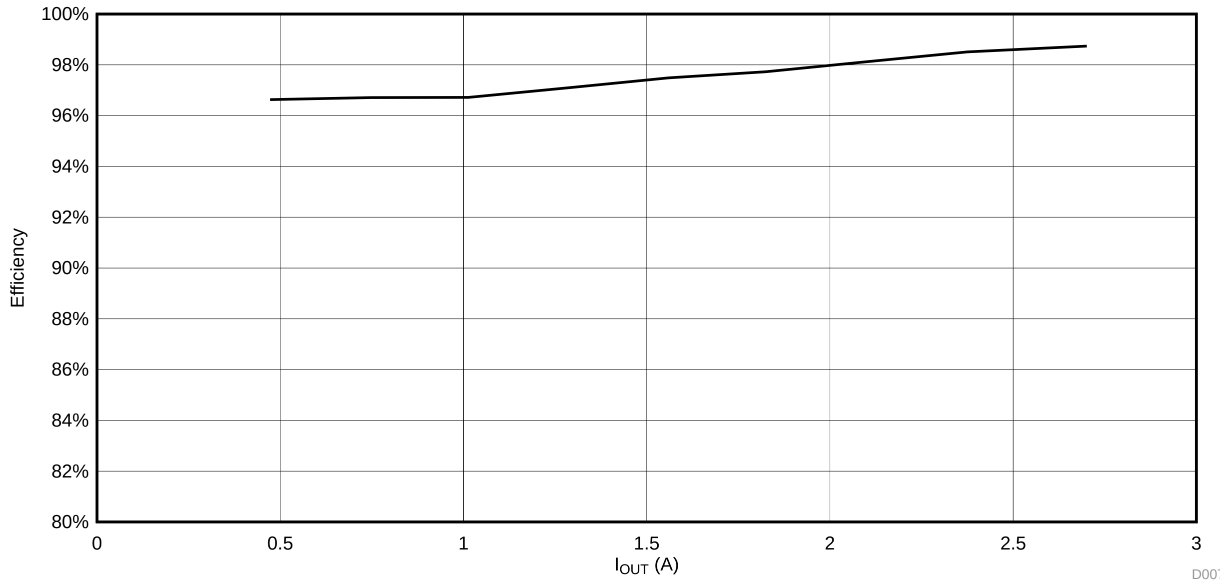

Figure 21. Efficiency versus I_{OUT} (A)

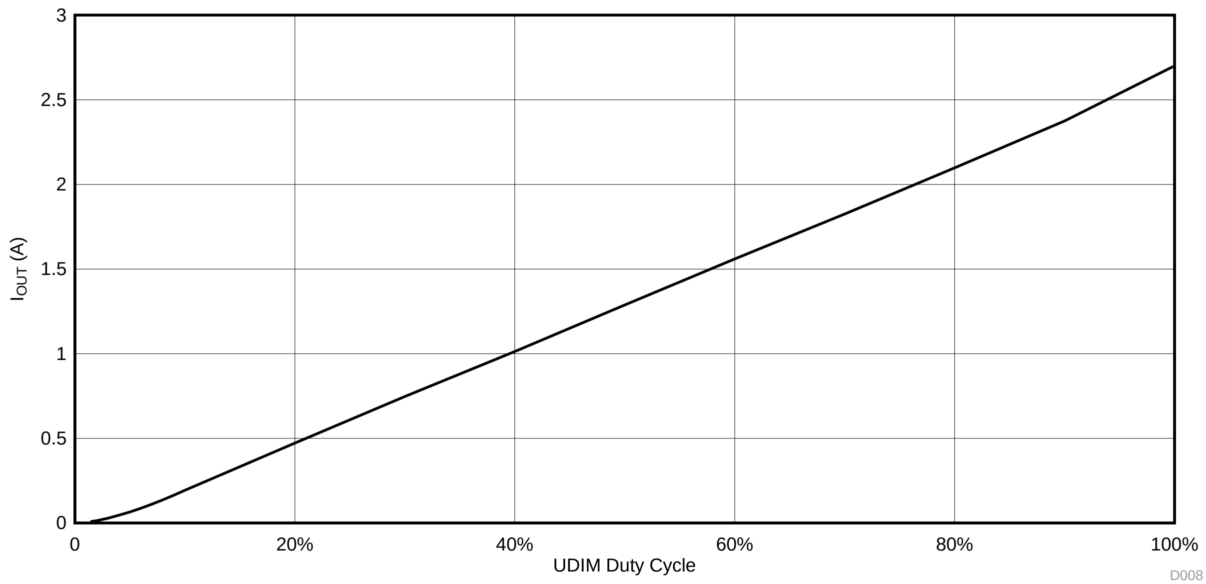

Figure 22. I_{OUT} (A) versus UDIM Duty Cycle

NOTE: In the preceding tables, there is a lack of output voltage for various duty cycles. The efficiency is calculated by multiplying the average value of output current (maximum ≈2.8 A during ON time and 0 A during the OFF time) with the value of the output voltage during the ON time to get the average power. This value of output voltage during the ON time is the same, regardless of the duty cycle.

4.3 Line Regulation

Table 8. Line Regulation

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	EFFICIENCY
42.31	1.902	80.474	39.43	2.023	79.767	99.12%
43.34	1.862	80.699	39.4	2.026	79.824	98.92%
44.35	1.823	80.85	39.39	2.027	79.844	98.76%
45.32	1.786	80.942	39.38	2.028	79.863	98.67%
46.42	1.745	81.003	39.35	2.03	79.881	98.61%
47.36	1.712	81.08	39.34	2.031	79.9	98.54%
48.4	1.679	81.264	39.33	2.034	79.997	98.44%
49.36	1.648	81.345	39.32	2.036	80.056	98.41%

