TI Designs

High-Efficiency, Tunable White-LED DC-DC Driver With Bluetooth® Smart Connectivity Reference Design

Description

The TIDA-01096 TI Design is a tested DC-DC LED driver subsystem for tunable, white LED luminaires. The design has been built-on a wireless system-on-chip (SoC) platform, which can enable intensity adjustment (dimming) and co-related color temperature (CCT) control using any *Bluetooth*® low energy (BLE) device.

Tunable white luminaries simulate daylight conditions. With a separate warm-white and cold-white LED string, the design allows CCT tuning, which helps achieve proper circadian stimulation.

The TIDA-01096 TI Design provides high-efficiency DC-DC conversion and allows dimming and color temperature control over more than 1:25 and 1:50 range using analog and PWM methods.

Resources

TIDA-01096	Design Folder
TPS92513HV	Product Folder
OPA376	Product Folder
OPT3001	Product Folder
LMT84	Product Folder
LAUNCHXL-CC2650	Tools Folder

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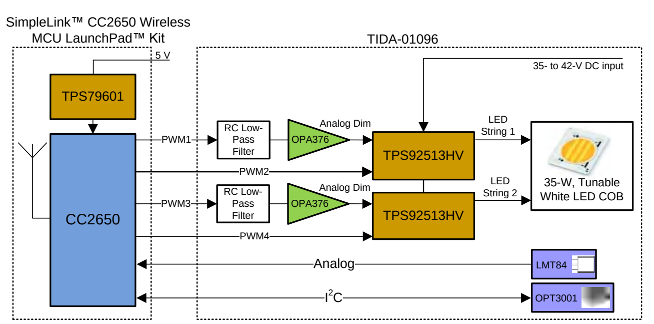
Features

- 98% Efficiency Over 100% to 50% Brightness With Analog Dimming
- 1:25 Contrast Ratio With Analog Dimming and 1:50 With PWM Dimming
- PWM-Based dimming With Modulation Frequency up to 5 kHz
- Ambient Light Sensor OPT3001-Based Light Measurement Enabling Daylight Harvesting and Constant Lumen Implementations in Software
- MCU PWM used as 12-Bit DAC for I_{ADJ} Setting in Analog Dimming
- Overcurrent and Overtemperature Protection for Driver and LED Module

Applications

- Indoor LED Lighting (Residential, Retail, Hospitality, and Accent Lighting)
- Wireless Connected Lighting
- Low-Voltage DC LED Lighting



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1 System Overview

1.1 System Description

Light-emitting diodes (LEDs) are increasingly being used as a light source. At the time of this writing, the focus of lighting is currently shifting from simply illuminating areas with constant light output to providing quality and controlled light output. High quality lighting with adjustable intensity and adjustable color temperature plays a key role in enhancing the architecture. Dimming combined with the daylight sensing helps to increase the energy efficiency as well. To change the color temperature of white light, the designer can implement a combination of warm LEDs (color temperature of around 2500 K) and cold LEDs (color temperature of around 5700 K). Another approach is to use RGBW or RGBA LED arrays. Tunable, white chip-on-board (COB) LEDs are available with two separate strings. By changing the current through the strings, the designer can create color temperatures ranging from 2500 K to 5700 K. The tunable white-LED engine with the drivers can be used as a platform for circadian lighting, which targets human wellness.

Figure 1 shows an example of a tunable white light fixture, which is useful for various indoor lighting applications.

Figure 1. Tunable White Light Fixture

Lighting has a profound effect on sleep, alertness, work efficiency, and health. A tunable, white-LED lighting system can be used for proper maintenance of the circadian rhythm, allowing the necessary amount of white light and warm light, which improves wellness in indoor conditions. Tunable, white LED luminaries can automatically adjust the Kelvin temperature and the dimming of light to provide the same lighting conditions as daylight and nightlight.

1.2 Key System Specifications

Table 1. Key System Specifications

PARAMETERS	TEST CONDITIONS AND NOTES	MIN	TYP	MAX	UNIT
INPUT CHARACTERISTICS					
Input voltage	—	35	—	42	V
Input UVLO setting	—	28	30.5	32.5	V
OUTPUT CHARACTERISTICS					
Output (LED) current	—	0	—	700	mA
LED ripple current	Peak-to-peak LED ripple current	—	—	5	mA
SYSTEMS CHARACTERISTICS					
Switching frequency	—	—	600	—	kHz
Current sensing resistor	—	—	0.05	—	Ω
PWM dimming frequency	—	200		5000	Hz
LOAD CHARACTERISTICS(1)					
Warm LED forward voltage	Warm LED (2700 K), I_F = 700 mA	34	37	40	V
Cold LED forward voltage	Cool LED (5700 K), I_F = 700 mA	35	38	41	V
Warm LED forward current	—	—	—	840	mA
Cool LED forward current	—	—	—	840	mA
LED COB forward current	Summation of warm and cool LED	—	—	840	mA
Power dissipation	Summation of warm and cool LED	—	—	34	W
Operating temperature	—	–30	—	100	°C

(1) LED load used is GW6TGCBGff40C (SHARP - Tiger Zenigata 25-W Series)
T_C = 25°C unless specified

1.3 Block Diagram

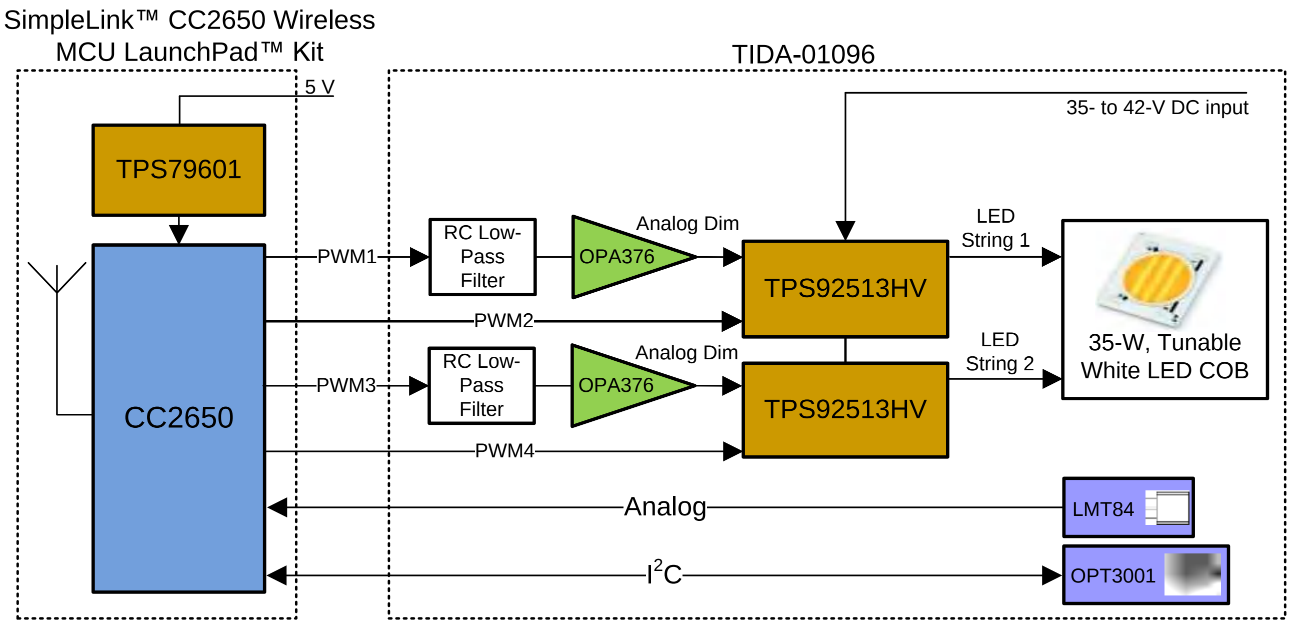

Figure 2. Block Diagram

1.4 Highlighted Products

1.4.1 TPS92513

The TPS92513/HV are 1.5-A step-down (buck) current regulators with an integrated MOSFET to drive high current LEDs. Available with 42- and 60-V (HV) input ranges, these LED drivers operate at a user-selected fixed frequency with peak-current mode control and deliver excellent line and load regulation.

The TPS92513/HV LED drivers feature separate inputs for analog and pulse width modulation (PWM) dimming for brightness control without compromise, which allows achieving contrast ratios of greater than 100:1. The PWM input is compatible with low-voltage logic standards for easy interface to a broad range of microcontrollers (MCUs). The analog LED current setpoint is adjustable from 0 V to 300 mV using the I_{ADJ} input with an external 0- to 1.8-V signal.

For multi-string applications using two or more TPS92513/HV LED drivers, the internal oscillator can be overdriven by an external clock to ensure that all of the converters operate at a common frequency, thereby reducing the potential for beat frequencies and simplifying the system electromagnetic interference (EMI) filtering. An adjustable input under-voltage lockout (UVLO) with hysteresis provides flexibility in setting start and stop voltages based upon supply voltage conditions.

The TPS92513 includes cycle-by-cycle overcurrent protection and thermal shutdown protection. The device is available in a 10-pin HVSSOP PowerPAD™ package.

Features:

- Integrated 220-mΩ high-side MOSFET
- 4.5- to 42-V input voltage range
- (4.5 V to 60 V for the TPS92513HV)
- 0- to 300-mV adjustable voltage reference
- ±5% LED current accuracy
- 100-kHz to 2-MHz switching frequency range
- Dedicated PWM dimming input
- Adjustable UVLO

- Overcurrent protection
- Overtemperature protection
- MSOP-10 package with PowerPAD™

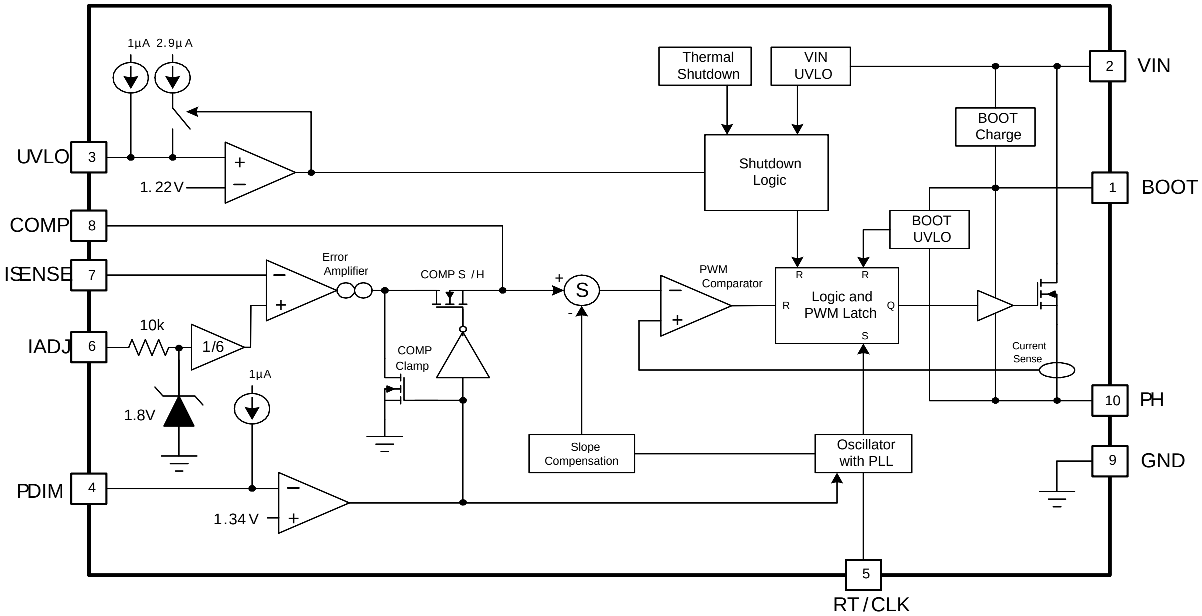

Figure 3. TPS92513 Functional Block Diagram

1.4.2 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

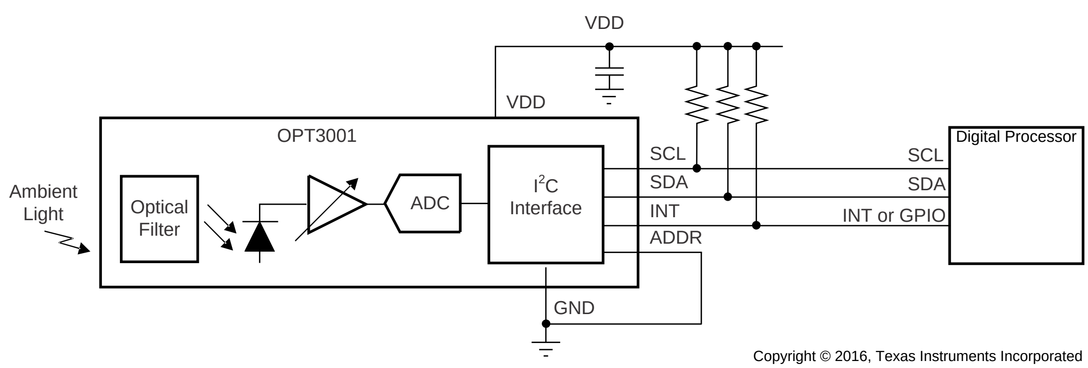

Figure 4. OPT3001 Block Diagram

1.4.3 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.