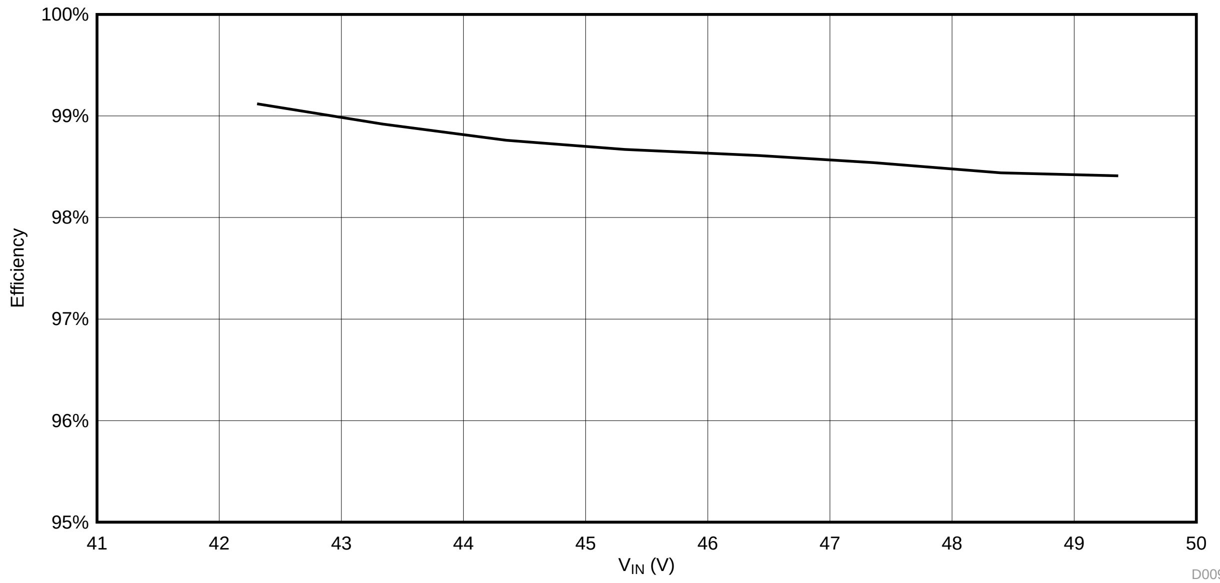

Figure 23. Efficiency versus Input Voltage (V)

4.4 OPT3001 – LUX Measurements

Table 9. LUX Measurements

I_{OUT} (A)	DATA IN HEX	MSB	MSB IN DECIMAL	MULTIPLIER	DEC TO HEX	LSB IN DECIMAL	LUX
2.699	BBEA	B	11	20.48	48106	3050	62464
2.416	BB48	B	11	20.48	47944	2888	59146
2.132	BA85	B	11	20.48	47749	2693	55153
1.845	B993	B	11	20.48	47507	2451	50196
1.557	B87C	B	11	20.48	47228	2172	44483
1.269	AE72	A	10	10.24	44658	3698	37868
0.979	AB9E	A	10	10.24	43934	2974	30454
0.689	A87B	A	10	10.24	43131	2171	22231
0.400	9A31	9	9	5.12	39473	2609	13358
0.112	7BAF	7	7	1.28	31663	2991	3828
0.083	78A9	7	7	1.28	30889	2217	2838
0.055	6B7C	6	6	0.64	27516	2940	1882
0.028	5BA3	5	5	0.32	23459	2979	953
0.015	4B99	4	4	0.16	19353	2969	475
0.005	2CCE	2	2	0.04	11470	3278	131
0.00022	1Ba2	1	1	0.02	7074	2978	60
0.00000	00D9	0	0	0.01	217	217	2

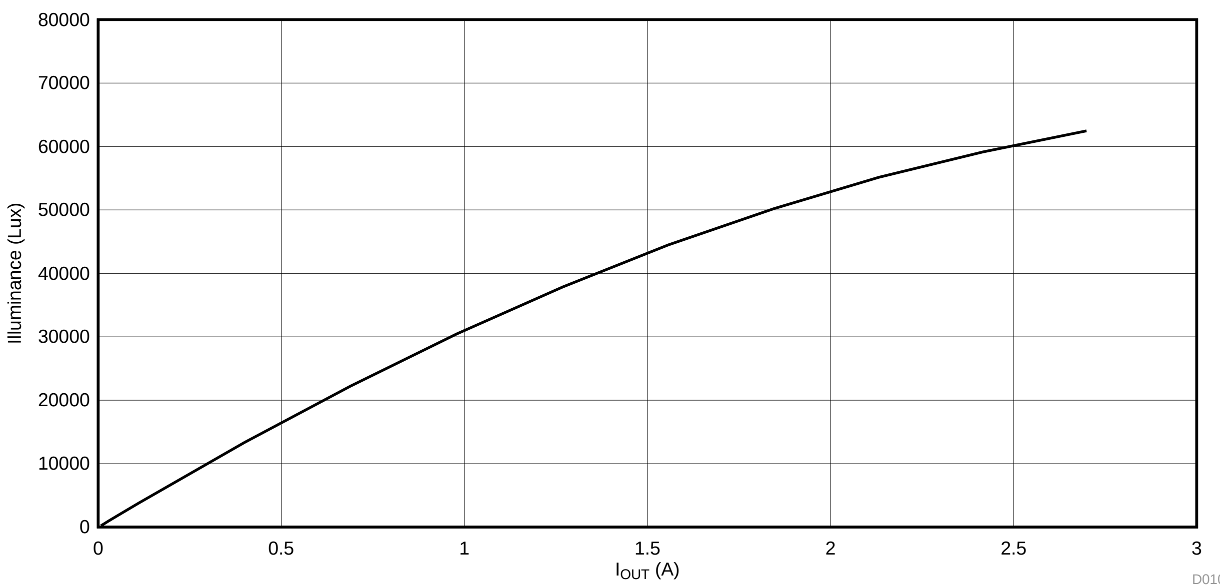

Figure 24. Illuminance versus I_{OUT} (A)

4.4.1 Conversion From OPT3001 Sensor Reading in HEX to LUX

The HEX reading obtained from the OPT3001 sensor can be converted into LUX as follows.

Example, 4CB1:

1. Extract the most significant nibble, four in this example, and calculate LSB_size as:
   LSB_size = $0.01 \times 2^4 = 0.16$.

   This nibble may even be A, B, C, D, E, or F, in which case the exponent should be taken as the corresponding decimal number; that is, 10, 11, 12, 13, 14, and 15, respectively.
2. Convert the remaining three least significant nibbles into decimals and multiply by LSB_size to get the LUX value.

   CB1h = 3249d

   LUX = $3249 \times 0.16 = 519.84$

4.5 Waveforms at 1-kHz UDIM Frequency

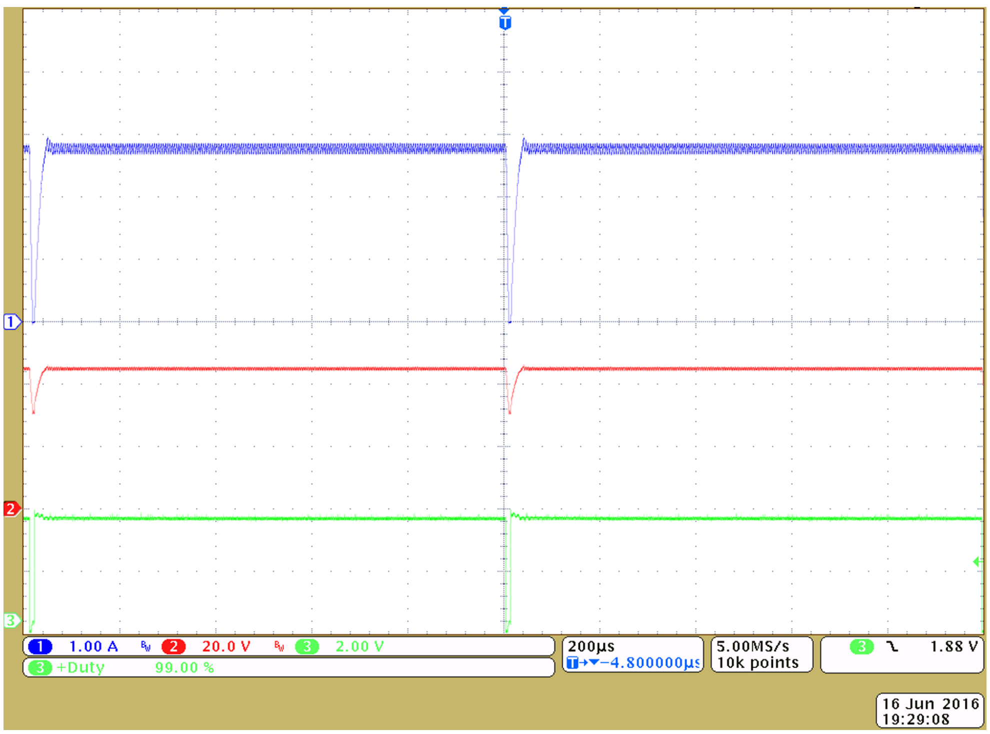

Figure 25. LED Current, LED Voltage, and UDIM Input Waveforms at 99% Duty Cycle

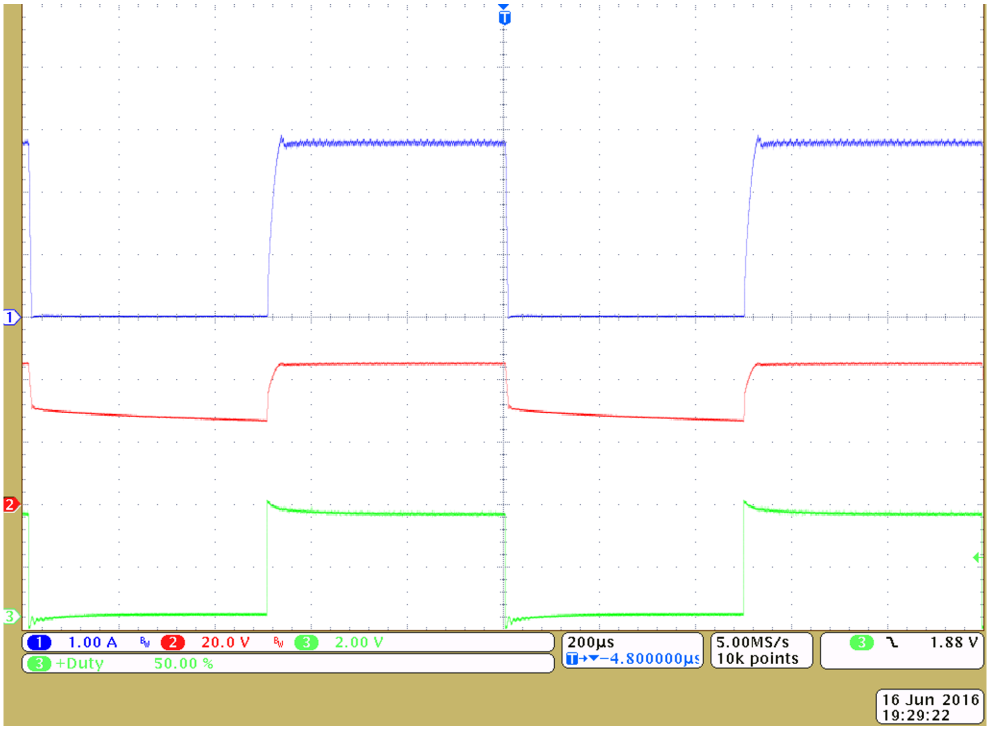

Figure 26. LED Current, LED Voltage, and UDIM Input Waveforms at 50% Duty Cycle

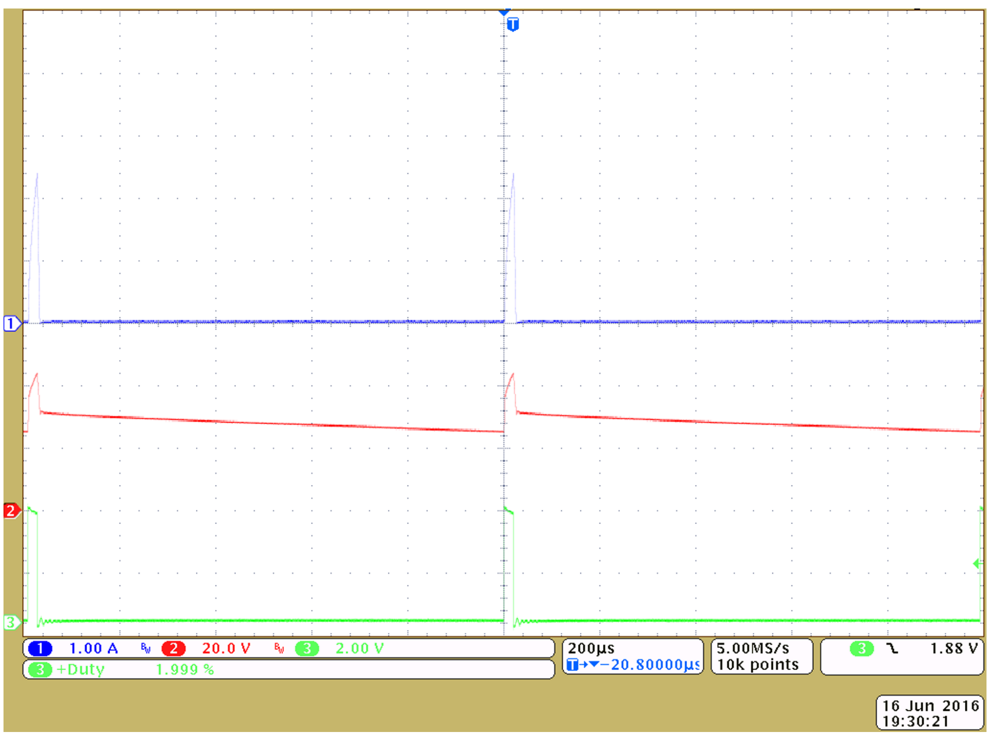

Figure 27. LED Current, LED Voltage, and UDIM Input Waveforms at 2% Duty Cycle

4.6 Thermal Image at Full Load

Figure 28 shows the thermal image of the TIDA-01095 board at the full load condition.