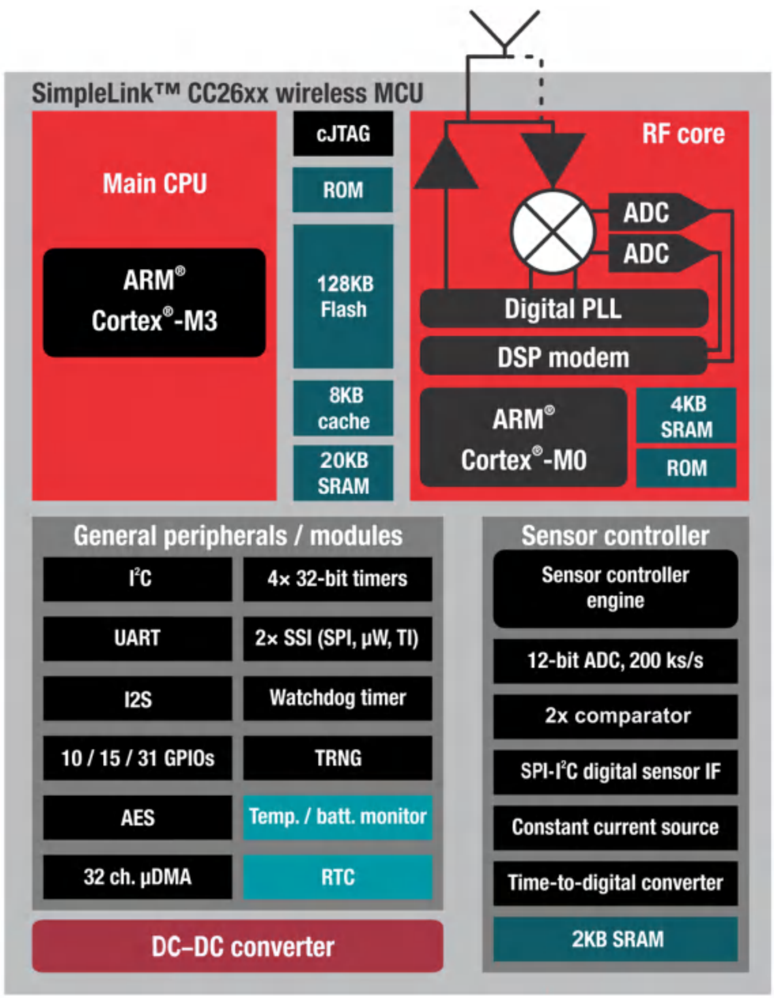

Figure 5. CC2650 Block Diagram

1.4.4 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

1.4.5 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 tunable white light requires current in two separate LED strings to be varied and controlled. A tunable white LED luminaire requires an AC-DC constant-voltage power supply combined with two DC-DC buck current controllers to vary the current through the LED strings. In the case of DC lighting systems, low voltage DC is directly available, so using a two-channel current controller is adequate. To enable dimming and control requires a wireless control or wired control system. Wireless lighting controls are becoming more common because of ease of use and availability.

The TIDA-01096 platform uses two TPS92513HV buck LED drivers with integrated analog current adjust for controlling the current through warm and cold LED strings. The TPS92513/HV LED drivers feature separate inputs for analog and pulse width modulation (PWM) dimming for no-compromise brightness control to achieve contrast ratios greater than 100:1. The PWM input is compatible with low-voltage logic standards for easy interface to a broad range of MCUs. The buck LED drivers are controlled by the SimpleLink™ CC2650 Wireless MCU LaunchPad™ kit, which generates two PWMs for PWM dimming of both strings. Achieving analog dimming requires two variable analog inputs to set the I_{ADJ} of the buck LED drivers. Variable I_{ADJ} is derived using the PWM from the CC2650 device as a digital-to-analog converter (DAC). For this process, the PWM generated from the CC2650 device is filtered by a four-stage low-pass RC filter and the filtered output is buffered using op amp OPA376. The op amps output is used to set the current reference for the buck LED driver. 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 and Low Power Shutdown (UVLO Pin) Setting

The minimum input voltage, V_{IN}, at which TPS92513 operates can be set through the UVLO pin. The device locks out when the voltage at this pin falls below 1.22 V (typical). For the device to shut down at 30.5 V, a suitable resistor can be placed between the VIN and GND pins to set the minimum V_{IN}. R1 and R6 can be taken as 120 k and 5 k, respectively, to produce 1.22 V at the output of the divider when V_{IN} = 30.5 V.

2.1.2 Converter Switching Frequency (RT/CLK Pin)

For setting the f_{SW} = 600 kHz, R_{RT} must be set according to Equation 1 from the data sheet for TPS92513.

$$R_{RT}\;k \quad \frac{206033}{f_{SW}^{\;1.092}\;kHz} \quad \frac{206033}{600^{1.092}} \quad 190.63\;k \tag{1}$$

2.1.3 Synchronizing Switching Frequency to External Clock (RT/CLK Pin)

The RT/CLK pin can be used to synchronize the regulator to an external system clock by connecting a square wave to the RT/CLK pin. The square wave amplitude must transition lower than 0.63 V and higher than 1.81 V on the RT/CLK pin and have an ON time greater than 51 ns and an OFF time greater than 100 ns. The synchronization frequency range is
300 kHz to 2 MHz. AC coupling the synchronization signal through a 470-pF ceramic capacitor and a 4-kΩ series resistor to the RT/CLK pin is required. Refer to the TPS92513 data sheet for more information regarding the switching frequency synchronization and transitioning from output synchronization frequency to R_{RT} determined frequency [1].

2.1.4 Adjustable LED Current (I_{ADJ} and I_{SENSE} Pins)

The following Equation 2 and Equation 3 govern the set current with respect the I_{ADJ} and I_{SENSE} voltages.

$$V_{ISENSE} \quad \frac{V_{IADJ}}{6} \tag{2}$$

$$R_{ISENSE} \quad \frac{V_{ISENSE}}{I_{LED}} \tag{3}$$

The maximum desired LED current is 700 mA and the current sensing resistor must to be at 0.05 Ω. Therefore, V_{ISENSE} = 0.035 = 35 mV and V_{IADJ} = 0.210 V = 210 mV. At the maximum load current, V_{IADJ} must be 0.210 V and can be varied until 0 V to dim the current in the load.

2.1.5 Variable I_{ADJ} Voltage for Analog Dimming

Generation of variable voltage for analog dimming is accomplished using the MCU PWM. The PWM is filtered using a multi-stage, low-pass filter and buffered. The four-stage, passive, RC low-pass filter provides an analog voltage output with 12 bits of resolution (see Equation 4).

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

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) (4)

$$\text{Minimum Ripple} \quad \frac{\text{Resolution}}{2} \quad \frac{V_{PWM}}{2 \quad 2^n} \tag{5}$$

$$\text{Ripple} \quad \frac{V_{PWM}}{10^{order}} \tag{6}$$

$$\frac{V_{PWM}}{10^{order}} \quad \frac{V_{PWM}}{2 \quad 2^n} \tag{7}$$

$$\text{order} \quad n \quad 1 \quad \log 2 \tag{8}$$

Therefore, the order = 13 × 0.3 = 3.9.

Round up the order to the next highest integer, in case it is fractional, to achieve a performance higher than the goal. So, in this case, the order = 4.

The equation that sets the cutoff frequency for a simple first-order, RC low-pass filter is given as the following Equation 9.

$$R_1 \quad \frac{1}{2 \quad f_{cutoff} \quad C_1} \quad \frac{1}{2 \quad 391\,\text{Hz} \quad 470\ \text{nF}} \quad 866$$

where
- $f_{cutoff} = f_{pwm}$ / 10 = (3.91 kHz) / 10 = 391 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 is divided by 10 (9)

The RC filter loads the MCU. The load current is at a maximum when the PWM signal makes a logic level transition (that is, low-to-high or high-to-low). The transient current can be estimated using the following Equation 10.

$$I_{transient} \quad \frac{V_{CC}}{R_1} \quad \frac{3.3}{866} \quad 3.8\ \text{mA} \tag{10}$$

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, ensuring that subsequent stages do not load the initial stage is important. A simple approach to prevent the loading is to increase the impedance of each subsequent stage by a factor of ten (see Table 2). Further, between the final stage of the RC filter and the IADJ pin, a low-output, offset operational amplifier (op amp) OPA376 is used.

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

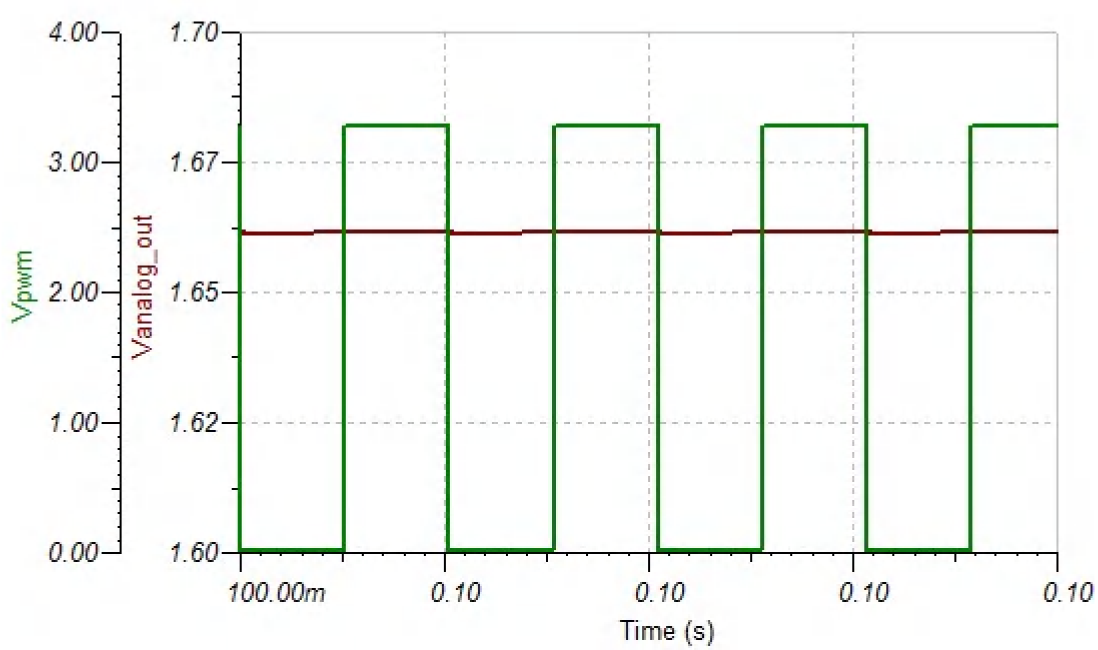

Figure 6. V_{PWM} versus Time (1 of 2)

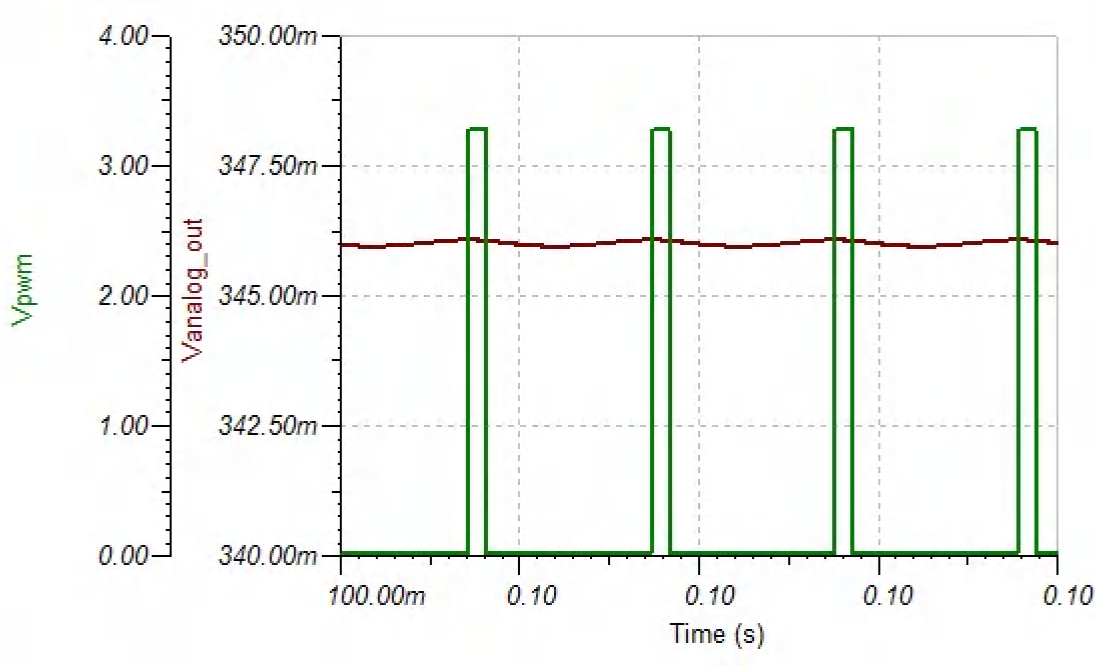

Figure 7. V_{PWM} versus Time (2 of 2)

2.1.6 Inductor Selection

The value of the buck inductor impacts the peak-to-peak ripple-current amplitude. According to the TPS92513 data sheet, TI recommends that the peak-to-peak ripple current (I_R) is greater than 75 mA for dependable operation. The following Equation 11 calculates the buck inductance given the minimum ripple current of I_R = 75 mA.

$$L = \frac{V_{OUT} \times (V_{IN} - V_{OUT})}{I_R \times V_{IN} \times f_{SW}} \tag{11}$$

For this application, taking V_{IN} = 42 V and V_{OUT} = 35 V and keeping the ripple current at 40% of the full-load current (that is, I_R = 275 mA), the preceding Equation 11 results in the following Equation 12.

$$I_R = \frac{V_{OUT} \times (V_{IN} - V_{OUT})}{L \times V_{IN} \times f_{SW}} = 294 \text{ mA} \tag{12}$$

2.1.7 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 strict as the requirements for 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 ripple current of 5 mA.