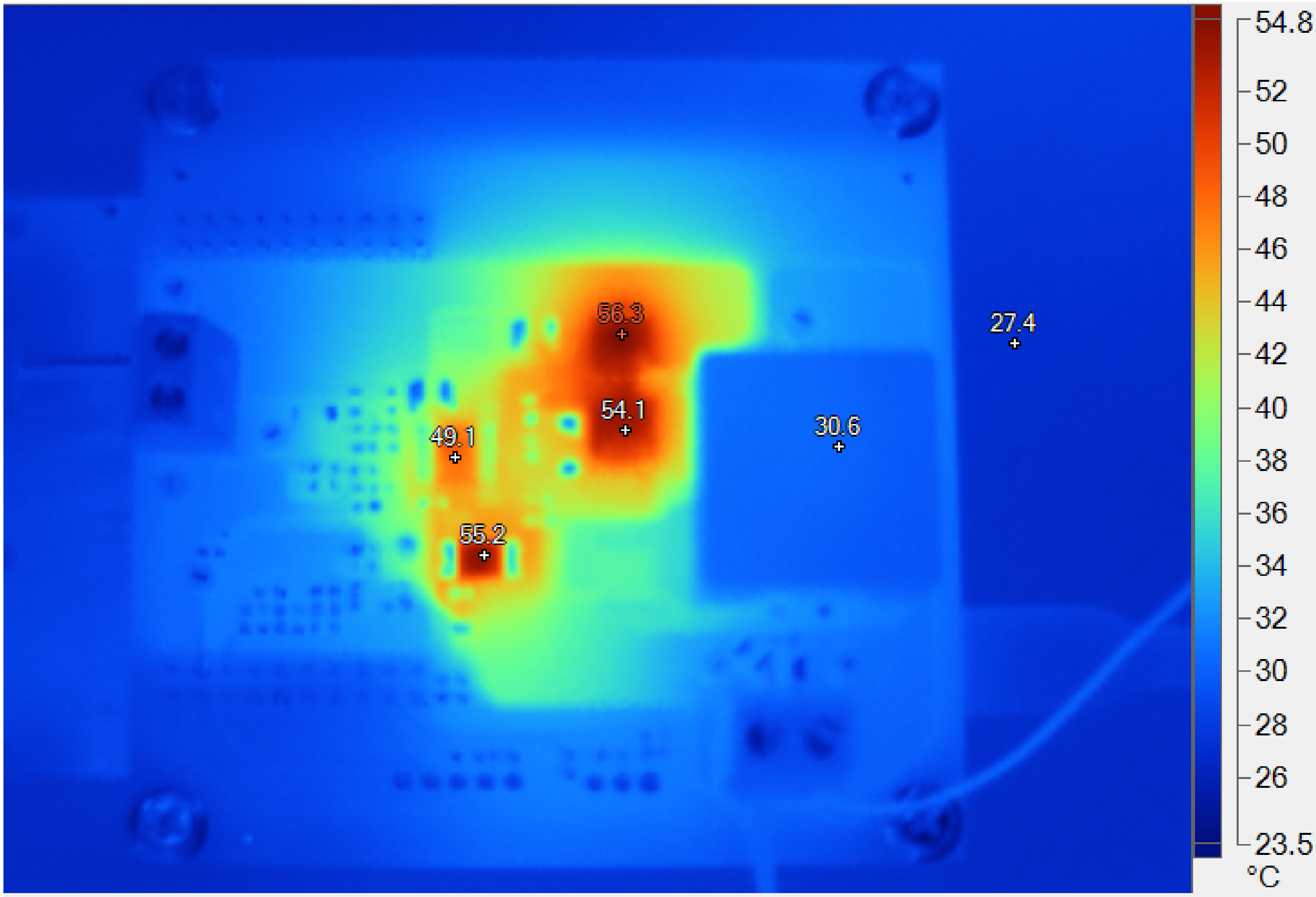

Figure 28. Thermal Image at Full Load

Table 10. Temperature Values

TEMPERATURE (°C)	DEVICE NAME
56.30	High Side MOSFET
55.20	Current Sensing Resistor
54.30	Low Side MOSFET
49.10	TPS92641 IC
30.60	Inductor
27.40	Surface temperature

5 Test Data (With 100-V MOSFETs)

In this section, the measurements are done with 100-V MOSFETs used for Q1 and Q2, as mentioned in Section 2.1.12.

5.1 Efficiency and Output Current With I_{ADJ} Feature

Table 11 shows the efficiency and output current results.

Table 11. Efficiency and Output Current

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	EFFICIENCY	V_{IADJ} (V)
47.94	2.432	116.590	41.71	2.750	114.703	98.38%	1.545
48.02	2.120	101.802	40.67	2.461	100.089	98.32%	1.391
48.09	1.825	87.764	39.68	2.172	86.185	98.20%	1.237
48.16	1.542	74.263	38.71	1.881	72.814	98.05%	1.082
48.23	1.272	61.349	37.74	1.589	59.969	97.75%	0.928
48.29	1.014	48.966	36.77	1.297	47.691	97.40%	0.773
48.35	0.766	37.036	35.72	1.002	35.791	96.64%	0.619
48.41	0.531	25.706	34.60	0.707	24.462	95.16%	0.464
48.47	0.308	14.929	33.35	0.413	13.774	92.26%	0.309
48.52	0.101	4.901	31.75	0.121	3.842	78.39%	0.154
48.52	0.080	3.882	31.57	0.091	2.873	74.01%	0.140
48.52	0.062	3.008	31.29	0.063	1.971	65.53%	0.125
48.52	0.042	2.038	30.92	0.035	1.082	53.11%	0.109
48.53	0.025	1.213	30.29	0.009	0.273	22.47%	0.093
48.53	0.020	0.971	29.42	0.0007	0.021	2.12%	0.0086
48.53	0.019	0.922	28.94	0.0002	0.006	0.63%	0.00084
48.54	0.020	0.971	27.76	0.0000	0.000	0.00%	0.00770

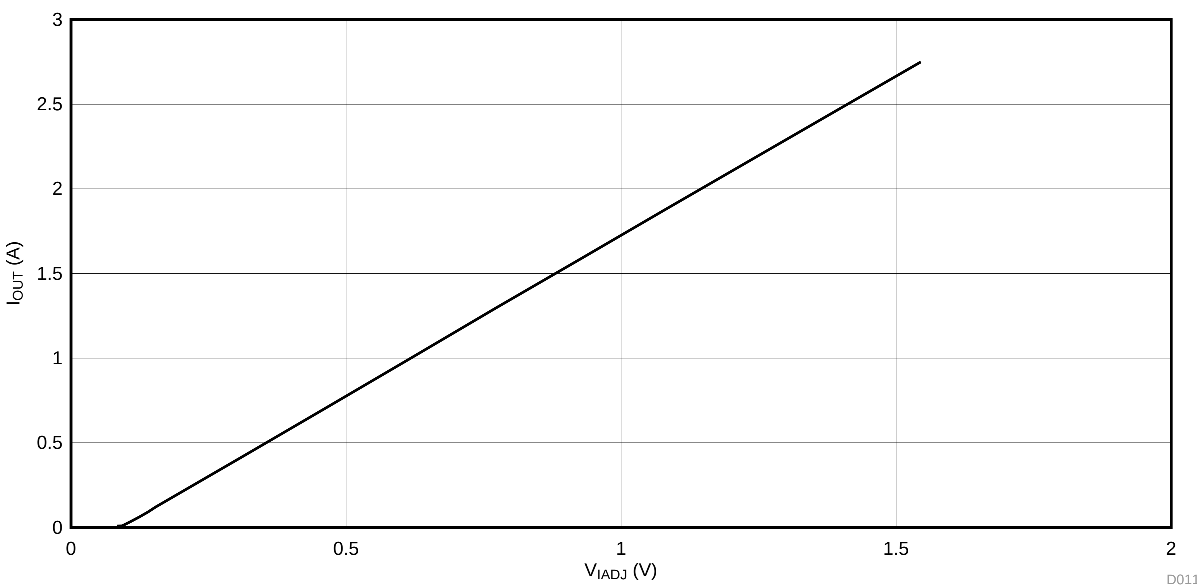

Figure 29. I_{OUT} (A) versus V_{IADJ} (V)