2.1.8 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 also 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_{LED}, 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 I-V measurements).

Table 3. Forward Current and Voltage

FORWARD CURRENT (A)	FORWARD VOLTAGE (V)
0.2	32.54
0.3	32.87
0.4	33.28
0.5	33.77
0.6	34.26

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 = 4.34I + 31.608. Therefore, the dynamic resistance, R_{LED}, comes out to 4.34 Ω.

2.1.9 Output Capacitor Selection

During start-up, the TPS92513 device uses the discharged output capacitor as a charging path for the BOOT capacitor. To ensure that the BOOT capacitor charges and that the converter begins switching immediately, the value of the output capacitor must be ten times larger than the BOOT capacitor. If the BOOT capacitor is 0.1 µF, then the minimum output capacitor should be 1 µF for the fastest start-up time. If the output capacitor is selected to be a smaller value, or none at all, then the BOOT capacitor can charge through the LED string itself; however, this method of charging the BOOT capacitor results in longer start-up times.

The value of the output capacitor is determined based upon the LED ripple current (ΔI_{LED}) requirements while using the calculated value of the inductor ripple current (I_R) in the preceding Section 2.1.6. For this application, select ΔI_{LED} as 5 mA as described in Section 2.1.7 and the specifications.

$$Z_{COUT} \quad \frac{R_{LED} \quad I_{LED}}{I_R \quad I_{LED}} \quad \frac{4.34 \quad 5.005}{0.294 \quad 0.005} \quad \frac{217}{2890}$$

$$C_{COUT} \quad \frac{1}{2 \quad f_{SW} \quad Z_{COUT}} \quad \frac{1}{2 \quad 0.6 \quad 0.075} \quad 3.53 \quad F$$

where

- R_{LED} = Dynamic resistance of the LED
- ΔI_{LED} = LED peak-to-peak ripple current
- I_{RIPPLE} = Inductor ripple current, as calculated in Section 2.1.6 (13)

An output capacitor of 4.7 µF has been selected, which is more than the required value of 3.53 µF and further reduces ΔI_{LED}.

2.1.10 Minimum Input Capacitance and Required RMS Current Rating

The TPS92513 device requires a high-quality ceramic, type X5R or X7R, input decoupling capacitor of at least 2 µF of effective capacitance per 1 A of output current. Ceramic capacitance tends to decrease as the applied DC voltage increases. This depreciation must be accounted for to ensure that the minimum input capacitance has been satisfied. In some applications, additional capacitance is required to provide bulk energy storage such as high current PWM dimming applications. The input capacitor voltage rating must be greater than the maximum input voltage and have a ripple current rating greater than the maximum input current ripple of the converter.

2.1.11 External Compensation (COMP Pin)

The TPS92513 error amplifier output is connected to the COMP pin. The TPS92513 is a simple device to stabilize and only requires a capacitor from the COMP pin to ground (C_{COMP}). A 0.1 µF capacitor is recommended and works well for most applications. Approximate the overall system bandwidth using the following Equation 14:

$$BW \quad \frac{g_{M\ ea}}{2 \quad C_{COMP}} \tag{14}$$

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 buffer. 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 buffer 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 700 mA, 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 PDIM

The TPS92513 device incorporates a PWM-dimming input pin, which directly controls the enable and disable state of the internal gate driver. When the PDIM is low, the gate driver is disabled. The PDIM pin has a 1-µA pullup current source, which creates a default ON state when the PDIM pin is floating. When the PDIM goes low, the gate driver shuts off and the LED current quickly reduces to zero. A square wave of variable duty cycle must be used and must have a low level below 0.79 V and a high level of 1.45 V or above. The dimming frequency range is 200 Hz to 5 kHz and the minimum duty cycle is only limited in cases where the BOOT capacitor can discharge below its undervoltage threshold of 2 V (V_{IN} is within 2 V of the total output voltage). Refer to Section 4 for the set of measurements obtained using this feature.

2.2.3 Hybrid Dimming Using I_{ADJ} and PDIM

As evident from the measurements in Section 4, analog dimming is a more efficient method than PWM dimming. So, analog dimming can be preferred to dim the load and PWM dimming can be used to fine tune and obtain better resolution. At low currents, the PWM dimming can be used to obtain a linear dimming profile. Refer to Section 4 for the set of measurements taken using this feature.

2.2.4 Flicker-Free Dimming at Low Output LED Current

2.2.4.1 Flicker-Free Analog Dimming

With the 50-mΩ current resistor, the current can be reduced from the full-load current of 700 mA to the level of about 20 mA. TIDA-01096 can also be used to achieve flicker-free operation of output LED current up to 6 mA by just modifying the value of the current-sensing resistor from 50 mΩ to 250 mΩ.

NOTE: To obtain the maximum LED current, the resistor divider in the schematic comprising R19 and R22 must be changed because the V_{IADJ} voltage changes along with the change in the current sensing resistor (R_{ISENSE}). The maximum desired LED current is 700 mA and the current sensing resistor must be 0.25 Ω; therefore, V_{ISENSE} = 0.175 = 175 mV and V_{IADJ} = 1.05 V. At the maximum load current, V_{IADJ} must be 1.05 V and can be varied until 0 V to dim the current in the load.

2.2.4.2 Flicker-Free PWM Dimming at 1 kHz

With the 50-mΩ current resistor, the current can be reduced from the full-load current of 700 mA to the level of about 20 mA. TIDA-01096 can also be used to achieve flicker-free operation of output LED current up to 6 mA by just modifying the value of the current-sensing resistor from 50 mΩ to 250 mΩ.

3 Getting Started Hardware and Software

3.1 Hardware Connections

Figure 8 shows the hardware interconnections and wireless connections required for the TIDA-01096 to work as expected. As mentioned earlier, the TIDA-01096 connects as a BoosterPack™ Plug-in Module upon the CC2650 LaunchPad. 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.

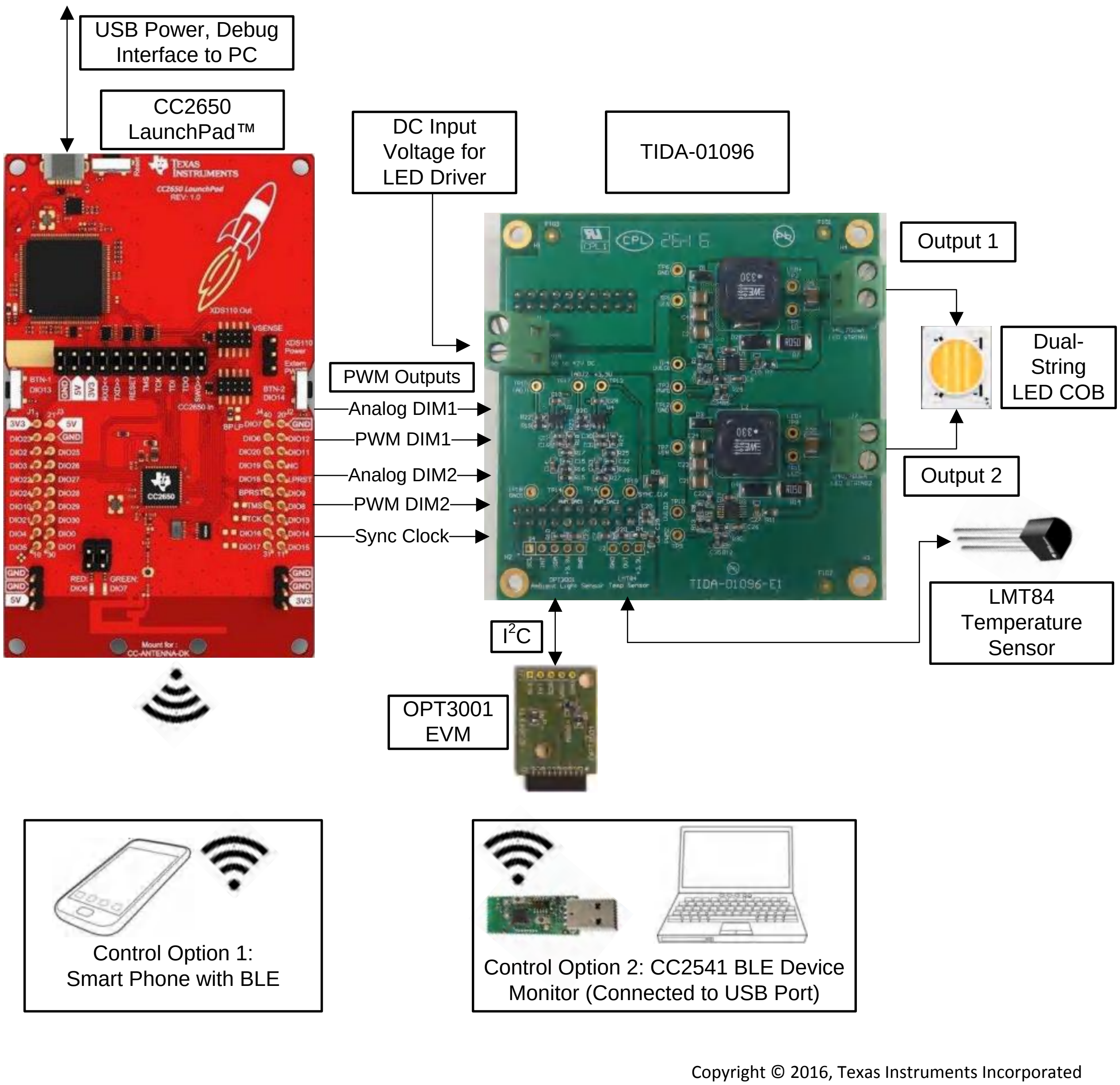

Figure 8. Hardware Connections

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.

3.3 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 and color tuning. Refer to the *BLE Device Monitor User Guide* [2] to get started with the BLE Device Monitor and using it to connect to other BLE devices.

Figure 9 is a screenshot of the BLE Device Monitor showing the SimpleBLEPeripheral in the BLE Network tab.

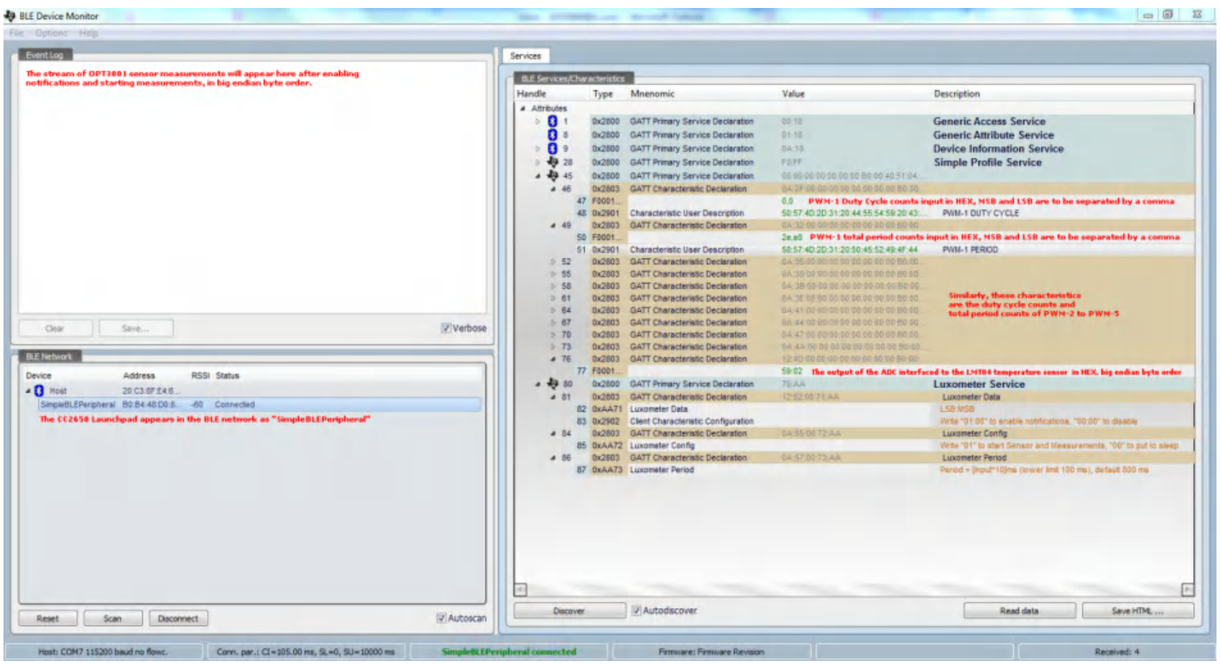

Figure 9. SimpleBLEPeripheral in BLE Network Tab

From the BLE Device Monitor, the frequency and the duty cycle of the five 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 9, 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

4.1 Efficiency and Output Current With I_{ADJ} Feature

Table 4 shows the efficiency of the string 1 LED driver with varying current reference values of V_{IADJ}.

Table 4. Efficiency With Analog Dimming

V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	V_{IADJ} (mV)	P_{IN} (W)	P_{OUT} (W)	EFFICIENCY
36.77	0.650	33.950	0.691	210.78	23.901	23.459	98.15%
36.79	0.581	33.700	0.622	190.27	21.375	20.961	98.07%
36.82	0.514	33.570	0.553	169.4	18.925	18.564	98.09%
36.84	0.445	33.360	0.482	148.29	16.394	16.080	98.08%
36.86	0.380	33.250	0.413	127.25	14.007	13.732	98.04%
36.89	0.313	33.000	0.343	106.13	11.547	11.319	98.03%
36.91	0.247	32.700	0.272	84.97	9.117	8.894	97.56%
36.93	0.181	32.250	0.201	63.77	6.684	6.482	96.98%
36.96	0.118	31.910	0.131	42.53	4.361	4.180	95.85%
36.98	0.054	31.270	0.059	21.27	1.997	1.845	92.39%
36.99	0.023	30.720	0.025	10.64	0.851	0.768	90.27%
36.99	0.017	30.510	0.018	8.52	0.629	0.549	87.33%

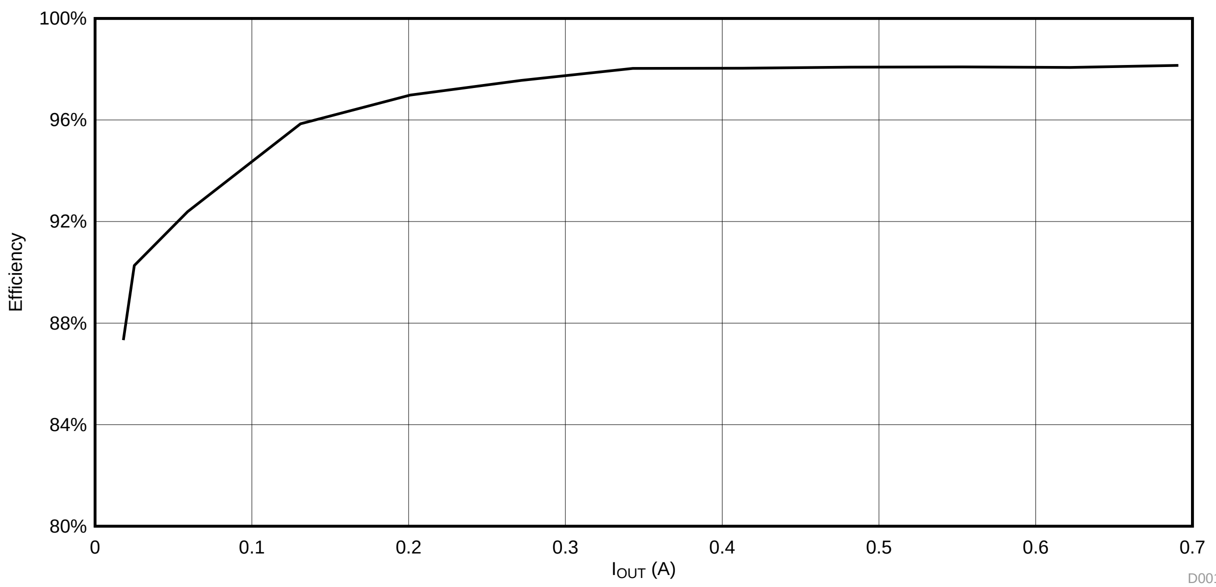

Figure 10. Individual TPS92513 Driver Efficiency With Analog Dimming

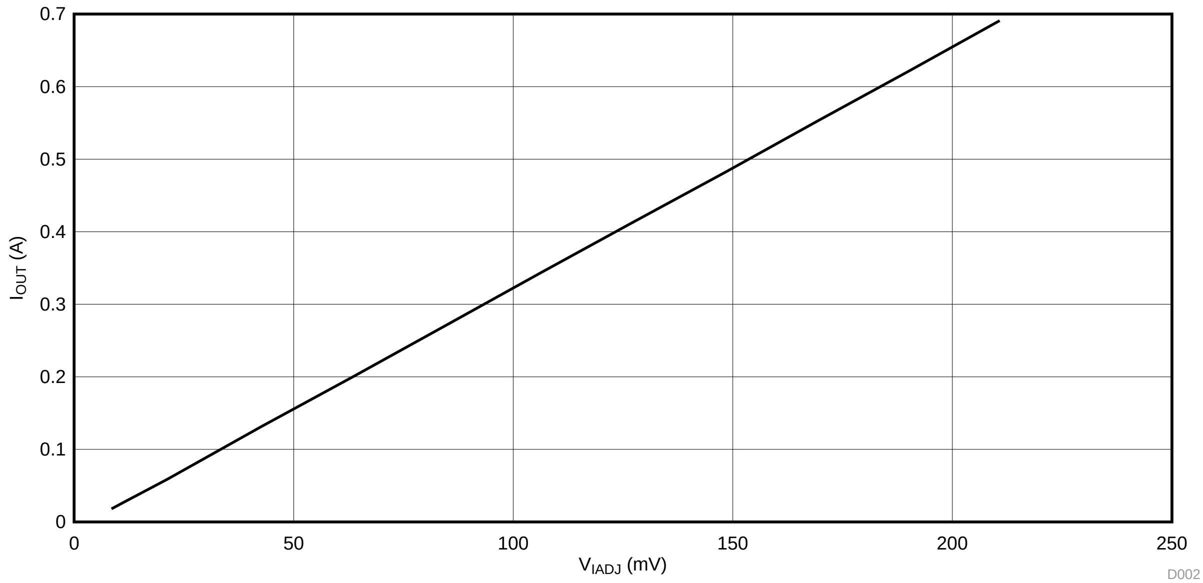

Figure 11. LED Driver Current Output Linearity With V_{IADJ}

4.2 Efficiency and Output Current With PDIM Feature

4.2.1 At 1-kHz PDIM Frequency

Table 5 shows the efficiency of the string 1 LED driver with a 1-kHz PWM dimming.

Table 5. Efficiency With 1-kHz PWM Dimming

V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	DUTY CYCLE	P_{IN} (W)	P_{OUT} (W)	EFFICIENCY
41.78	0.577	33.78	0.695	100%	24.107	23.477	97.39%
41.80	0.520	33.49	0.626	90%	21.736	20.965	96.45%
41.82	0.460	32.95	0.556	80%	19.237	18.320	95.23%
41.85	0.403	32.49	0.486	70%	16.866	15.790	93.62%
41.87	0.345	32.04	0.415	60%	14.445	13.297	92.05%
41.89	0.287	31.57	0.346	50%	12.022	10.923	90.86%
41.91	0.229	31.11	0.276	40%	9.597	8.586	89.47%
41.93	0.172	30.70	0.206	30%	7.212	6.324	87.69%
41.95	0.114	30.29	0.136	20%	4.782	4.119	86.14%
41.96	0.086	30.76	0.101	15%	3.609	3.107	86.09%
41.96	0.072	30.63	0.084	12.5%	3.021	2.573	85.16%
41.97	0.055	29.92	0.066	10%	2.308	1.975	85.55%
41.98	0.042	30.37	0.049	7.5%	1.763	1.488	84.40%
41.98	0.027	30.34	0.031	5%	1.133	0.941	82.98%
41.99	0.021	29.71	0.025	4%	0.882	0.743	84.23%
41.99	0.015	29.70	0.018	3%	0.630	0.535	84.88%

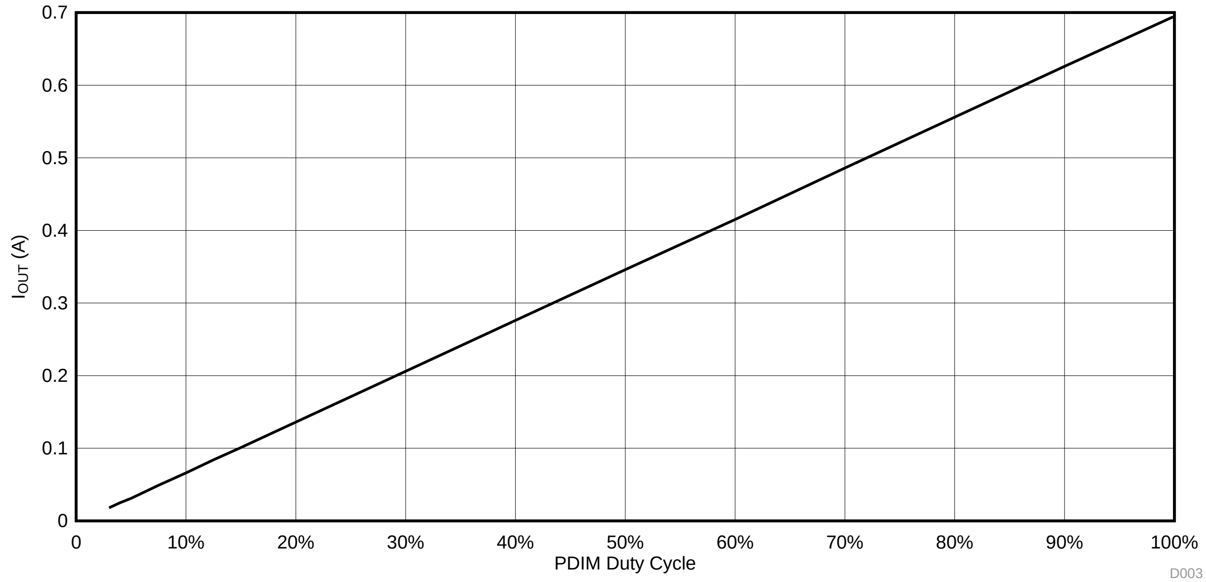

Figure 12. LED Driver Output Current Linearity With 1-kHz PWM Dimming

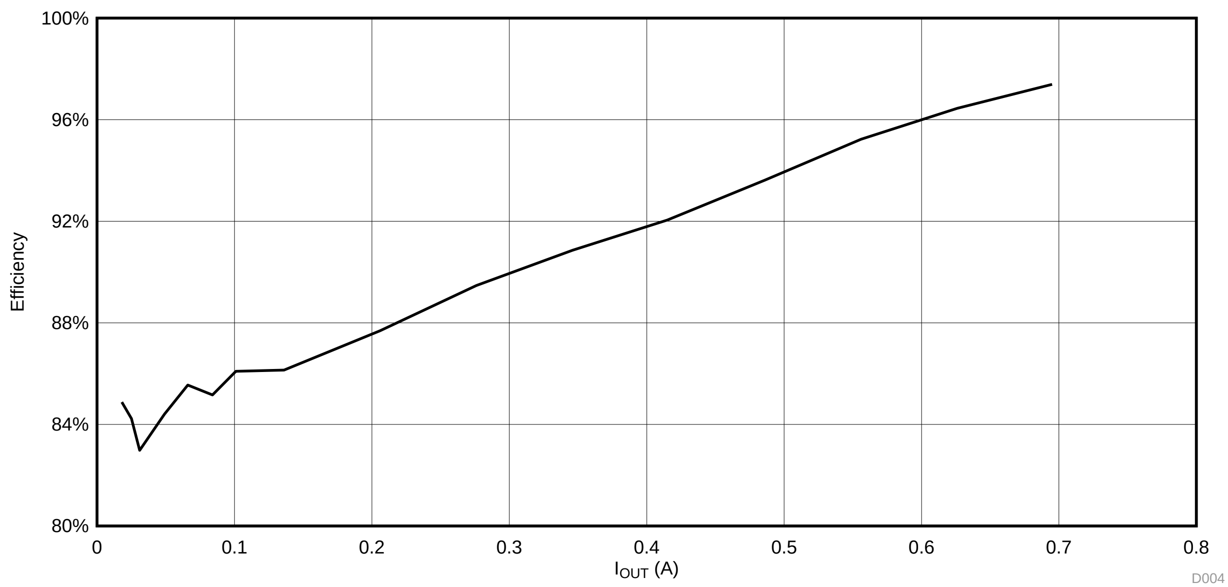

Figure 13. Individual TPS92513 Driver Efficiency With 1-kHz PWM Dimming

4.2.2 At 5-kHz PDIM Frequency

Table 6 shows the efficiency of the string 1 LED driver with a 5-kHz PWM dimming.

Table 6. Efficiency With 5-kHz PWM Dimming

V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	DUTY CYCLE	P_{IN} (W)	P_{OUT} (W)	EFFICIENCY
41.77	0.587	34.51	0.695	100%	24.519	23.984	97.82%
41.8	0.525	34.15	0.624	90%	21.945	21.310	97.10%
41.82	0.465	33.77	0.554	80%	19.446	18.709	96.21%
41.84	0.406	33.36	0.485	70%	16.987	16.180	95.25%
41.86	0.346	32.95	0.415	60%	14.484	13.674	94.41%
41.88	0.288	32.54	0.345	50%	12.061	11.226	93.08%
41.91	0.229	32.13	0.276	40%	9.597	8.868	92.40%
41.93	0.170	31.74	0.206	30%	7.128	6.538	91.73%
41.95	0.111	31.32	0.136	20%	4.656	4.260	91.48%
41.96	0.083	31.44	0.102	15%	3.483	3.207	92.08%
41.97	0.068	31.31	0.084	12.5%	2.854	2.630	92.15%
41.97	0.054	30.87	0.066	10%	2.266	2.037	89.90%
41.98	0.039	31.05	0.048	7.5%	1.637	1.490	91.03%
41.98	0.023	30.53	0.029	5%	0.966	0.885	91.70%
41.99	0.018	30.45	0.023	4%	0.756	0.700	92.66%
41.99	0.010	30.25	0.013	3%	0.420	0.393	93.65%