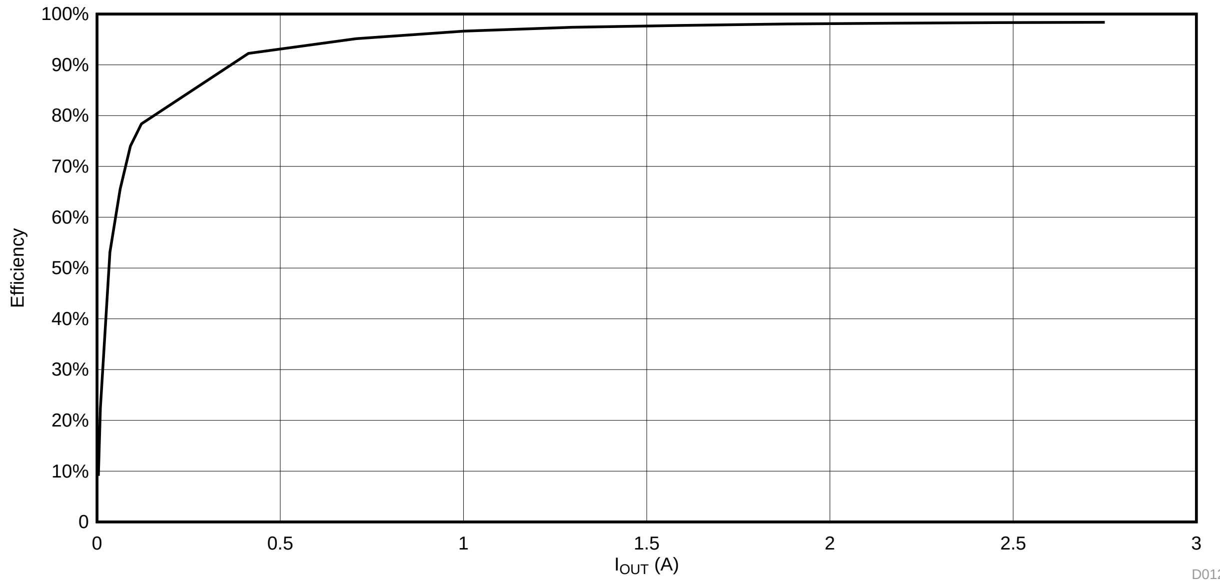

Figure 30. Efficiency versus I_{OUT} (A)

5.2 Efficiency and Output Current With UDIM Feature

5.2.1 At 1-kHz UDIM Frequency

V_{OUT} = 41.74 V is the forward voltage drop for I_{OUT} = 2.759 A (see Table 12).

Table 12. Efficiency and Output Current at 1-kHz UDIM Frequency

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	I_{OUT} (A)	P_{OUT} (W)	EFFICIENCY	UDIM DUTY CYCLE
47.88	2.442	116.923	2.759	115.161	98.49%	100%
47.93	2.186	104.775	2.469	103.056	98.36%	90%
47.98	1.944	93.273	2.192	91.494	98.09%	80%
48.04	1.704	81.860	1.917	80.016	97.75%	70%
48.09	1.462	70.308	1.641	68.495	97.42%	60%
48.14	1.220	58.731	1.364	56.933	96.94%	50%
48.20	0.976	47.043	1.089	45.455	96.62%	40%
48.25	0.731	35.271	0.813	33.935	96.21%	30%
48.30	0.486	23.474	0.537	22.414	95.49%	20%
48.35	0.236	11.411	0.260	10.852	95.11%	10%
48.39	0.112	5.420	0.122	5.092	93.96%	5%
48.39	0.086	4.162	0.094	3.924	94.28%	4%
48.40	0.061	2.952	0.065	2.713	91.89%	3%
48.40	0.036	1.742	0.038	1.586	91.03%	2%
48.41	0.013	0.629	0.013	0.543	86.22%	1%
48.41	0.006	0.290	0.003	0.125	43.11%	0.5%
48.41	0.005	0.242	0.002	0.083	34.49%	0.4%
48.41	0.004	0.194	0.000	0.000	0.00%	0.3%

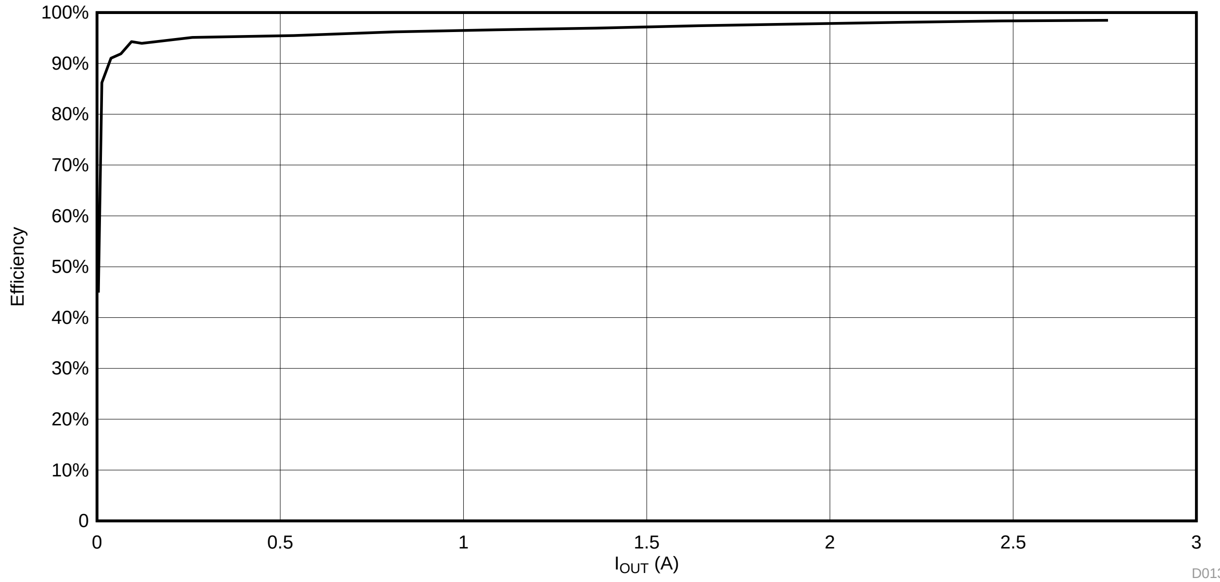

Figure 31. Efficiency versus I_{OUT} (A)