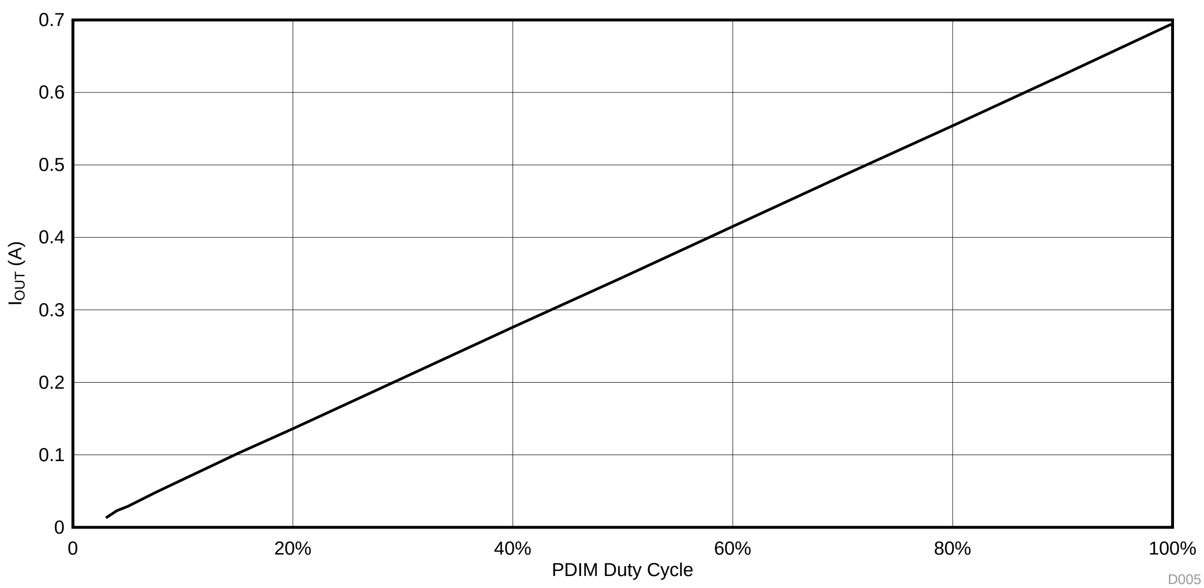

Figure 14. LED Driver Output Current Linearity With 1-kHz PWM Dimming

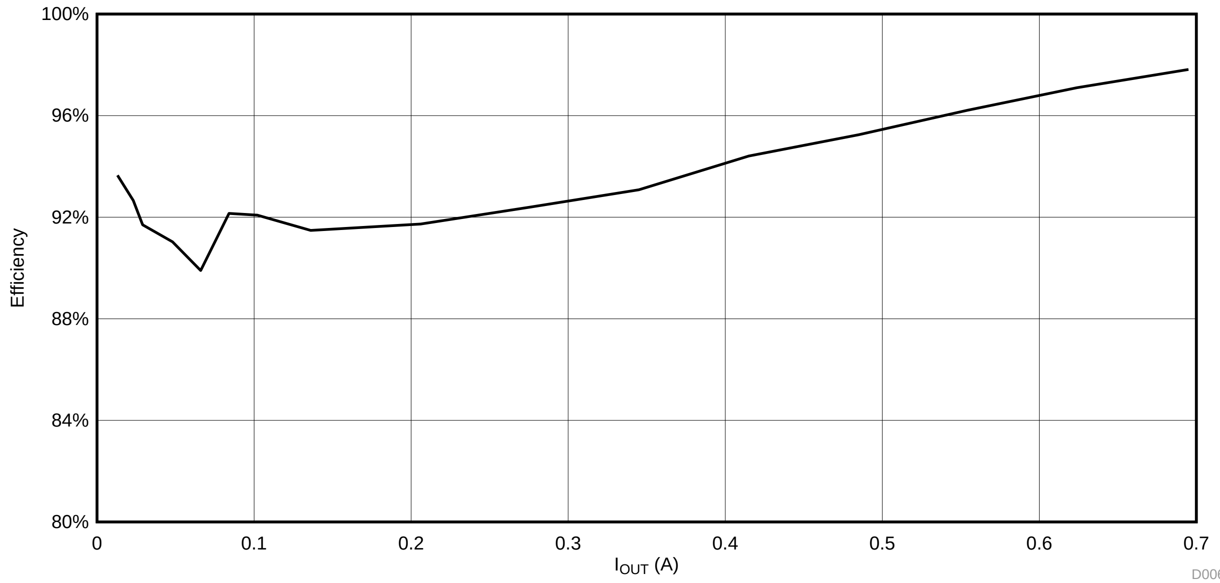

Figure 15. Individual TPS92513 Driver Efficiency With 1-kHz PWM Dimming

4.2.3 Efficiency With Variable Input Voltage

Table 7 shows the variation in efficiency with varying input voltages.

Table 7. Converter Efficiency for Different Input Voltages

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	EFFICIENCY
35.71	0.67	23.9257	34.48	0.689	23.75672	99.29%
36.79	0.656	24.13424	34.49	0.691	23.83259	98.75%
37.76	0.64	24.1664	34.49	0.691	23.83259	98.62%
38.78	0.626	24.27628	34.49	0.692	23.86708	98.31%
39.8	0.611	24.3178	34.5	0.693	23.9085	98.32%
40.82	0.597	24.36954	34.5	0.694	23.943	98.25%
41.78	0.584	24.39952	34.5	0.695	23.9775	98.27%
42.8	0.572	24.4816	34.5	0.695	23.9775	97.94%
43.76	0.562	24.59312	34.5	0.697	24.0465	97.78%
44.79	0.55	24.6345	34.51	0.698	24.08798	97.78%
45.8	0.54	24.732	34.51	0.699	24.12249	97.54%
46.83	0.529	24.77307	34.52	0.701	24.19852	97.68%
47.85	0.52	24.882	34.52	0.702	24.23304	97.39%

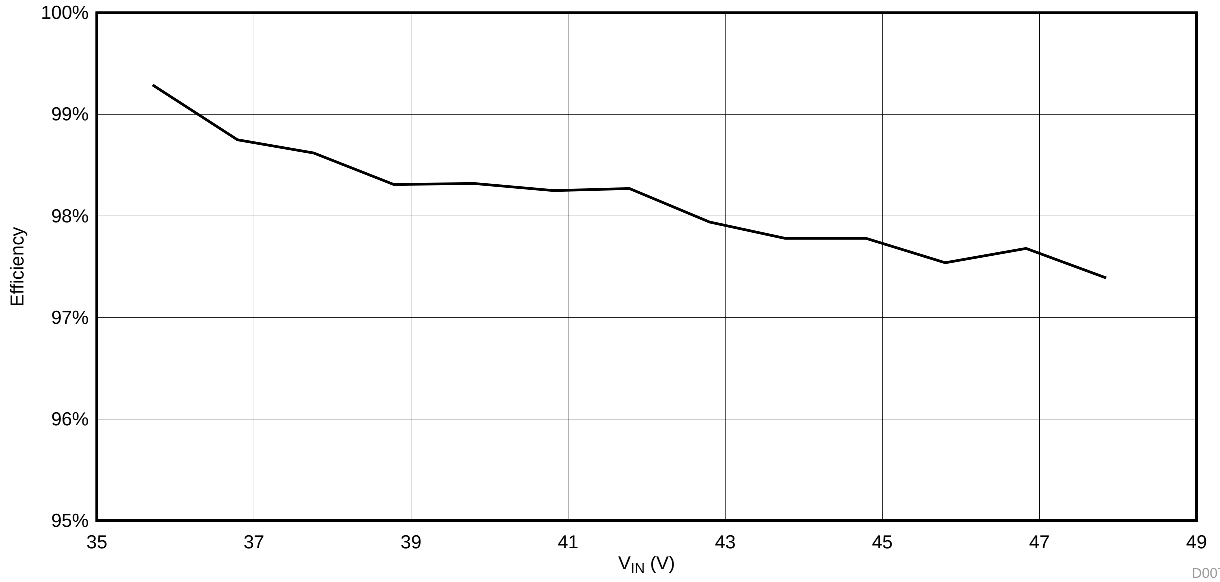

Figure 16. Efficiency versus V_{IN} (V)

4.3 Tunable White Using Both LED Strings

4.3.1 At 100% Brightness

Table 8 shows the total system efficiency while changing the color temperature of the light from extreme cold white to extreme warm white. The maximum total current of the LED COB was set at its 100% rating.

Table 8. Efficiency With Changing Color Temperature at 100% Brightness

TUNABLE DUTY CYCLE	V_{IN} (V)	I_{IN} (A)	V_{OUT} WARM (A)	I_{OUT} WARM (A)	V_{OUT} COLD (V)	I_{OUT} COLD (A)	P_{IN} (W)	P_{OUT} WARM (W)	P_{OUT} COLD (W)	P_{OUT} (W)	EFFICIENCY
0%	41.74	0.622	28.86	0.000	35.22	0.717	25.962	0.000	25.253	25.253	97.27%
10%	41.74	0.616	30.15	0.066	34.8	0.645	25.712	1.990	22.446	24.436	95.04%
20%	41.74	0.610	30.68	0.136	34.31	0.573	25.461	4.172	19.660	23.832	93.60%
30%	41.75	0.609	31.20	0.206	33.78	0.502	25.426	6.427	16.958	23.385	91.97%
40%	41.75	0.608	31.77	0.275	33.29	0.430	25.384	8.737	14.315	23.051	90.81%
45%	41.75	0.605	31.97	0.310	32.96	0.393	25.259	9.911	12.953	22.864	90.52%
50%	41.75	0.604	32.22	0.346	32.67	0.358	25.217	11.148	11.696	22.844	90.59%
55%	41.75	0.603	32.47	0.380	32.39	0.321	25.175	12.339	10.397	22.736	90.31%
60%	41.75	0.601	32.73	0.415	32.11	0.285	25.092	13.583	9.151	22.734	90.60%
70%	41.75	0.596	33.22	0.485	31.53	0.213	24.883	16.112	6.716	22.828	91.74%
80%	41.75	0.591	33.69	0.555	30.94	0.141	24.674	18.698	4.363	23.060	93.46%
90%	41.76	0.586	34.13	0.625	30.36	0.069	24.471	21.331	2.095	23.426	95.73%
100%	41.76	0.585	34.50	0.695	28.88	0.000	24.430	23.978	0.000	23.978	98.15%

4.3.2 At 75% Brightness

Table 9 shows the total system efficiency while changing the color temperature of the light from extreme cold white to extreme warm white. The maximum total current of the LED COB was set at its 75% rating.

Table 9. Efficiency With Changing Color Temperature at 75% Brightness

TUNABLE DUTY CYCLE	V_{IN} (V)	I_{IN} (A)	V_{OUT} WARM (A)	I_{OUT} WARM (A)	V_{OUT} COLD (V)	I_{OUT} COLD (A)	P_{IN} (W)	P_{OUT} WARM (W)	P_{OUT} COLD (W)	P_{OUT} (W)	EFFICIENCY
0%	41.8	0.471	28.92	0.000	34.62	0.553	19.688	0.000	19.145	19.145	97.24%
10%	41.8	0.465	30.24	0.050	34.29	0.497	19.437	1.512	17.042	18.554	95.46%
20%	41.81	0.461	30.72	0.102	33.88	0.441	19.274	3.133	14.941	18.075	93.77%
30%	41.81	0.457	31.17	0.154	33.42	0.386	19.107	4.800	12.900	17.700	92.64%
40%	41.81	0.454	31.61	0.206	32.96	0.330	18.982	6.512	10.877	17.388	91.61%
45%	41.81	0.452	31.83	0.233	32.72	0.303	18.898	7.416	9.914	17.331	91.71%
50%	41.81	0.451	32.06	0.253	32.49	0.275	18.856	8.111	8.935	17.046	90.40%
55%	41.81	0.450	32.38	0.285	32.24	0.247	18.815	9.228	7.963	17.192	91.37%
60%	41.81	0.448	32.49	0.311	31.99	0.219	18.731	10.104	7.006	17.110	91.35%
70%	41.81	0.444	32.92	0.365	31.49	0.164	18.564	12.016	5.164	17.180	92.55%
80%	41.81	0.439	33.32	0.417	30.99	0.108	18.355	13.894	3.347	17.241	93.93%
90%	41.81	0.435	33.70	0.470	30.48	0.052	18.187	15.839	1.585	17.424	95.80%
100%	41.82	0.433	34.00	0.522	28.98	0.000	18.108	17.748	0.000	17.748	98.01%

4.3.3 At 50% Brightness

Table 10 shows the total system efficiency while changing the color temperature of the light from extreme cold white to extreme warm white. The maximum total current of the LED COB was set at its 50% rating.

Table 10. Efficiency With Changing Color Temperature at 50% Brightness

TUNABLE DUTY CYCLE	V_{IN} (V)	I_{IN} (A)	V_{OUT} WARM (A)	I_{OUT} WARM (A)	V_{OUT} COLD (V)	I_{OUT} COLD (A)	P_{IN} (W)	P_{OUT} WARM (W)	P_{OUT} COLD (W)	P_{OUT} (W)	EFFICIENCY
0%	41.86	0.319	28.96	0.000	33.97	0.382	13.353	0.000	12.977	12.977	97.18%
10%	41.87	0.315	30.37	0.032	33.73	0.344	13.189	0.972	11.603	12.575	95.34%
20%	41.87	0.31	30.78	0.066	33.41	0.305	12.980	2.031	10.190	12.222	94.16%
30%	41.87	0.307	31.15	0.101	33.04	0.267	12.854	3.146	8.822	11.968	93.11%
40%	41.87	0.304	31.52	0.136	32.67	0.228	12.728	4.287	7.449	11.735	92.20%
45%	41.87	0.302	31.71	0.154	32.47	0.209	12.645	4.883	6.786	11.669	92.28%
50%	41.87	0.3	31.89	0.171	32.27	0.190	12.561	5.453	6.131	11.584	92.23%
55%	41.87	0.299	32.05	0.188	32.07	0.171	12.519	6.025	5.484	11.509	91.93%
60%	41.87	0.297	32.22	0.206	31.85	0.151	12.435	6.637	4.809	11.447	92.05%
70%	41.87	0.293	32.57	0.241	31.44	0.113	12.268	7.849	3.553	11.402	92.94%
80%	41.87	0.289	32.90	0.275	31.03	0.074	12.100	9.048	2.296	11.344	93.75%
90%	41.87	0.284	33.19	0.310	30.60	0.035	11.891	10.289	1.071	11.360	95.53%
100%	41.87	0.281	33.43	0.346	29.01	0.000	11.765	11.567	0.000	11.567	98.31%

4.4 OPT3001 – LUX Measurements

Table 11 lists the lux measurement from OPT3001 while varying current in one of the LED strings.

Table 11. Lux Measurements

I_{OUT} (A)	OPT IN HEX	MSB	MSB IN DECIMAL	MULTIPLIER	DEC TO HEX	LSB IN DECIMAL	OPT SENSOR (LUX)
0.000	101	0	0	0.01	257	257	2.57
0.066	6865	6	6	0.64	26725	2149	1375.36
0.136	785B	7	7	1.28	30811	2139	2737.92
0.206	8638	8	8	2.56	34360	1592	4075.52
0.276	8855	8	8	2.56	34901	2133	5460.48
0.346	8A56	8	8	2.56	35414	2646	6773.76
0.415	8C63	8	8	2.56	35939	3171	8117.76
0.486	8E63	8	8	2.56	36451	3683	9428.48
0.556	9822	9	9	5.12	38946	2082	10659.84
0.626	98FC	9	9	5.12	39164	2300	11776
0.695	99D8	9	9	5.12	39384	2520	12902.4

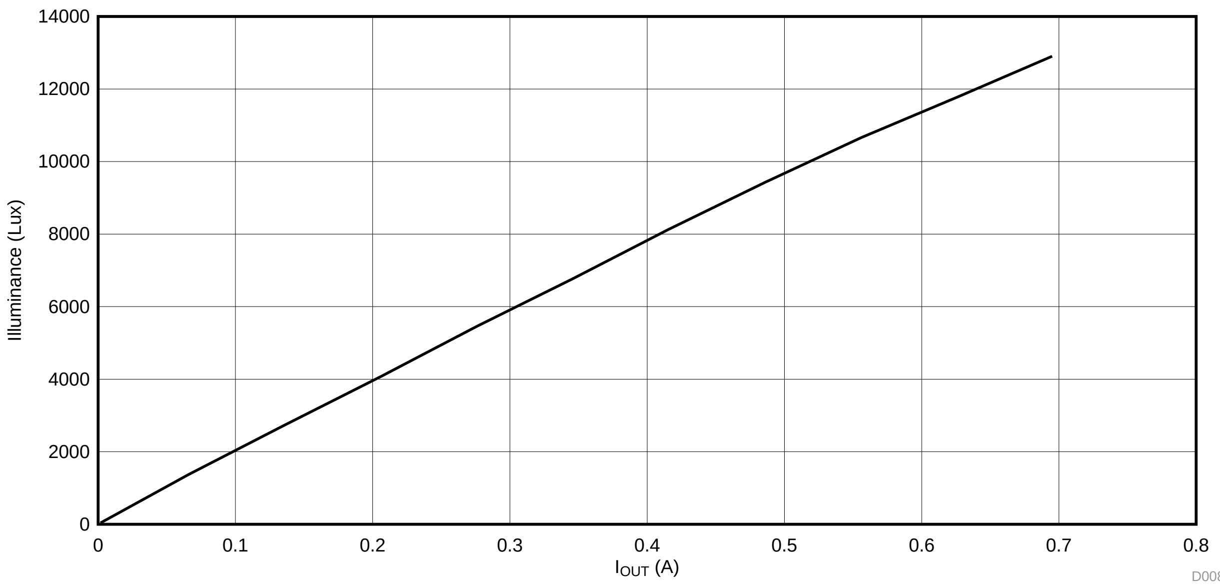

Figure 17. Illuminance versus I_{OUT} (A)

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, or 4 in this case, and calculate LSB_size as
   LSB_size = $0.01 \times 2^4 = 0.16$.

NOTE: This nibble may even be A, B, C, D, E or F, in which case the exponent must be taken as the corresponding decimal number: that is, 10, 11, 12, 13, 14, and 15 respectively.

2. Convert the remaining 3 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 LMT84 – Temperature Measurements

Table 12 shows the temperature measurements of the LED COB heatsink using the LMT84 temperature sensor with different LED currents. The temperature rise is dependent on the power loss in the LED COB, size of the heatsink, and the velocity of air flow. The temperature readings of the LED COB heatsink were taken at an ambient temperature of 25°C and without any forced air cooling.

Table 12. LED COB Heatsink Temperature Measurements

V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	TEMPERATURE (°C)	ADC OUTPUT (HEX)	HEX TO DECIMAL	LMT84 OUTPUT VOLTAGE
48.02	0.054	31.93	0.073	36.21	31C	796	0.836
47.99	0.091	32.37	0.125	40.41	306	774	0.813
47.96	0.152	32.54	0.213	52.44	2C7	711	0.747
47.95	0.178	32.66	0.248	55.11	2B9	697	0.732
47.95	0.203	32.78	0.282	57.97	2AA	682	0.716
47.94	0.227	32.88	0.317	60.07	29F	671	0.705
47.93	0.254	33.02	0.352	60.84	29B	667	0.700
47.92	0.279	33.18	0.385	61.60	297	663	0.696

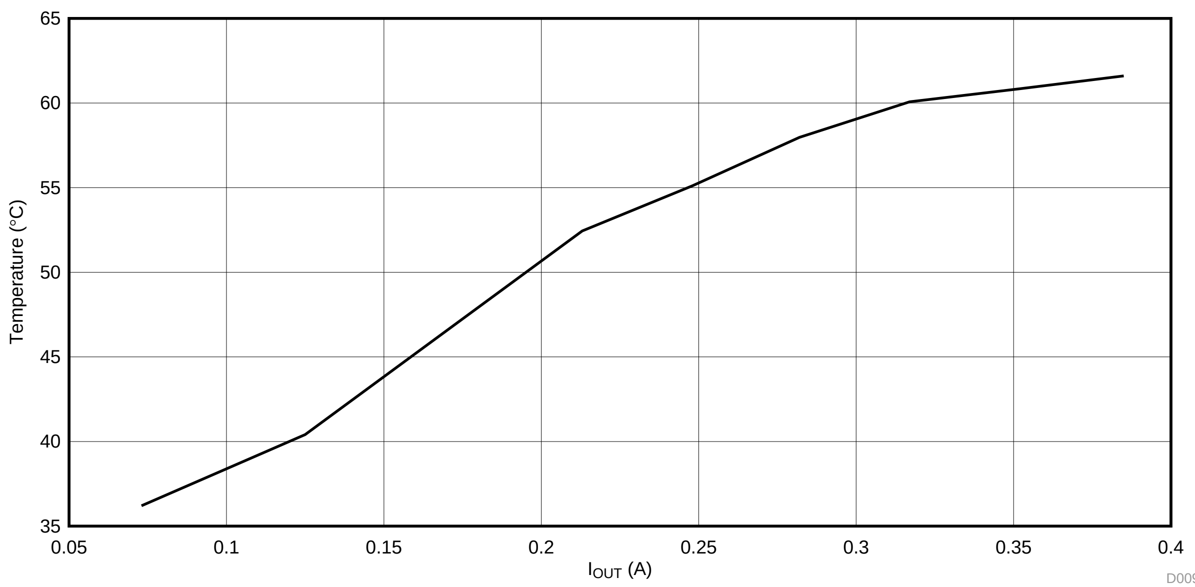

Figure 18. Temperature (°C) versus I_{OUT} (A)

4.5.1 Conversion From ADC Output in HEX to 0°C

If the output of the ADC is 0306, then it evaluates to 774 in decimal. CC2650 has a 12-bit ADC with a reference voltage of 4.3 V. So, the analog voltage value that 0306 corresponds to is:
(4.3 × 774) / (212 – 1) = 0.812 V. The mapping table in the LMT84 data sheet shows that the temperature is 410°C.