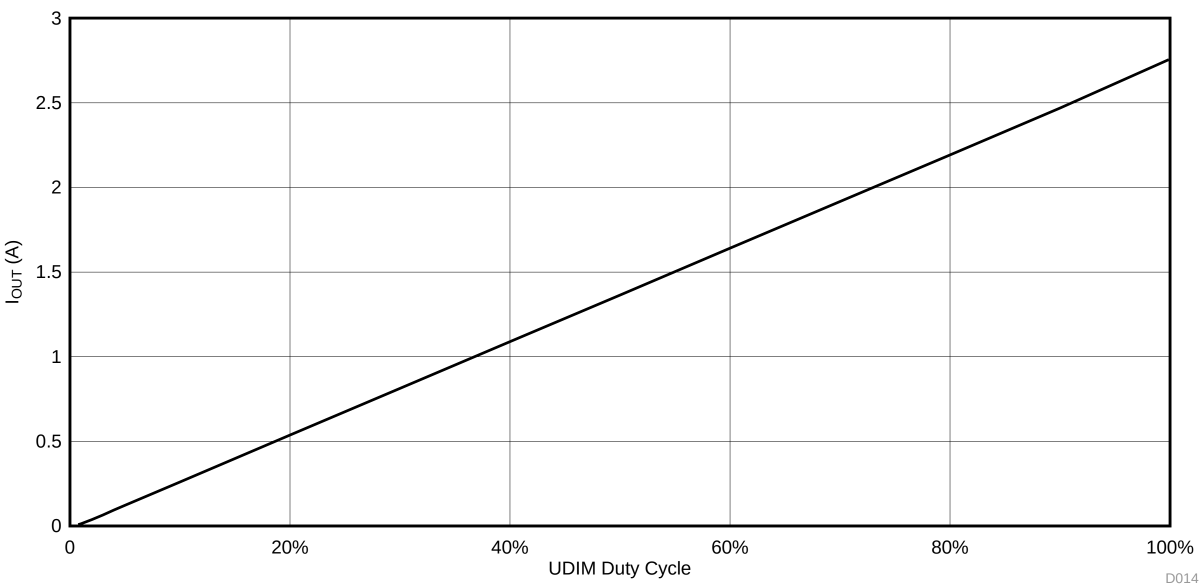

Figure 32. I_{OUT} (A) versus UDIM Duty Cycle

5.2.2 At 5-kHz UDIM Frequency

V_{OUT} = 41.76 V is the forward voltage drop for I_{OUT} = 2.753 A (see Table 13).

Table 13. Efficiency and Output Current at 5-kHz UDIM Frequency

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	I_{OUT} (A)	P_{OUT} (W)	EFFICIENCY	UDIM DUTY CYCLE
47.89	2.442	116.947	2.753	114.965	98.31%	100%
47.98	2.136	102.485	2.413	100.767	98.32%	90%
48.04	1.897	91.132	2.139	89.325	98.02%	80%
48.10	1.652	79.461	1.858	77.590	97.65%	70%
48.17	1.405	67.679	1.578	65.897	97.37%	60%
48.23	1.164	56.140	1.307	54.580	97.22%	50%
48.30	0.916	44.243	1.026	42.846	96.84%	40%
48.36	0.668	32.304	0.748	31.236	96.69%	30%
48.43	0.422	20.437	0.474	19.794	96.85%	20%
48.49	0.160	7.758	0.188	—	—	10%
48.50	0.141	6.839	0.165	—	—	9%
48.50	0.117	5.675	0.140	—	—	8%
48.51	0.095	4.608	0.112	—	—	7%
48.51	0.074	3.590	0.088	—	—	6%
48.52	0.055	2.669	0.065	—	—	5%
48.52	0.039	1.892	0.047	—	—	4%
48.53	0.024	1.165	0.028	—	—	3%
48.53	0.013	0.631	0.014	—	—	2%
48.53	0.006	0.291	0.0043	—	—	1%
48.53	0.005	0.243	0.0035	—	—	0.9%
48.53	0.005	0.243	0.0028	—	—	0.8%
48.53	0.002	0.097	0	—	—	0.1%

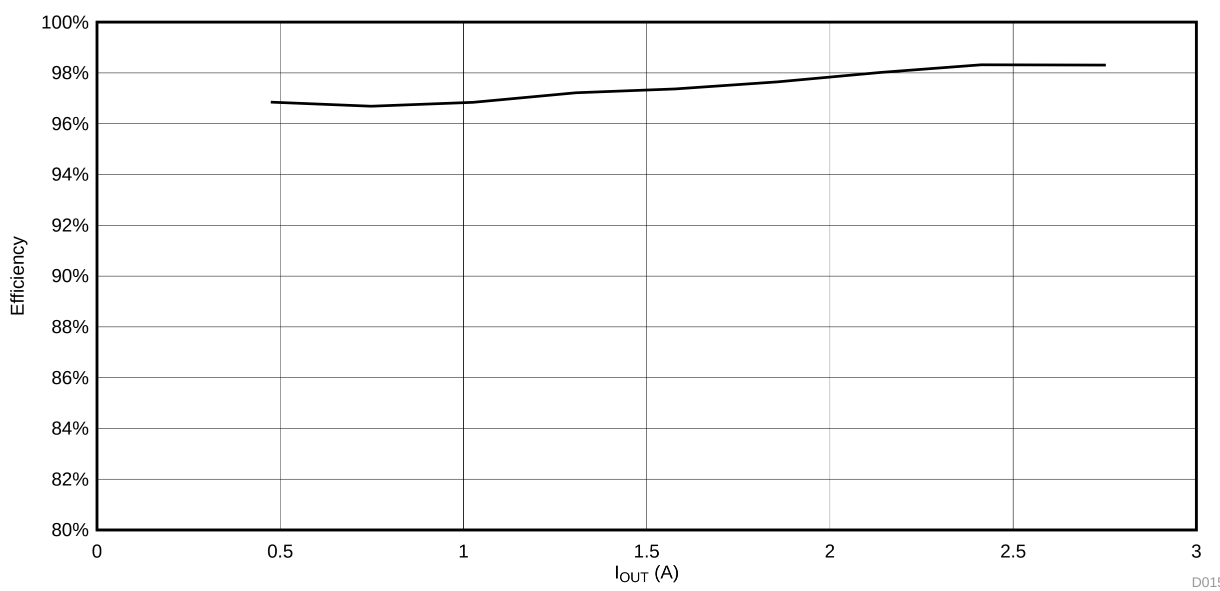

Figure 33. Efficiency versus I_{OUT} (A)