4.6 Waveforms

4.6.1 At 5-kHz PDIM Frequency

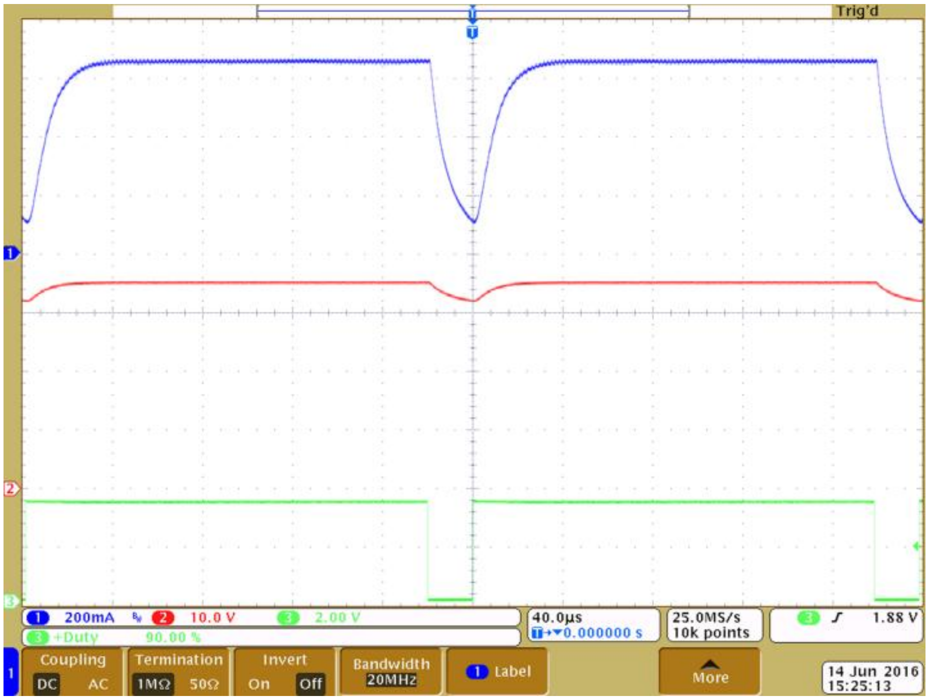

Figure 19. LED Current, LED Voltage, and PDIM Input Waveforms at 90% Duty Cycle

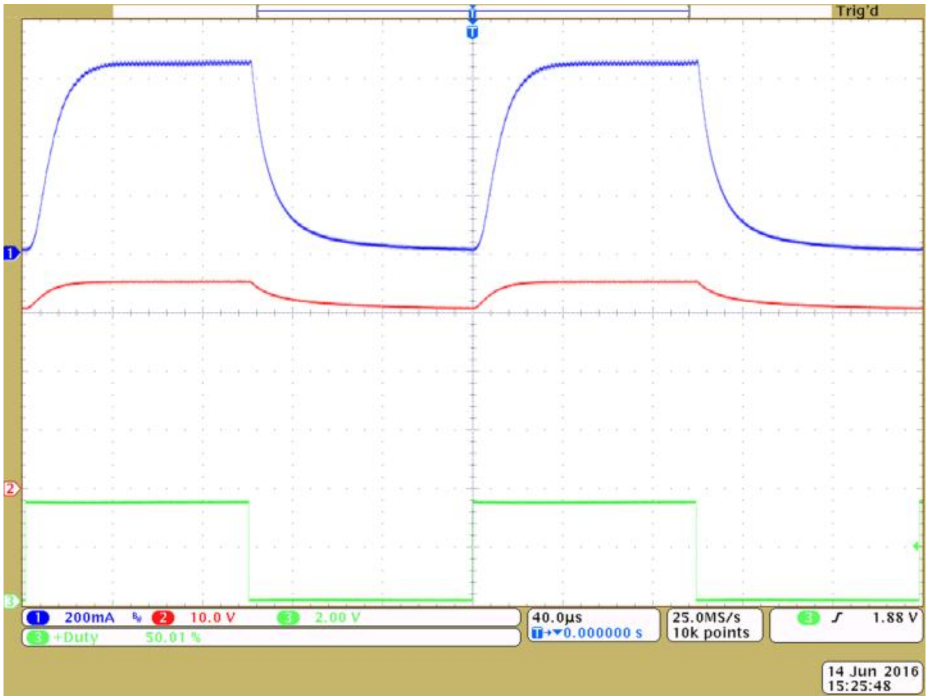

Figure 20. LED Current, LED Voltage, and PDIM Input Waveforms at 50% Duty Cycle

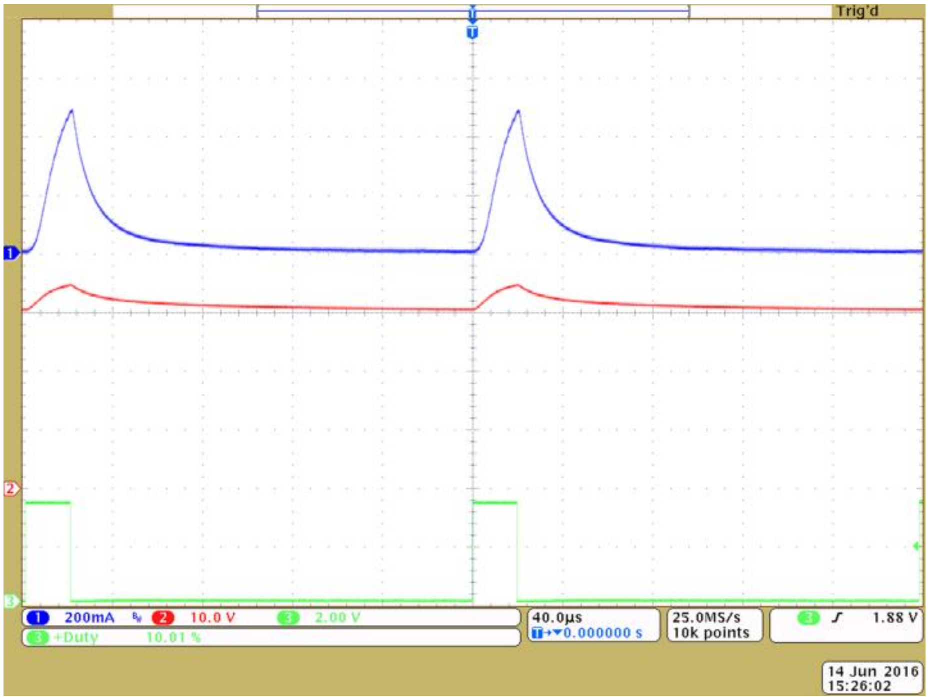

Figure 21. LED Current, LED Voltage, and PDIM Input Waveforms at 10% Duty Cycle

4.6.2 At 1-kHz PDIM Frequency

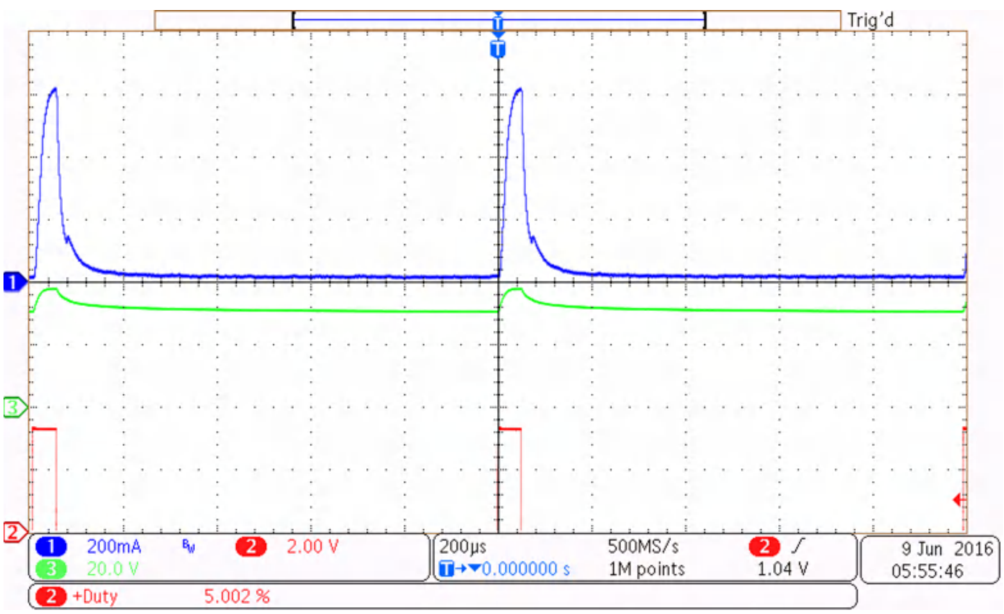

Figure 22. LED Current, LED Voltage, and PDIM Input Waveforms at 5% Duty Cycle

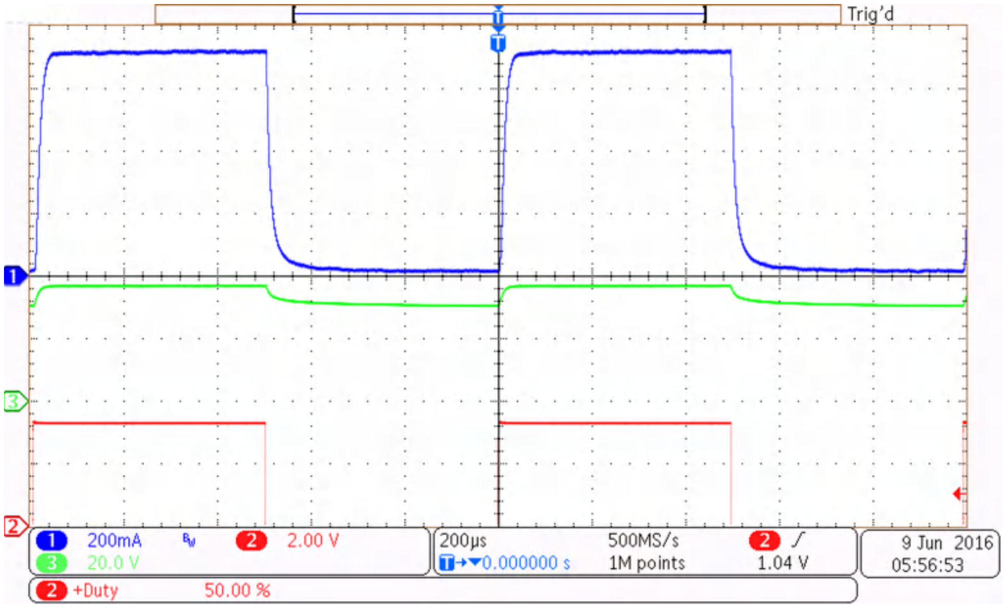

Figure 23. LED Current, LED Voltage, and PDIM Input Waveforms at 50% Duty Cycle

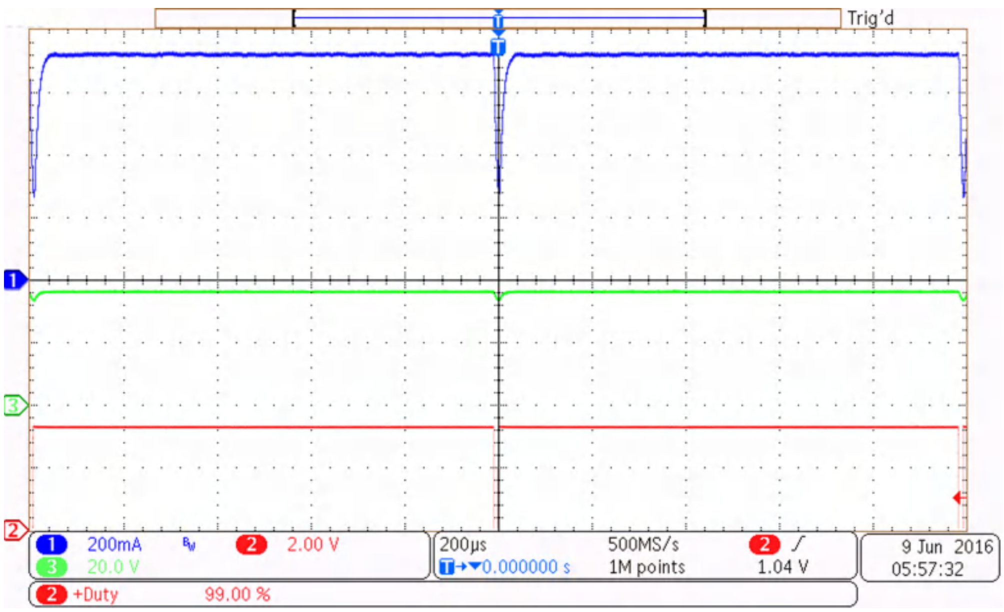

Figure 24. LED Current, LED Voltage, and PDIM Input Waveforms at 99% Duty Cycle

4.6.3 At 200-Hz PDIM Frequency

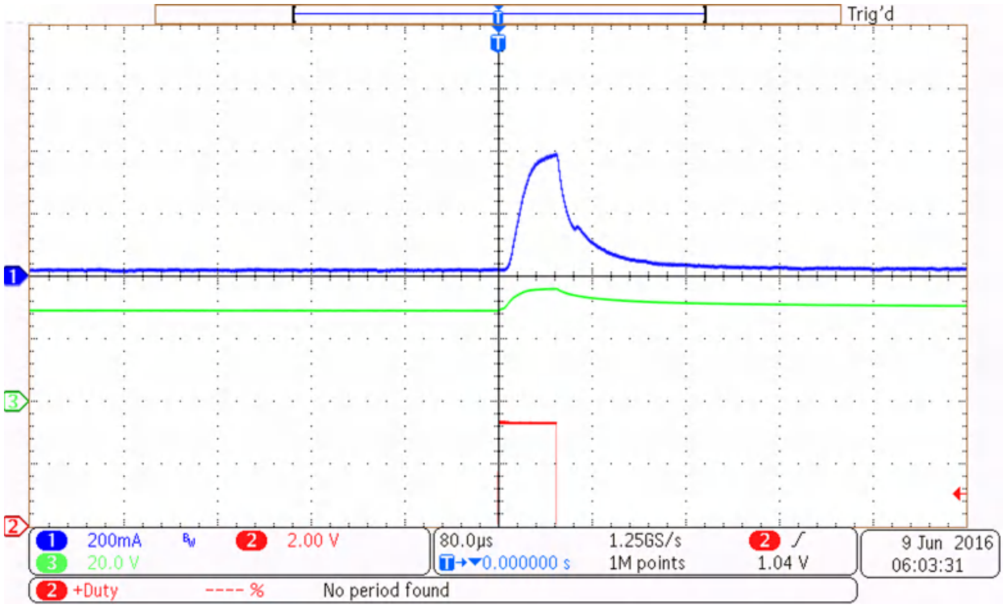

Figure 25. LED Current, LED Voltage, and PDIM Input Waveforms at 1% Duty Cycle

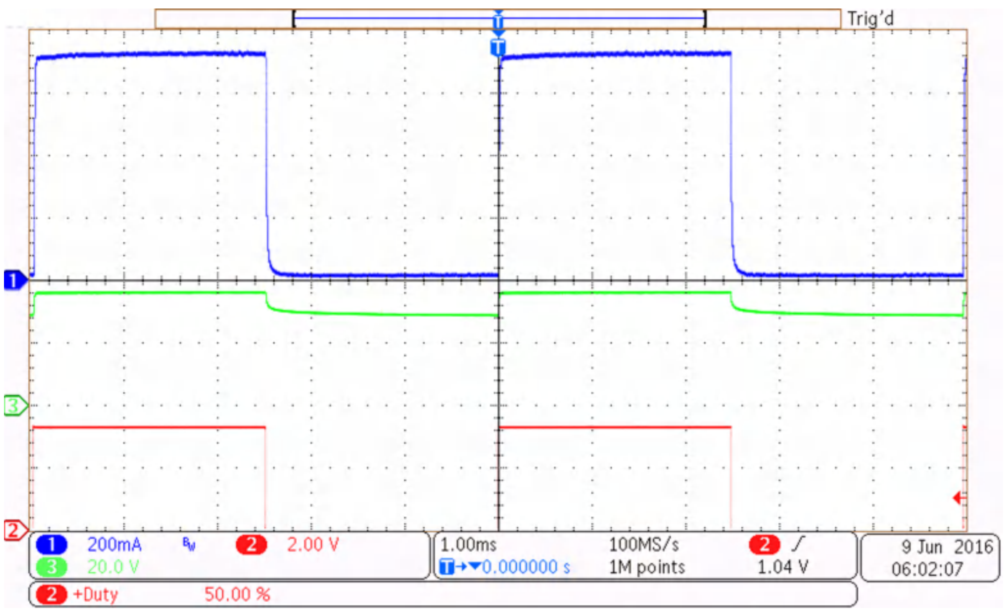

Figure 26. LED Current, LED Voltage, and PDIM Input Waveforms at 50% Duty Cycle

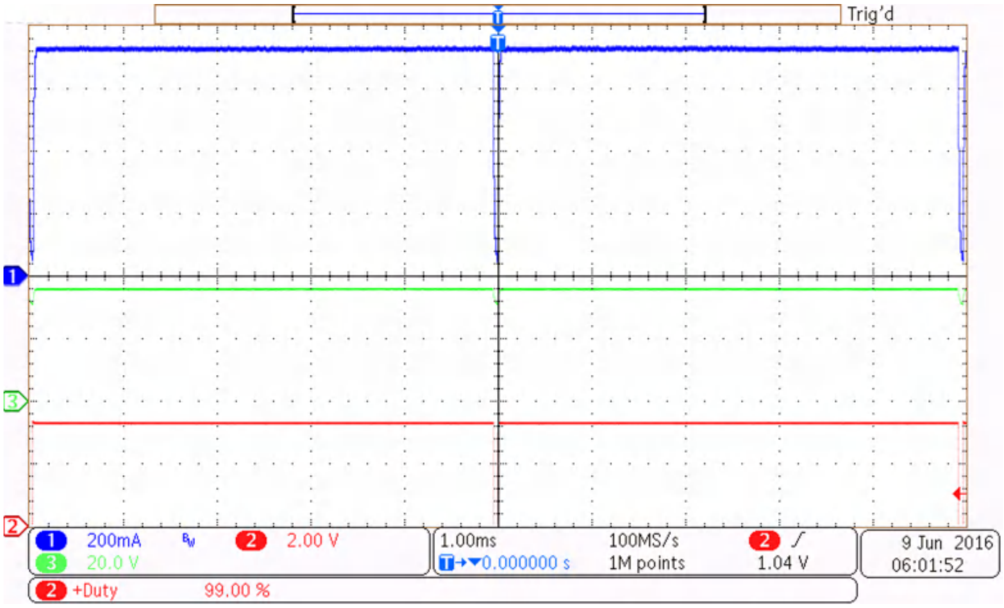

Figure 27. LED Current, LED Voltage, and PDIM Input Waveforms at 99% Duty Cycle

4.6.4 RT/CLK Synchronization Waveforms

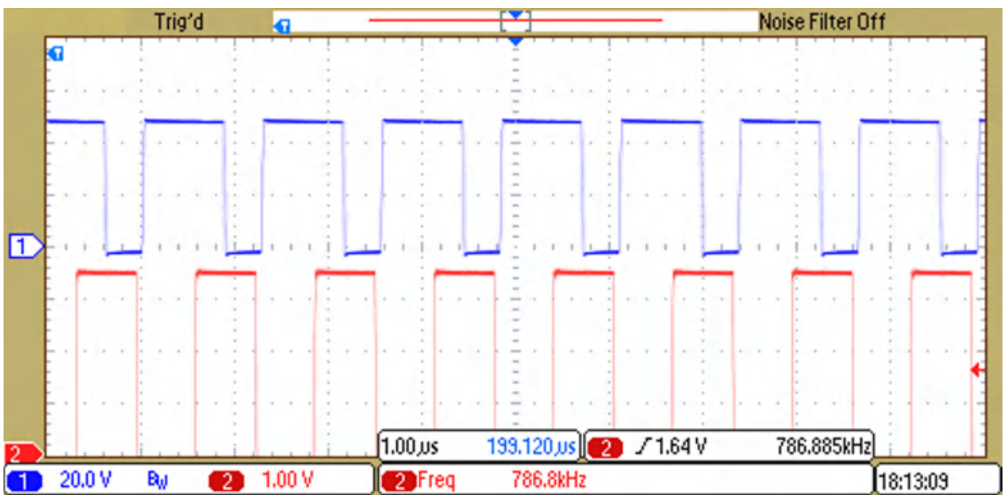

Figure 28. PH Pin Voltage—RT/CLK Pin PWM Input at 800 kHz

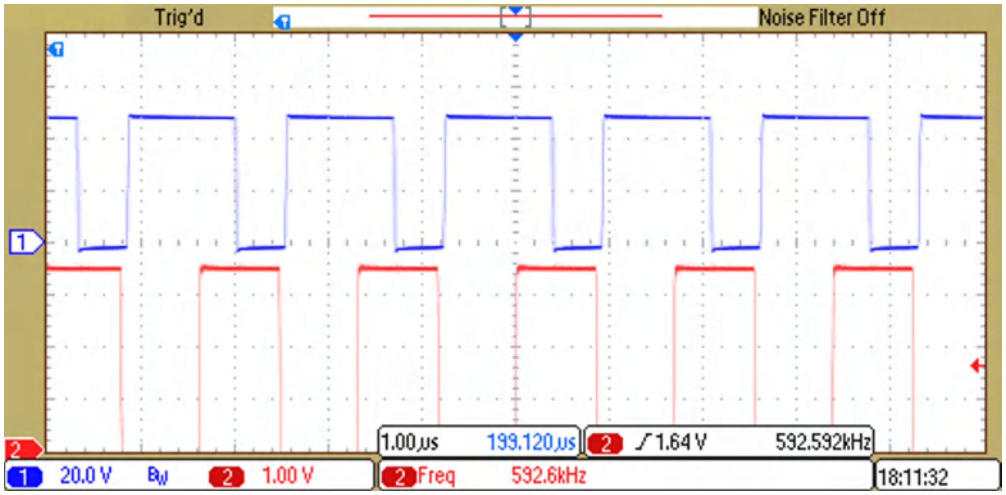

Figure 29. PH Pin Voltage—RT/CLK Pin PWM Input at 600 kHz

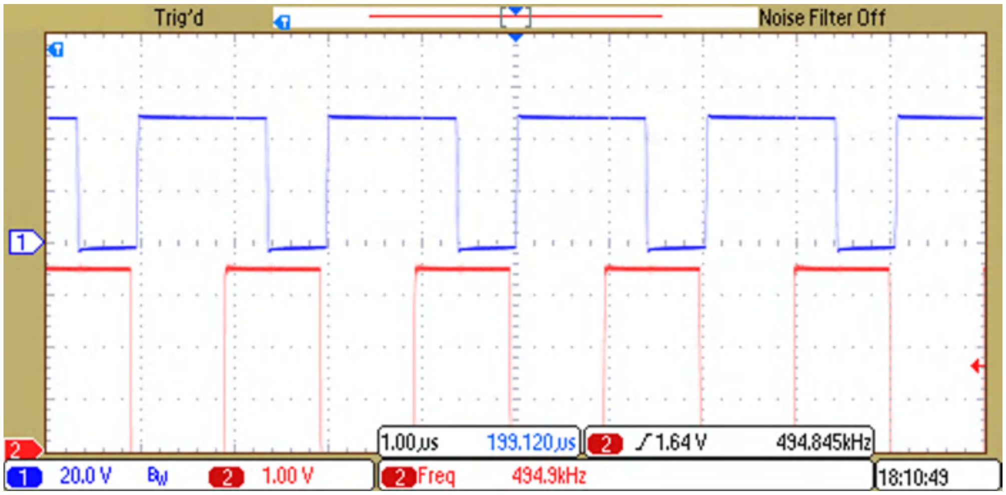

Figure 30. PH Pin Voltage—RT/CLK Pin PWM Input at 500 kHz

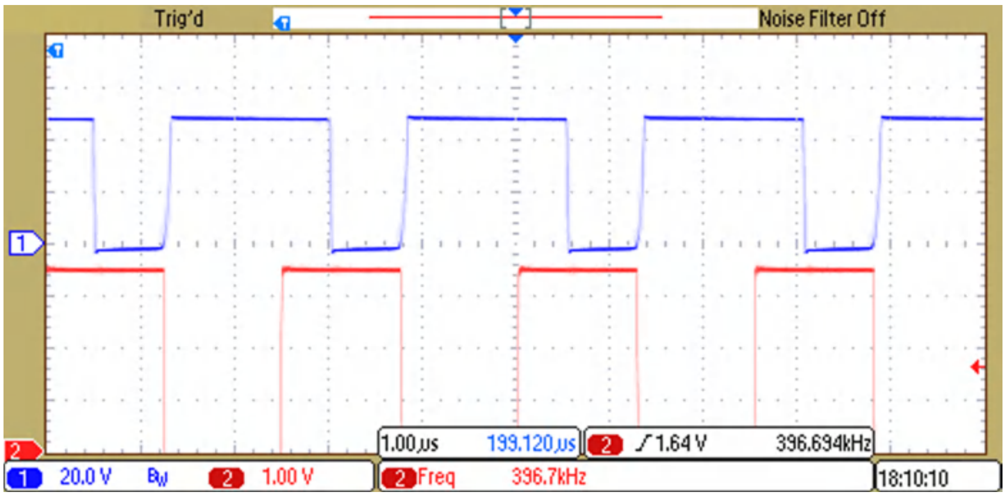

Figure 31. PH Pin Voltage—RT/CLK Pin PWM Input at 400 kHz

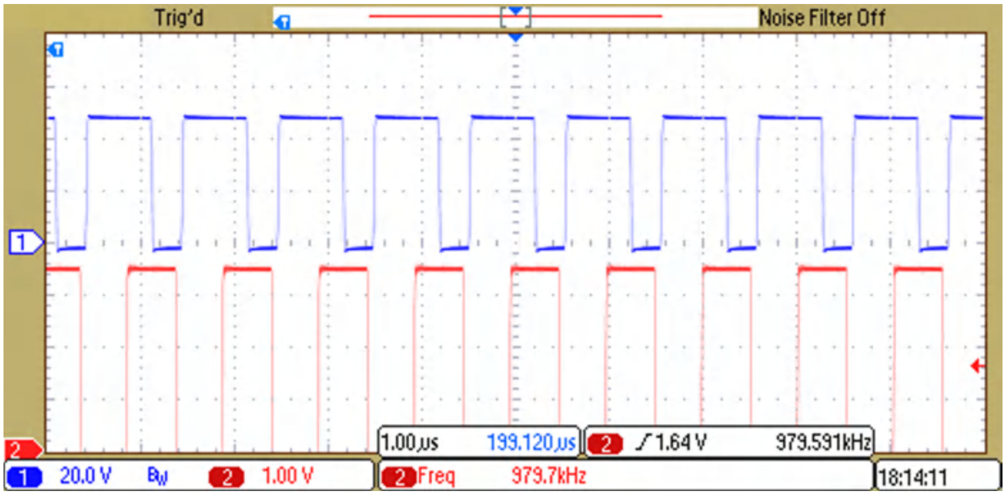

Figure 32. PH Pin Voltage—RT/CLK Pin PWM Input at 1000 kHz

5 Design Files

5.1 Schematics

To download the schematics, see the design files at TIDA-01096.

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01096.

5.3 PCB Layout Recommendations

The TIDA-01096 PCB has been designed as a BoosterPack for the CC2650 LaunchPad hardware. The BoosterPack is a two-layer PCB. The layout guidelines are as follows:

- Creating a large GND plane under the integrated circuit (IC) for good electrical and thermal performance is important.
- The GND pin of the device must connect to the GND plane directly beneath the IC.
- Thermal vias can be used to connect the topside GND plane to additional PCB layers for heat spreading and more solid grounding.
- The input capacitors must be located as close as possible to the VIN pin and the GND plane and should be tied to a solid backside ground plane using multiple vias.
- The compensation components must be located as close as possible to the COMP and GND pins to minimize noise sensitivity.