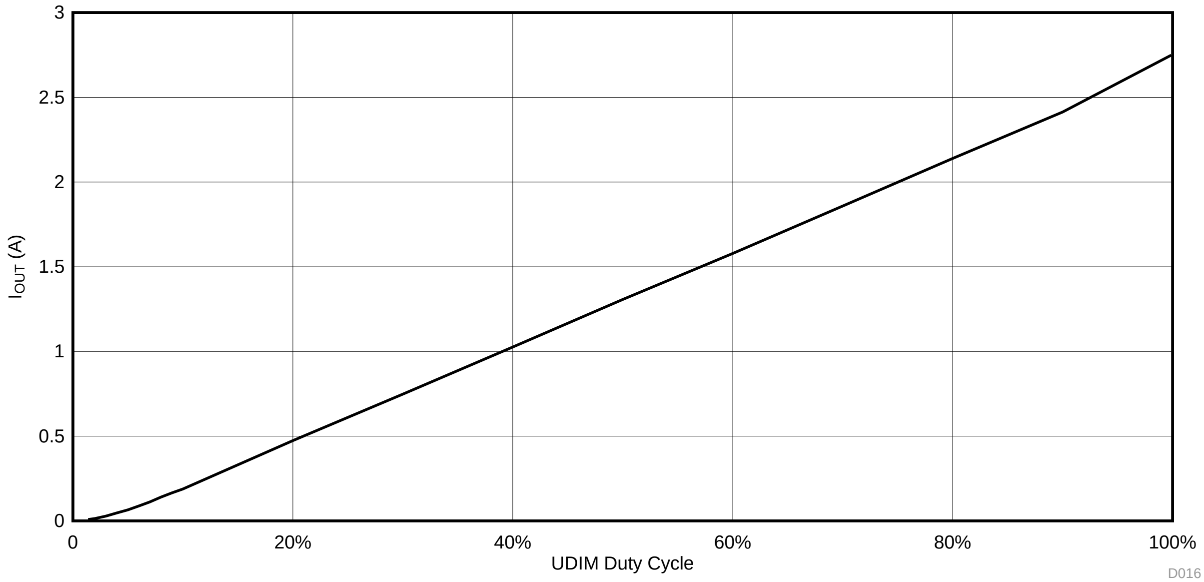

Figure 34. I_{OUT} (A) versus UDIM Duty Cycle

5.3 Line Regulation

Table 14 shows the line regulation results.

Table 14. Line Regulation

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	EFFICIENCY
41.82	0.816	34.125	35.57	0.931	33.116	97.04%
42.84	0.799	34.229	35.56	0.931	33.106	96.72%
43.8	0.783	34.295	35.56	0.932	33.142	96.64%
44.82	0.766	34.332	35.55	0.933	33.168	96.61%
45.84	0.751	34.426	35.55	0.934	33.204	96.45%
46.8	0.737	34.492	35.55	0.935	33.239	96.37%
47.82	0.722	34.526	35.55	0.935	33.239	96.27%
48.78	0.709	34.585	35.55	0.936	33.275	96.21%

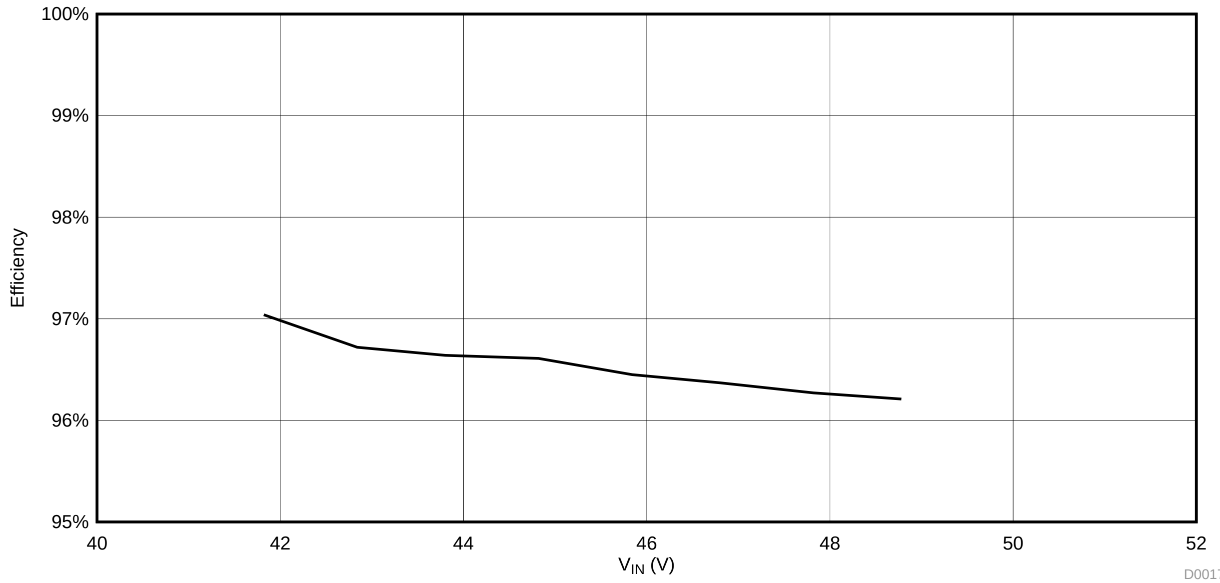

Figure 35. Efficiency versus Input Voltage (V)

5.4 LMT84 – Temperature Measurements

Table 15 shows the temperature measurements of the LED COBs heatsink using the LMT84 device with different LED currents. The temperature rise with a load is dependent on the size of the heatsink and the velocity of air flow from the cooling fan.

Table 15. Temperature Measurements

V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	TEMP (°C)	ADC OUTPUT (HEX)	HEX TO DECIMAL	LMT84 OUPUT VOLTAGE
48.00	0.061	31.55	0.063	27.62	349	841	0.883
47.91	0.320	33.71	0.420	29.91	33D	829	0.871
47.73	0.802	36.16	1.019	32.96	32D	813	0.854
47.65	1.009	37.03	1.258	34.49	325	805	0.845
47.57	1.225	37.86	1.497	36.02	31D	797	0.837
47.49	1.448	38.68	1.735	37.93	313	787	0.826
47.40	1.679	39.36	1.972	39.45	30B	779	0.818
47.32	1.918	40.26	2.208	40.41	306	774	0.813