- The PH trace must be kept as short as possible to reduce the possibility of radiated noise or EMI.
- The ISENSE node must be kept as short as possible and shielded from noise.
- The RT/CLK pin is sensitive and its routing must be kept as short as possible.
- In higher current applications, routing the load current of the current-sense resistor to the junction of the input capacitor and rectifier diode GND node may be necessary. The easiest way to accomplish this is to use a backside ground plane and arrays of vias to connect the topside ground connections solidly to the backside plane. This configuration steers the high current away from the sensitive RT/CLK-to-GND connection.
- If possible, the current loop created when the internal MOSFET is ON should be in the same direction as the current loop when the internal MOSFET is OFF and the Schottky diode is conducting. This configuration prevents magnetic field reversal, reduces radiated noise, and simplifies EMI filtering.

5.3.1 Layout Guidelines

At lower PWM dimming frequencies, the output ceramic capacitor can cause acoustic noise. To minimize the noise, two ceramic capacitors are placed exactly opposing each other on the top and bottom layer of the PCB (see Figure 33. and Figure 34). The ground plane of the CC2650 LaunchPad and the LED driver section are separated clearly and connected through a 0-Ω resistor.

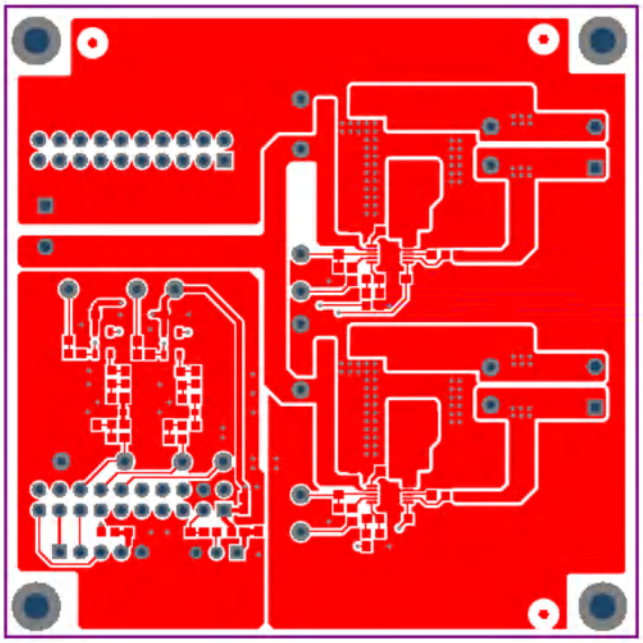

Figure 33. Layout Guidelines—Top Layer

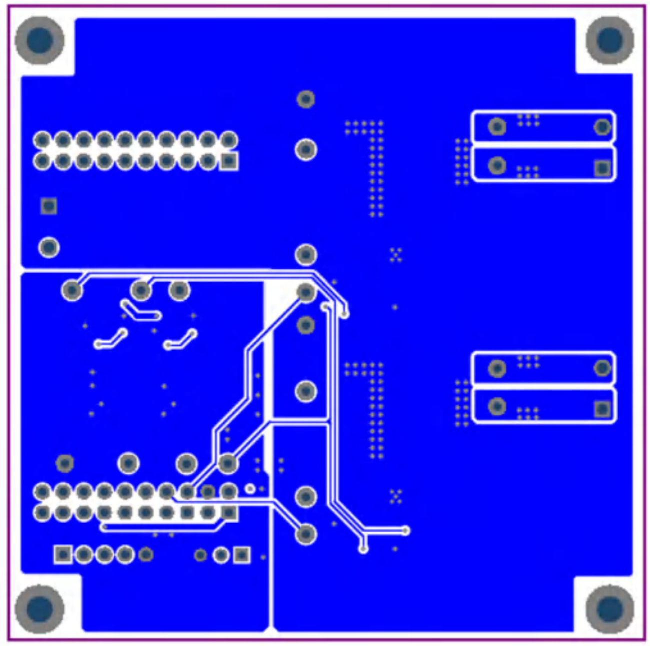

Figure 34. Layout Guidelines—Bottom Layer

5.3.2 Layout Prints

To download the layer plots, see the design files at TIDA-01096.

5.4 Altium Project

To download the Altium project files, see the design files at TIDA-01096.

5.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01096.

5.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01096.

6 Software Files

To download the software files, see the design files at TIDA-01096.

7 References

1. Texas Instruments, *TPS92513 1.5A Buck LED Driver with Integrated Analog Current Adjust*, TPS92513/HV Data Sheet (SLVSCX6)
2. Texas Instruments, *BLE Device Monitor User Guide*, TI Wiki (http://processors.wiki.ti.com/index.php/BLE_Device_Monitor_User_Guide)
3. Texas Instruments, *Dimming Techniques for Switched-Mode LED Drivers*, LM3406 and LM3409 Application Report (SNVA605)
4. Texas Instruments, *Microcontroller PWM to 12bit Analog Out*, TIPD127 User's Guide (TIDU027)
5. Texas Instruments, *WEBENCH® Design Center*, TI Design Center (http://www.ti.com/lsds/ti/analog/webench/overview.page)

8 About the Author

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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 design from preview mode to active and added remainder of design content	1

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