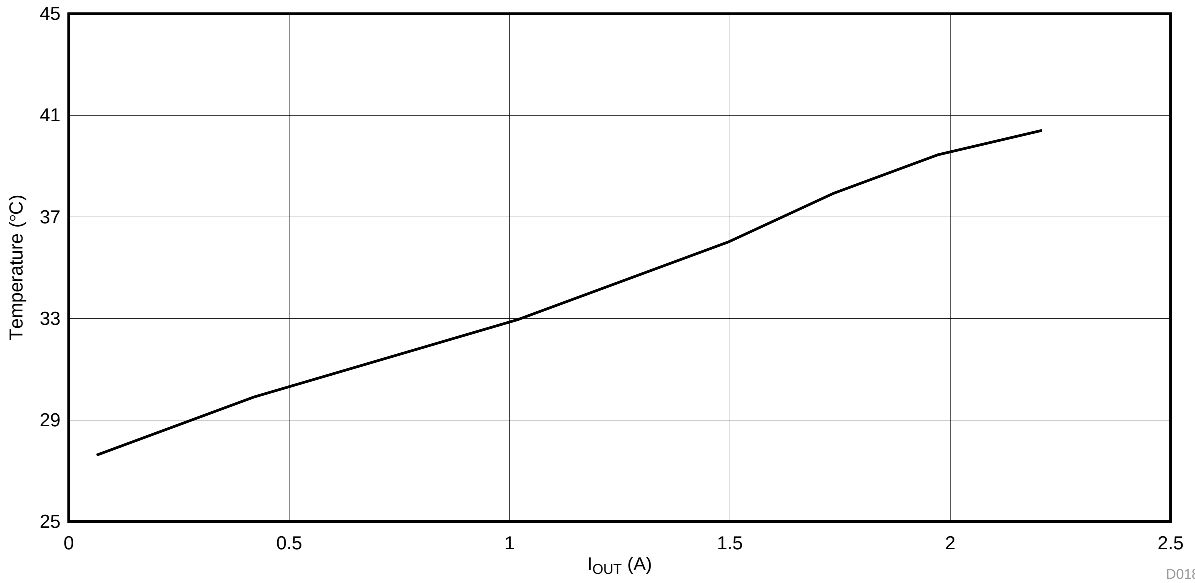

Figure 36. Temperature (°C) versus I_{OUT} (A)

If the output of the ADC is 0306, then it evaluates to 774 in decimal. The CC2650 has a 12-bit ADC with a reference voltage of 4.3 V. Thus, the analog voltage value 0306 corresponds to is:
(4.3 × 774) / (212 – 1) = 0.812 V. From the mapping table in the LMT84 data sheet, the temperature is 41°C.

6 Design Files

6.1 Schematics

To download the schematics, see the design files at TIDA-010905.

6.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-010905.

6.3 PCB Layout Recommendations

The performance of any switching converter depends as much upon the layout of the PCB as the component selection. Follow a few simple guidelines to maximize noise rejection and minimize the generation of EMI within the circuit.

Discontinuous currents are the most likely to generate EMI, therefore take care when routing these paths. The main path for discontinuous current in the TPS92640 and TPS92641 buck converters contains the input capacitor (CIN), the low-side MOSFET (QLS), and the high-side MOSFET (QHS). This loop should be kept as small as possible, and the connections between all three components should be short and thick to minimize parasitic inductance. In particular, the switch node (where L, QLS, and QHS connect) should be just large enough to connect the components without excessive heating from the current it carries. The current sense trace (CS pin) should be run along with a ground plane or have differential traces run for CS and ground.

In some applications, the LED or LED array can be far away (several inches or more) from the circuit, or on a separate PCB connected by a wiring harness. When an output capacitor is used and the LED array is large or separated from the rest of the converter, the output capacitor should be placed close to the LEDs to reduce the effects of parasitic inductance on the AC impedance of the capacitor.

6.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-010905.

6.4 Altium Project

To download the Altium project files, see the design files at TIDA-010905.

6.5 Layout Guidelines

The ground plane of the CC2650 LaunchPad and the LED driver section are separated clearly and connected through a 0-Ω resistor.

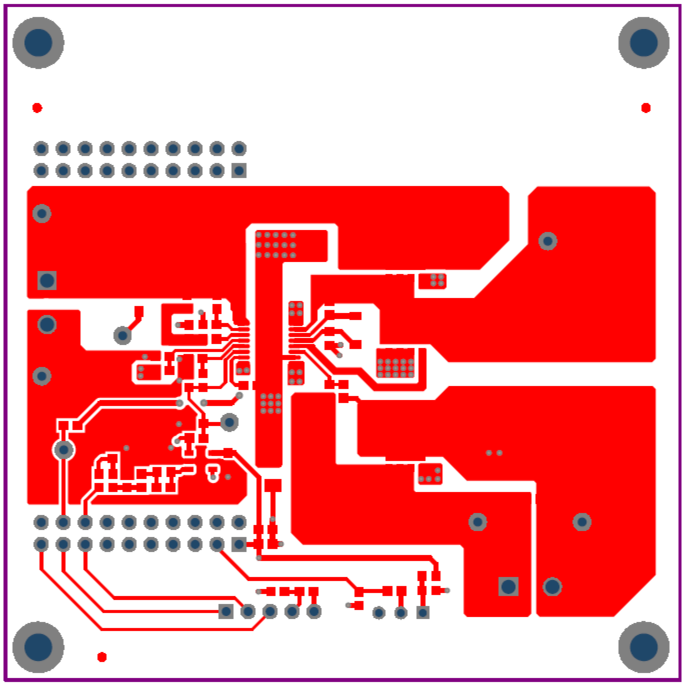

Figure 37. Layout Guidelines 1

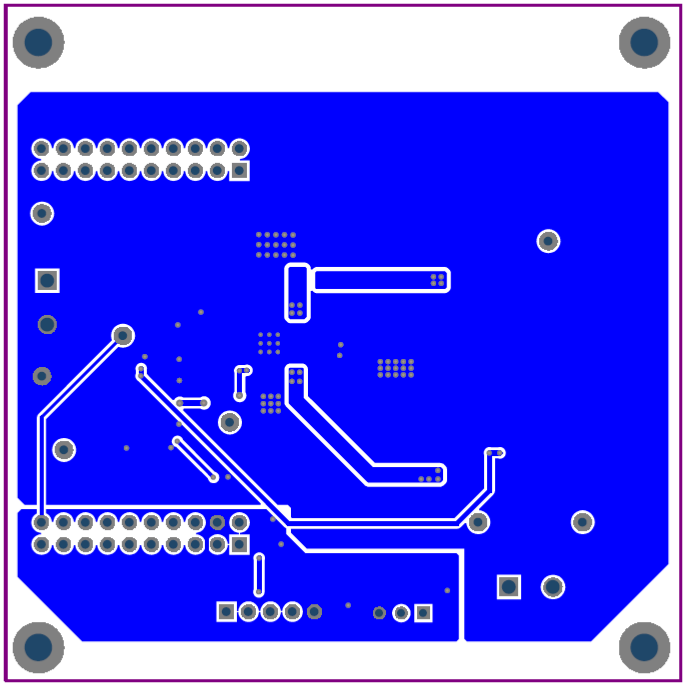

Figure 38. Layout Guidelines 2

6.6 Gerber Files

To download the Gerber files, see the design files at TIDA-010905.

6.7 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-010905.

7 Software Files

To download the software files, see the design files at TIDA-010905.

8 References

1. Texas Instruments, *BLE Device Monitor User Guide*, TI Wiki (http://processors.wiki.ti.com/index.php/BLE_Device_Monitor_User_Guide)
2. Texas Instruments, *Dimming Techniques for Switched-Mode LED Drivers*, LM3406/LM3409 Application Report (SNVA605)
3. Texas Instruments, *Ringing Reduction Techniques for NexFET High Performance MOSFETs*, Application Report (SLPA010)
4. Texas Instruments, *Microcontroller PWM to 12-Bit Analog Out*, TIPD127 User's Guide (TIDU027)
5. Texas Instruments, *WEBENCH® Design Center*, (http://www.ti.com/webench)

9 About the Authors

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Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (June 2016) to A Revision	Page
• Changed the design guide from preview to active and added remaining material	1